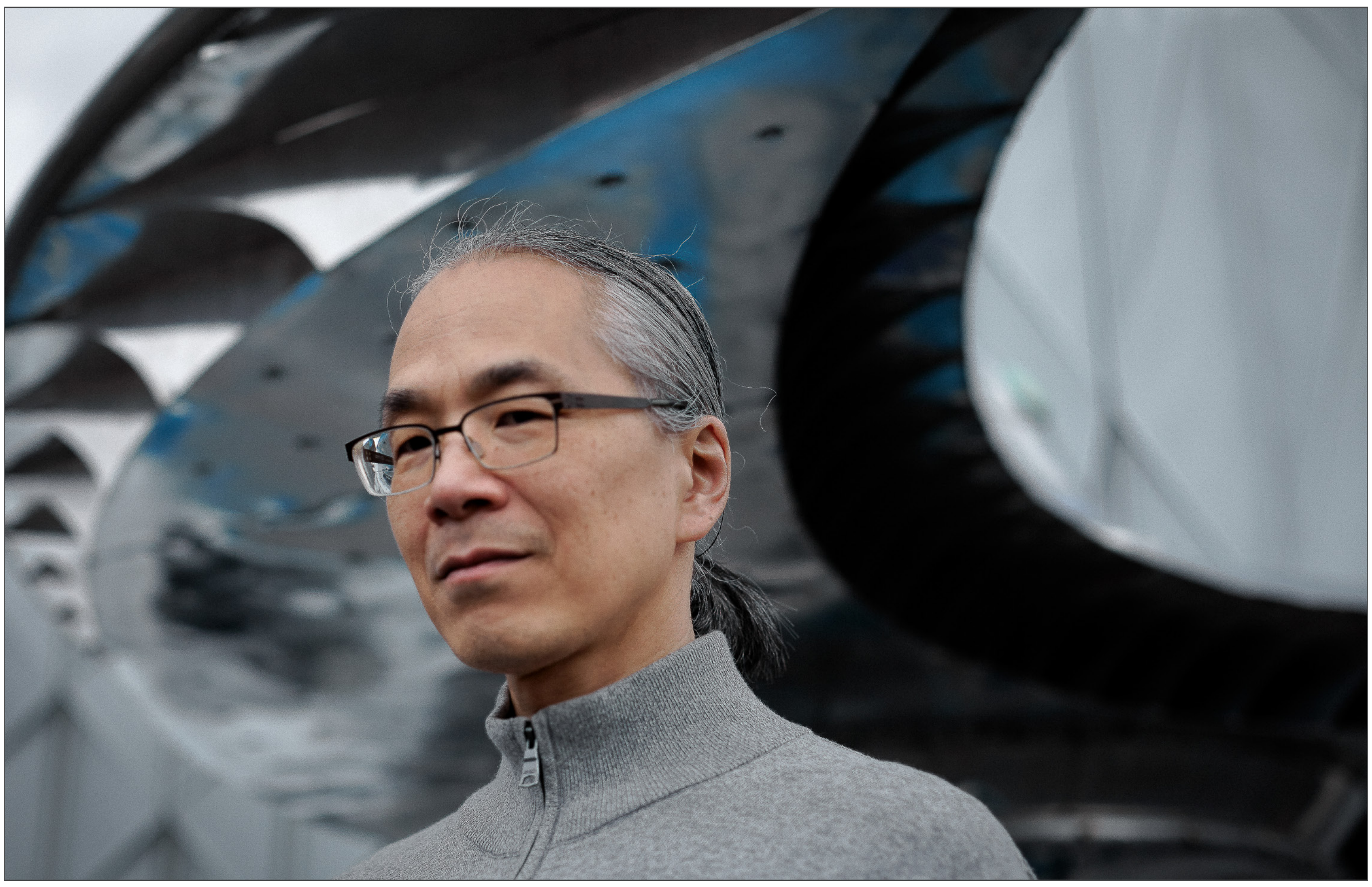
SPRING 2023

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE



Ted Chiang, science fiction author and SFI Miller Scholar, stands in front of a UFO sculpture during the 2022 InterPlanetary Festival at SITE Santa Fe. (image: Kate Joyce)

Ted Chiang named Miller Scholar

As an intellectually restless high school student in the 1980s, Ted Chiang took a break from the science fiction giants Isaac Asimov and Arthur C. Clarke to read, just for tickles, *The Feynman Lectures on Physics*. It's not quite right to say the book launched Chiang's celebrated science fiction writing career. By then, the bookish teenager had already been submitting stories to magazines. But Feynman's passage on the Principle of Least Action did spark the idea for "Story of Your Life," the short story that would make Chiang the internationally renowned writer he is today. It would just take him another decade or so to get there.

Chiang is the author of 14 short stories and two novellas that together have won 27 major writing prizes. His stories are often thought experiments that explore ideas perched at the confluence of scientific disciplines that, at first blush, may seem unrelated: behavioral science and software engineering; linguistics and physics; dendrochronology and cosmology. He holds his pieces together with emotionally rich narratives written with tautness and intentionality. The results linger long after reading. *The New Yorker* called Chiang "one of the most influential science writers of his generation." The *New York Journal of Books* said, "His writing shows how crucial written fiction still is." The *Washington Post* called his stories "a fusion of pure intellect and molten emotion."

In the winter of 2022, Chiang joined the Santa Fe Institute as a Miller Scholar, a position held by highly accomplished creative thinkers. It will be the first period in his writing career that Chiang spends substantial time with scientists. He has never interviewed a scientist for any of his stories despite the fact that, because of their fidelity to scientific ideas, they often read like they were written by one. "My understanding of science comes entirely from the written word," Chiang says. Just as SFI's scientists can't predict what fresh perspective they might glean from conversations with Chiang, Chiang can't predict whether those conversations will spur him to write new stories.

Feynman's Principle of Least Action describes (loosely) the idea that with a specified beginning and an endpoint, physicists can determine all that happened in between. When Chiang read about it, he wanted to represent the Principle through science fiction. But the "bolt of

> MORE ON PAGE 5

Complexity Explorer turns 10

On February 7, 2023, SFI celebrated the 10th anniversary of ComplexityExplorer.org, the Institute's online learning platform. For a decade, the platform has offered affordable introductory and in-depth courses to students around the globe. To celebrate its anniversary, all courses offered in 2023 will be free of charge.

More than a decade ago, SFI Professor Melanie Mitchell, who was then an SFI External Professor based at Portland State University, and then-Vice President for Education Ginger Richardson saw a need to expand the Institute's educational reach.

"I had been director of the SFI Summer School for several years, and every year there were many qualified students whom we didn't have space for, or who couldn't afford the expense or time to come to SFI in person for four weeks," says Mitchell. "There were people from all over the world contacting me all the time asking how they could get involved with SFI and attend its courses."

On the day the site launched in 2013, more than 3,500 students and researchers registered, eager for a deeper foundation in complexity science. Since then, some 77,000 learners have joined, including more than 44,000 for Mitchell's Introduction to Complexity, the platform's cornerstone offering.

> MORE ON PAGE 7

Melanie Mitchell and Ginger Richardson, who launched Complexity Explorer in 2013, celebrate the program's 10th anniversary. (image: Katherine Mast/SFI)

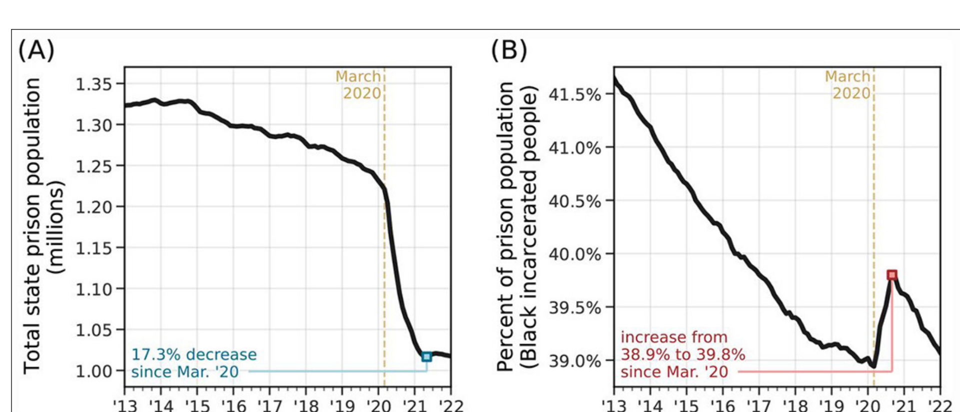
How COVID exacerbated racial inequalities in US criminal justice

As COVID-19 roared through prisons in 2020, the U.S. prison population fell by as much as 30 percent, creating the largest, fastest reduction in prison population in the country's history. But this decarceration disproportionately benefited white incarcerated people, sharply increasing the fraction of incarcerated Black and Latino people. A new study in *Nature* shows that this increased racial disparity in U.S. prisons stems in large part from a long-standing problem with the justice system: Non-white people tend to get longer sentences than white people for the same crimes.

The study, published on April 19 and co-authored by SFI External Professors Brandon Ogbunu (Yale University), Tina Eliassi-Rad (Northeastern University), and Sam Scarpino (Northeastern University), with others, explores the complex dynamics behind this disparity, which both highlighted and exacerbated existing inequalities in the prison system.

The prison population as a whole fell for two main reasons: almost all courts shut down, reducing the admission rate by 70 percent; and

> MORE ON PAGE 7



Dynamics of the U.S. prison population, showing (A) the total number of incarcerated people in the U.S. from January 2013 to January 2022 and (B) the total percent of incarcerated Black people. (image: PNAS/Klein et. al..)

INSIDE: Collective adaptation · Reporting on AI research · Information architectures · Simulation games . . .

BEYOND BORDERS

COMPLEXITY AS HISTORY & HISTORY AS COMPLEXITY

At a recent meeting at SFI, my colleagues Kyle Harper (history of Rome and pandemics) and David Wolpert (physics of information and computation) encouraged a small group of historians and complexity scientists to reflect on recent developments in the thermodynamics of computation. The premise of the meeting was that a full account of history requires some means of connecting the energetics of the natural world with information required for human societies to access and utilize this free energy. In Harper's account, history is a series of "algorithmic" inventions that more effectively couple the energy supply to societal growth, diversification, and maintenance.

The "special relationship" between history and complexity has its own curious history — starting *in media res* with Philip Anderson's foundational paper, "More is Different" (1972), in which he pointed out the absolutely central role of broken symmetry in establishing the basis for all complexity. Broken symmetry describes the "historical" selection of one state from a set of states, all more or less equivalent, with respect to the underlying symmetrical laws of physics. The best-known example is the chirality of biological molecules: nearly all biological molecules are "left-handed" or levorotatory, whereas physical law tells us that left and right should be in equal proportion. All mesoscopic and macroscopic structures (molecules and up) are built on broken symmetries, including mechanisms of gene regulation and neural decision-making — the "algorithms" that have come to define the evolution of complex life.

In 1948 Claude Shannon introduced a mathematical theory of communication that sought to explain the absolute limits to reproducing at one point in space a message encoded at another point in space. The information is measured as the number of messages that can be reliably selected from a large set — "all choices being equally likely." In other words, the Shannon information measures broken symmetry in a space of equally probable messages. Consider the game of 20 questions. One starts in a state of maximum uncertainty (symmetry — where all possibilities are exchangeable) and through a series of binary questions (animal or vegetable? etc.) symmetries are broken. If we slightly change Shannon's framework, replacing space with time (transmitting messages forward in time rather than across space), then history describes those moments in time where accidents become frozen (the archduke was shot, the Bastille was stormed, or a plague rat boarded a trade ship).

In 1961 a researcher at IBM, Rolf Landauer, attempted to connect Shannon's message-bits to thermodynamics. Landauer realized that for every broken symmetry, energy would need to be expended. He proposed that in a given temperature environment, the least possible expenditure of energy would be greater than or equal to $kT\ln 2$, where T is the temperature and k the Boltzmann constant. Hence information

> MORE ON PAGE 4

CREDITS

EDITOR: Katherine Mast

CONTRIBUTORS: Karen Coates, Carrie Cowan, Kyle Dickman, Anthony Eagan, William Ferguson, Lucy Fleming, Stephen Ornes, Abha Eli Phoboo, April Reese, Julie Rehmeyer, Dinsa Sachan, Shafaq Zia

DESIGN & PRODUCTION: Melissa Latham-Stevens

COPYEDITORS: Abha Eli Phoboo, Sienna Latham

VP FOR SCIENCE: Jennifer Dunne

Funding details for research and meetings available in associated stories at www.santafe.edu/news

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

www.santafe.edu

SFI IN THE MEDIA

As AI became part of our daily discourse this year, outlets including *The New York Times*, *Gizmodo*, and *Vox* have reached out to **Melanie Mitchell** for insight.

Michael Mauboussin appeared on *The Tim Ferris Show* to discuss how investors make decisions, the wisdom (and madness!) of crowds, race horses, and more.

In January, the *London Review of Books* reviewed **Cormac McCarthy**'s recent books, "The Passenger" and "Stella Maris."

Nerdwallet mentions SFI research in a story about one man's quest to begin building generational wealth.

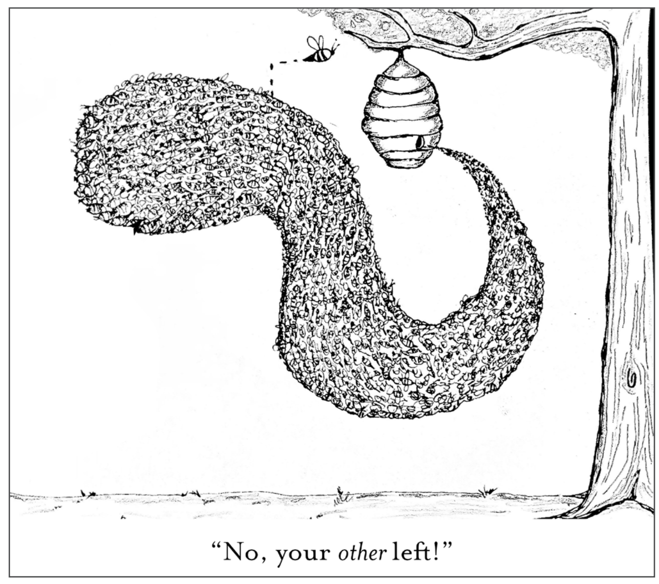
Beyond collective intelligence: collective adaptation

In times of crisis, groups of people respond in a variety of ways — with sometimes vastly different outcomes. One company might be resilient during a recession while another fails. Some groups refused to get vaccinated for COVID-19, remaining more vulnerable to the virus, while others quickly adopted the new vaccine. Why do some communities and organizations struggle to respond deftly to threats? A new paper in the *Journal of the Royal Society Interface* presents a conceptual framework that could help provide answers.

Scientists across multiple disciplines have studied collective intelligence — how groups work together and solve problems — and have tried to understand which groups successfully manage a set of tasks. These types of insights are useful, but can only help so much in dealing with day-to-day issues.

"Rather than asking how successful a team is on a limited set of static tasks, we should seek to understand how collectives grapple with more complex and dynamic situations," says SFI External Professor Henrik Olsson, one of several SFI-affiliated authors of the new paper. The authors describe the concept of collective adaptation, which maps out how human groups, from families to countries, evolve as their circumstances change.

Most studies in collective intelligence focus on a team facing a single challenge. By contrast, the new approach acknowledges that groups constantly navigate a number of different issues. For example, a country consumed with war may be ill-equipped to tackle an emerging threat like a global pandemic.



Adam Copeland/SFI

The collective adaptation framework asks pertinent questions such as, "How did a group get here?" and "Where does it go from here?". It focuses on tracing a society's journey rather than evaluating its intelligence. "We want to see how collectives adapt over time and understand the path they take in solving various problems along the way so we can be better prepared for future problems we might face," says SFI Professor Mirta Galesic, the study's lead author.

The framework may also explain why groups can be susceptible to misinformation and pseudoscience, thwarting a society's ability to tackle a challenge.

The authors have also identified models, such as those in statistical physics and cultural evolution, that scientists can use to study adaptation in human collectives. Eventually, Galesic says, they may have to combine different modeling candidates to examine various elements of this complex process.

Galesic laments that social scientists often work in silos. But the conceptual framework, which integrates findings from many different fields, will pave the way for interdisciplinary research on group behavior and will help untangle pressing societal issues.

"We as social scientists have somehow failed so far to be very useful when it comes to big problems like war, pandemics, and clmate-change denial," says Galesic. She hopes the collective- adaptation paradigm will change that.

AI research papers tend to aggregate results, leaving out potentially important granular detail. (image: iStockphoto)

Rethinking how we report on AI research

Suppose that an artificial intelligence algorithm distinguishes between female and male faces with 90 percent accuracy. Sounds impressive, right? But now, suppose that algorithm is wrong 34.5 percent of the time for darker-skinned female faces, while erring on only 0.8 percent of lighter male faces. That's a big problem — but right now, AI research papers typically report only aggregate results, without the granular detail that will allow other researchers to spot issues like these.

SFI Professor Melanie Mitchell coauthored a paper published in *Science* on April 13, pointing out this problem and proposing solutions.

The problem of aggregation is made worse in the case of models like ChatGPT, because the system doesn't have a single, clearly defined goal. Benchmarks like "Beyond the Imitation Game" have been developed for such models, combining more than 200 tasks. A particular score on that benchmark tells researchers little about the strengths or weaknesses of a given model. Furthermore, the culture of AI centers on outdoing the current state-of-the-art performance rather than carefully understanding existing models.

> The culture of AI centers on outdoing the current state-of-the-art performance rather than carefully understanding existing models.

Mitchell and her colleagues offer two primary solutions. First, scientific journals should require far more granular analyses of the performance of AI models, revealing how well they do on all relevant subgroups. This is essential for understanding a model's behavior: For example, one computer vision system distinguished between objects like ships and horses with high precision, but analysis showed that it knew nothing about ships or horses and was recognizing features of the surrounding background or watermarks naming the image's source — features that wouldn't help in real-life situations.

The second recommendation is that data should be released showing the model's results on every instance it's tested on, so that outside researchers can do further analyses.

Because so much AI development is happening in industry rather than academia, changing publication practices can't do all that's needed.

"There's a lot of discussion of whether AI systems should go through regulatory approval like we have for medical products, where the FDA requires that certain tests or studies be done," Mitchell says. "Perhaps that's the next step for machine learning products being deployed in the world."

Study: higher-order interactions & synchronization

Researchers use networks to model the dynamics of coupled systems ranging from food webs to neurological processes. Those models originally focused on pairwise interactions, or behaviors that emerge from interactions between two entities. But in the last few years, network theorists have been asking, what about phenomena that involve three or more? In medicine, antibiotic combinations may fight a bacterial infection differently than they would on their own. In ecology, survival strategies may arise from three competing species that aren't observable when looking at individual pairs.

Network theorists call these phenomena "higher-order interactions". Understanding them can be tricky, says Yuanzhao Zhang, an SFI Complexity Postdoctoral Fellow who uses network theory to study collective behaviors. How the network is represented, for example, can influence how the phenomena emerge.

In a new paper in *Nature Communications*, Zhang and his colleagues show how the choice of network representation can influence the observed effects. Their work focuses on the phenomenon of synchronization, which emerges in systems from circadian clocks to vascular networks.

Previous studies have suggested that these behaviors can improve synchronization, but the question of when and why that happens has largely remained unexplored.

"People have been using those two frameworks interchangeably, choosing one or the other based on technical convenience"

"We don't have a very good understanding of how the higher-order coupling structure influences synchronization," says Zhang. "For systems with nonpairwise interactions, we want to know, how does their representation affect the dynamics?"

Zhang and his colleagues studied two frameworks used to model interactions beyond pairwise ones: hypergraphs and simplicial complexes. Hypergraphs use so-called "hyperedges" to connect three or more nodes, analogous to how conventional networks use edges. Simplicial complexes are more structured, using triangles (and higher-dimensional surfaces analogous to triangles) to represent those connections. Simplicial complexes are more specialized than general hypergraphs, says Zhang, which means that to model higher-order interactions, triangles can only be added in regions that are already well-connected. "It's this rich-gets-richer effect that makes simplicial complexes more heterogeneous than hypergraphs in general," Zhang says.

Researchers generally don't consider the two frameworks to be very different. "People have been using those two frameworks interchangeably, choosing one or the other based on technical convenience," Zhang says, "but we found that they might be very different" in how they influence synchronization.

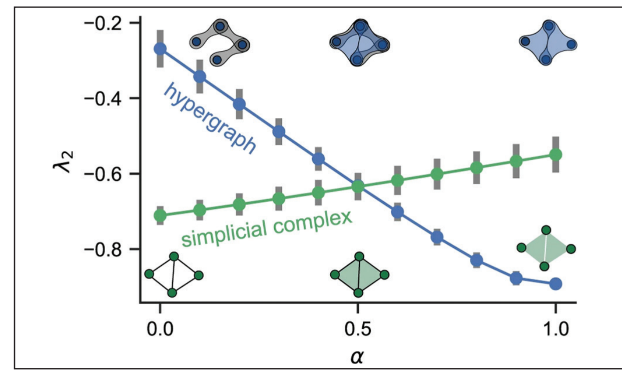
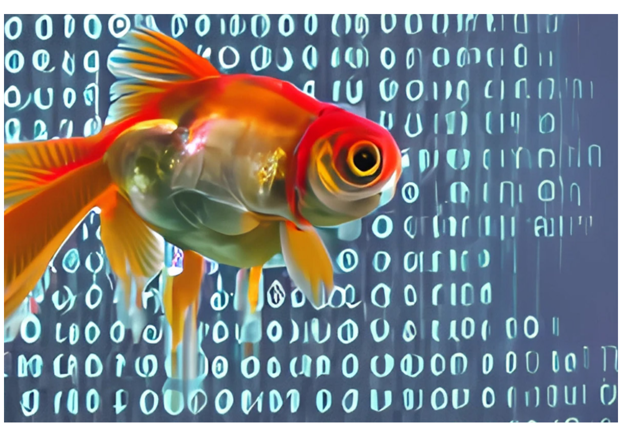


Figure 1 from study — Synchronization is enhanced by higher-order interactions in random hypergraphs but is impeded in simplicial complexes. (image: Nature Communications/Zhang et. al.)

In the paper, Zhang and his colleagues reported that networks modeled with hypergraphs easily give rise to synchronization, while simplicial complexes tend to complicate the process due to their highly heterogeneous structure. That suggests choices in higher-order representations can influence the outcome, and Zhang suspects the results can be extended to other dynamical processes such as diffusion or contagion.

"Structural heterogeneity is important not just in synchronization, but is fundamental to most dynamic processes," he says. "Whether we model the system as a hypergraph or simplicial complex can drastically affect our conclusions."

Study: could AI truly ever understand?



Goldfish swimming in an aquarium of binary code (image: Abha Eli Phoboo/Craiyon)

ChatGPT knows how to use the word "tickle" in a sentence but it cannot feel the sensation. Can it then be said to understand the meaning of the word tickle the same way we humans do?

In an ongoing debate, AI researchers are teasing apart whether large language models (LLMs) like ChatGPT and Google's PaLM understand language in any humanlike sense. The relationship between embodiment and understanding is one question, along with the nature of intelligence and understanding. Should concepts of meaning, understanding, and intelligence be revisited to create a distinction between how humans and machines understand the world?

SFI Professors Melanie Mitchell and David Krakauer survey "The debate over understanding in AI's large language models" in their paper published in the *PNAS* on March 21. The authors examine the characteristics that make LLMs impressive but also susceptible to unhumanlike errors and note the "fascinating divergence" emerging in how we humans think about understanding in intelligent systems.

"Humans do all kinds of experiments to learn about the world. Our embodiment is fundamental to our intelligence," says Mitchell. "Large language models have the appearance of understanding but do not have experiences."

LLMs are pre-trained on large datasets. Human understanding is based on a set of mental concepts that we map from our experiences as we interact with the world. This underlines the stark difference between mental models that rely on statistical correlations, such as what LLMs use, versus those that rely on causal mechanisms.

"Large language models are fact-rich like a big library and more autonomous than an abacus. And like an abacus, they are tools that can be used to augment our intelligence — a kind of steampunk mechanical library. But we cannot confuse having this tool with having an understanding," says Krakauer.

The paper also takes into account the many threads of debate in the AI research community, including the familiar human tendency to "attribute understanding and agency to machines with even the faintest hint of humanlike language and behavior" and the mystery behind how LLMs are able to give the appearance of humanlike reasoning.

"We really wanted to report on what people are talking about, to summarize the different modes of discussions. It is apparent that we need a new vocabulary to talk about it," says Mitchell.

Postdocs in Complexity X

On March 29–31, SFI hosted the 10th JSFM-SFI Postdocs in Complexity Conference. This biannual event provides a forum for postdoctoral fellows studying complex systems to share research ideas, develop new career skills, and expand their professional networks. When the program first began in 2017 it was launched as a way to serve postdocs based at SFI as well as complexity fellows funded through the James S. McDonnell Foundation.

"Our [JSMF] postdocs are drawn from a broad pool and are distributed at institutions around the world, but not necessarily at complexity institutions," says SFI Science Board Member Susan Fitzpatrick, who recently retired as President of JSMF and who has co-led the conference since it began. "We wanted to provide them an intellectual 'home' at SFI. And, it offered a way for the SFI postdocs to broaden their networks."

The format of the conference has changed somewhat since it began, says conference organizer Hilary Skolnik, Manager of SFI's Postdoctoral Fellows Program. Now, in addition to invited speakers, the conference also features more interactive sessions and prioritizes time to explore research questions in small groups.

"Each year, it's evolved in a sort of adaptive, complex-systems way," says Fitzpatrick. For instance, the small-group "research jams" used to begin and, largely, end within the conference. Now, they're a launchpad for continued collaborations throughout the year.

"These conferences are about networking, working together, and building relationships," says Skolnik. This spring's meeting reflected that idea and featured talks and field trips that explore collective intelligence through the theme of *The New Hive Mind*.

"Many of the participants at this conference will be attending for at least the third time. The group has gradually started to get to know one another, but there are still opportunities to meet new people," says Skolnik. Through creative, interactive one-on-one activities, this gathering continued to foster new connections.

While there are changes on the horizon, from funding structures to the makeup of the group as current postdocs move on to new positions and fresh graduates arrive, the conference will surely continue to evolve to support the changing needs of early-career complexity researchers.




With a goal of fostering participant connections, the 10th Postdocs in Complexity conference emphasized events like a scavenger hunt in downtown Santa Fe and small-group conversations at SFI's Cowan Campus. (images: Jeffrey Lockhart, Omer Karin, Hungtang Ko, and Scott Wagner/SFI)

Study: what limits prokaryotic endosymbiosis?

"One of the great mysteries of biology," says Eric Libby, former SFI Postdoctoral Fellow, now an associate professor at the Integrated Science Lab (IceLab), Umeå University in Sweden, "is eukaryogenesis, or how eukaryotes arose." Scientists consider this to be a period of major evolutionary transition, critical to our understanding of the history and evolution of life on Earth.

In an April 18 study published in *PNAS*, Libby, SFI Professor Christopher Kempes, and Jordan Okie from Arizona State University investigated the mystery by focusing on metabolism.

Eukaryotes likely formed when two prokaryotes — a bacterium and an archaeon — merged. This endosymbiosis, where one cell lives cooperatively within the walls of another, led to all complex life, including humans. Scientists see the traces of endosymbiosis inside the cells of modern eukaryotes, from mammals and birds to plants and fungi: cellular organelles like mitochondria and chloroplasts were once separate organisms.

Yet, in nature, endosymbioses are rare in prokaryotes.

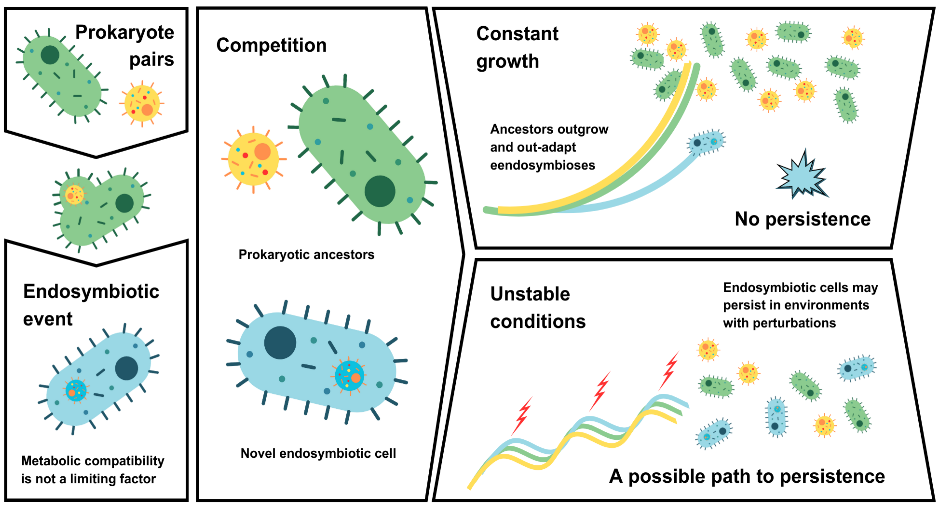
Why? Evolutionary biologists don't yet know. Many theories exist, but few have been modeled or quantified. "Metabolism is a fundamental challenge," says Libby. "If one cell swallows another can both grow? Can they compete in the population with others that do not have to sustain two cells?"

The team used three large databases with the complete genomes of a variety of prokaryotes to test evolutionary stages that might limit endosymbiosis: viability, persistence, and evolvability.

The first metabolic question — viability — asks if both organisms in an endosymbiosis can access the resources they need to survive. How hard is it for the endosymbiont — the individual living inside the other— to access everything it needs from within the host cell?

"As it turns out, it's pretty easy," says Kempes. "More than half the networks we tried to pair were viable."

In a recent paper, (from left) Eric Libby, Jordan Okie, and Christopher Kempes explore why endosymbioses are so rare in prokaryotes. (images: Gabrielle Beans/Umeå; Jennifer Richter/ASU; InSight Foto/SFI)



Endosymbiosis is common in eukaryotes but remarkably rare in prokaryotes. Metabolic compatibility isn't the limiting factor, finds a new study, but many theories remain to be tested rigorously. (image: Gabrielle Beans/Umeå)

The second and third questions — persistence and evolvability — measure how well the endosymbiosis can compete against its direct ancestors in a changing environment. The results show that most pairings were less fit and less evolvable than their ancestors, but not always.

"In some sense, it is surprising how over half of the possible endosymbioses between prokaryotes might actually survive," says Libby. "It was also surprising that given two genomes in endosymbioses, they are less able to adapt than their single-genome ancestors. Both of these results went against our initial expectations."

Okie adds, "This means they have a lower potential for diversifying and radiating across the planet, and may help explain why, with the exception of eukaryotes, there are relatively few prokaryote endosymbioses today."

However, one of the intriguing findings was that many of the modeled pairs did have an advantage when resources in the environment became scarce, says Okie. "This finding could help guide the exploration of the Earth's microbiomes to discover more prokaryotic endosymbioses living among us."

The study suggests that metabolic network compatibility is likely not the limiting factor in prokaryotic endosymbiosis. Still, a wide variety of other theories and claims exist.

"We need to start quantifying these claims," says Kempes. "How hard of a challenge is eukaryogenesis? We need a common scale, both for understanding the past and as a baseline for synthetic biologists who want to build new organelles or increase cellular efficiency." Quantifying the difficulty of this challenge is key to understanding how life may have evolved on Earth, the chances that it might exist elsewhere in the universe, and the possibility of creating it in a lab.

Study: nitrogen levels in marine life & their habitats

If it weren't for the oceans, our planet would be warming far faster. Oceans take up about 30 percent of the carbon dioxide emitted into the atmosphere each year, thanks in large part to marine microorganisms. Now, the results of a study published on March 15 in the journal *mSystems* may lead researchers to rethink the role of these microorganisms in the oceanic carbon cycle.

The work holds implications for climate modeling. Scientists have long assumed that marine microorganisms have a certain universal average ratio of carbon to nitrogen. Those assumptions underlie computer models of how the climate is changing.

In the study, titled "Microbial and Viral Genome and Proteome Nitrogen Demand Varies Across Multiple Spatial Scales Within a Marine Oxygen Minimum Zone," researchers measured the carbon-to-nitrogen ratio in marine microorganisms living in a "dead zone" off of Mexico's northwest coast. The authors found that the ratio can vary in DNA and proteins within the microorganisms depending on nitrogen levels in the surrounding environment.

"Our current way of doing Earth system climate modeling makes simplifying assumptions about the elemental contents of life, particularly marine microorganisms," says Daniel Muratore, an Omidyar Postdoctoral Fellow at the Santa Fe Institute, who led the study. "Our results suggest that a better model would take into account the supply of nitrogen and adjust cellular carbon-to-nitrogen accordingly, which would potentially have profound influences on the movement and efficiency with which carbon is removed from the atmosphere to the deep ocean in these model simulations" such as the simulations the Intergovernmental Panel on Climate Change uses in its assessments.

The study involved sequencing the genomes of marine bacteria, archaea, and viruses found in the water samples the team collected in the Eastern Tropical Northern Pacific Oxygen Minimum Zone. The researchers found that the makeup of these microorganisms is influenced by the amount of nitrogen in their habitat. In the upper part of the water column, where nitrogen concentrations were low, bacteria contained genes that had less nitrogen, while at slightly deeper levels, where nitrogen levels were higher, the bacteria contained more nitrogen.

This is possible because of how nitrogen shows up in DNA. The four types of bases found in a DNA molecule — adenine (A), cytosine (C), guanine (G), and thymine (T) — form pairs. The GC pair has one more nitrogen atom than the AT pair. Consequently, the more GC pairs there are, the more nitrogen that genome has. Similarly, different amino acid combinations can make proteins with varied nitrogen content. "For a small cell, these subtle atom-here-and-there changes add up to have a significant effect on the total nitrogen quota to keep the cell running," Muratore explains.

The team* also reconstructed the genomes of viruses that infect the bacteria. To their surprise, they found that the viruses, which they assumed would get enough resources from their host alone to thrive, were also influenced by the availability of nitrogen in the environment. Viruses at depths where nitrogen was more abundant used more nitrogen-rich nucleotides and amino acids for the proteins that make up the viral particle, the team found.

"Since viruses have no independent metabolism or nutrient uptake mechanism, we didn't expect there to be the same environmental correlation" as there was with the bacteria, Muratore says.

The study "shows us that the environmental conditions can have really sophisticated yet mechanistically intuitive influences on evolution and host–virus ecology," which allows for a better understanding of the makeup of genomes in different marine environments, says Muratore.

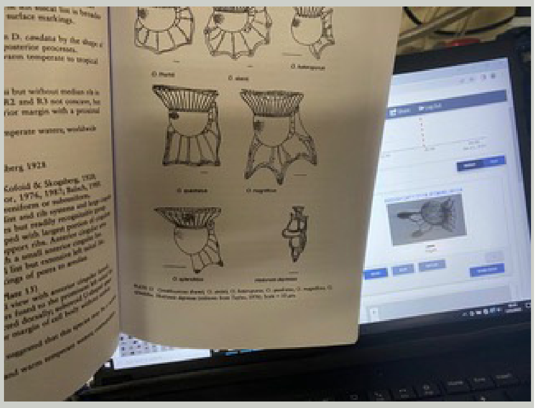
The findings also serve as an important reminder that information in cells influences the organism's physiology, they added. "In the sequencing era, I think we've implicitly adopted an understanding that genomes are simply information that appears on our computer screens instead of actual molecules that need to be synthesized from resources [such as nitrogen] that cells have to gather in order to persist."

Muratore returned to sea this past winter to sample microorganisms across a broader swath of ocean with varying nitrogen content. The research trip, conducted in tandem with researchers from the University of Hawaii and the University of Washington, will travel from the nitrogen-poor North Pacific Subtropical Gyre, near the site of the previous study, to the nitrogen-rich Equatorial Upwelling Region. The project will build on the previous work, this time focusing on whether patterns in protein and genomic nitrogen content predicted from DNA sequencing can be seen in the nucleotides and amino acids present in marine ecosystems with different nitrogen concentrations.

Blue incubators house experiments

Results of a surface seawater filtration

Recovering in situ primary production and nitrogen-fixation array



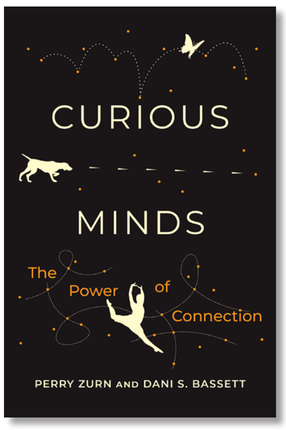
Taxonomic identification of a marine dinoflagellate

SFI Postdoctoral Fellow Daniel Muratore documented the scientific cruise that they went on from January 22 to February 18, 2023, with fellow researchers to measure the carbon-to-nitrogen ratio in marine microorganisms living across several key currents in the Pacific Ocean. Here's a selection of images from their time on board the R/V Thomas G. Thompson. (images: Daniel Muratore/SFI)

Study co-authors include Anthony Bertagnolli, Laura Bristow, Bo Thamdrup, Joshua S. Weitz, and Frank Stewart.

New books by SFI authors

Curious Minds



To most of us, curiosity is an individual experience. We all know the thrill of following where our curiosity leads us, and few of humanity's greatest achievements would have succeeded without its animating spark. Whether it's Marie Curie's unlocking of the secret of radioactivity or poet Mary Oliver's lyrical recognition of our place in the natural world, the yearning to know and understand lies at the heart of what it means to be human.

But curiosity is far more than a single-minded pursuit of knowledge or understanding, argue SFI External Professor Dani Bassett (University of Pennsylvania) and Perry Zurn (American University) in their new book, *Curious Minds: The Power of Connection*. Rather, curiosity is the product of networks, connecting the dots in unexpected ways.

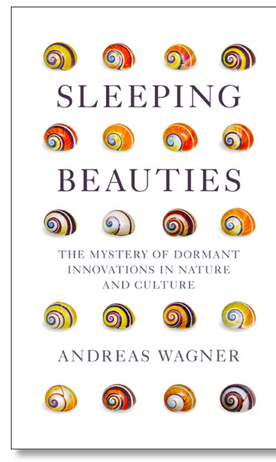
"Curiosity isn't just this capacity to acquire [information] but is rather the capacity to connect — ideas to ideas and experiences to experiences and facts to places and people to people and people to their world and to their lives and the way they want to live them," says Zurn. "Curiosity is connectional in a fundamental sense."

Bassett and Zurn, who are twins, examined 2,000 years of Western history and concluded that three types of curiosity have predominated: The butterfly, who is curious about everything; the hunter, who is focused on one or two things; and the Dancer, whose curiosity is more creative and relies on the imagination.

No matter one's individual approach to curiosity, the urge to explore is often hemmed in by limits imposed by society or institutions, Bassett adds. For example, researchers sometimes feel pressure to choose lines of inquiry that build upon a well-established body of research instead of striking out on a new path. Bassett calls this type of confining influence "the policing of curiosity." Colleagues may discourage deeply curious questions or ideas that are viewed as too far beyond the norm, they explain. "But many big discoveries happen when you move in a completely new direction."

Curious Minds is a thought-provoking work by two scholars whose own deep curiosity has given us a new way of seeing a familiar subject — and the world of possibility around us.

Sleeping Beauties



We often speak of human innovations as "ahead of their time": think Leonardo da Vinci's flying machines, Ada Lovelace's computer language, or Bi Sheng's tenth-century movable type. But evolution, we're told, has an eye on the clock, innovating only in response to environmental conditions. In his new book, *Sleeping Beauties: The Mystery of Dormant Innovations in Nature and Culture*, SFI External Professor Andreas Wagner (University of Zürich) urges us to consider another possibility. "What if," he asks, "many innovations arise before their time," in nature just as in human culture?

Take the human hand, whose nearly fifty bones and muscles allow us to write, perform surgery, or play complex musical instruments — all skills that the earliest primates, whose hands bore similar physical structures, could not have anticipated. Or consider ancient bacteria whose DNA was preserved in permafrost and recently discovered, already carrying genes that would have allowed the bacteria to resist modern antibiotics. Like our manual anatomy, this bacterial DNA is a "sleeping beauty": a structure that emerges many years before its unique capabilities can help its species truly thrive.

Wagner's 2019 book, *Life Finds a Way*, explored evolution and creativity; *Sleeping Beauties* investigates how and why the products of that creativity — natural or man-made — must sometimes wait for their moment in the sun.

In Wagner's analogy, it's not a charming prince who performs the pivotal "waking," but the environment itself. Subtle changes to our finger-bones allowed early humans to grip better than our nearest primate relatives, but it wasn't until the emergence of human culture that our hands' myriad other abilities could be exploited. Meanwhile, the genes for antibiotic resistance in ancient bacteria were "solutions in search of a problem," coding for proteins that were powerful but useless until the "right enemy" appeared. *Sleeping Beauties* offers other examples, from the earliest plant-eating insects to the grasslands of medieval Mongolia to experiments in his own Zürich laboratory and the success of Led Zeppelin.

Wagner's emphasis on the fundamental serendipity of success resonates for scientists, humanists, and artists alike. If the 50-part human hand can prove so versatile, "what about a brain with nearly a hundred billion neurons? What other skills lie dormant within, skills we have not even dreamed of?"

TED CHIANG *(cont. from page 1)*

lightning" that inspired him to write "Story of Your Life" arrived a decade later. By then, Chiang had graduated from Brown with a degree in computer science and had moved to Bellevue, Washington, where he was working as a technical writer at Microsoft. One night, he attended "Time Flies When You're Alive," a solo performance by Paul Linke, the American television actor. Among other things, the performance was about Linke's experience watching his wife die of cancer.

"Brutal," Chiang recalls. "They both knew how it was going to end." He conceived of a story that confronted the inevitable and questioned how it might feel to know the future but be unable to change it. His main character would be a linguist who develops a different idea of time through her translation of an alien language, and through her new fluency, learns that her yet-to-be-conceived daughter will die young.

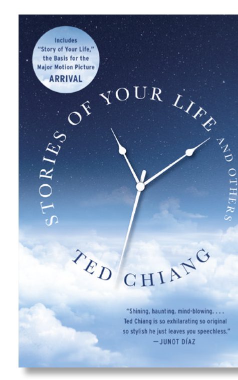
Chiang didn't start writing the story for five more years. "It's a very tough story to write on a technical level, and I probably wasn't up to the task yet," he says. Instead, he honed his skills and taught himself linguistics. When "Story of Your Life" was published in 1998, it won the prestigious Nebula, the Theodore Sturgeon, and the Seiun awards. "I'd been a nobody for my entire career," Chiang says. He'd found success in his niche. It would take almost two decades more to find success outside of it.

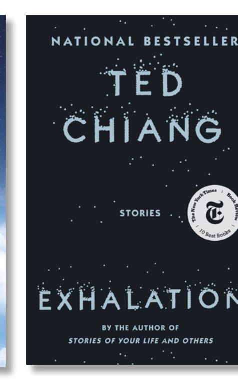
> "My understanding of science comes entirely from the written word."

Chiang's early stories were being printed by Small Beer Press, an indie publisher out of Massachusetts owned by Gavin Grant and the well-known fantasy writer Kelly Link. One day, Link and Grant told Chiang, "Your work could find a larger audience." At their prodding, Chiang found an agent who took his collection to New York publishing houses. Over the next couple years, Paramount released a $47 million adaptation of "Story of Your Life," the Oscar-nominated film Arrival that starred Amy Adams, and Chiang secured a contract with Vintage and reviews in national publications.

Chiang's latest collection of short stories, *Exhalation* (2019), became a national bestseller. Six of its nine stories have won major prizes. In "The Lifecycle of Software Objects," Chiang asks how "parents" who raise their digital creatures with the same love and attention as human parents would respond to their charge's right to self-determination. In "What's Expected of Us," he argues that the existence of a device that flashes a light one second before a button is pushed demonstrates that free will is an illusion. The stories in *Exhalation* display Chiang's curiosity and ability to explore scientific concepts that, as in all his work, are entirely self-taught.

Last summer, the normally reclusive writer took a more personal approach to contemplating big ideas when he joined a conference at SFI. The meeting had been convened to consider what a theory on life's origins needed. What were the physical limitations of intelligent life elsewhere in the universe? Could intelligent life be constructed with molecular building blocks beyond carbon, hydrogen, and oxygen?





Ted Chiang's "Story of your Life," the basis for the film Arrival, is featured in his 2002 collection, Stories of your Life and Others. Chiang's 2019 national bestseller collection Exhalation has won multiple awards. (images: Penguin Random House)

On a monsoonal afternoon, he sat in a conference room in Santa Fe with comparative and synthetic biologists, cosmologists, theorists, other writers, and experts on intelligence — all discussing in language grounded in the expertise of their respective disciplines one of humankind's oldest questions: Are we really alone in the universe? The scene could have been lifted from one of Chiang's own stories, except that this time, he was a central character.

Will his experience as a Miller Scholar inspire him to write? "I really can't know," Chiang says. But, for the first time in his writing career, Chiang has license to discuss science with scientists — to contemplate science's future alongside those defining it.

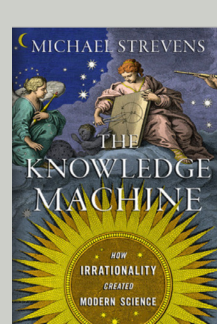
What we're reading

Books chosen by SFI scholars on Philosophy of Science

What is science? What are its methods? To what degree can we verify its conclusions, and, in so doing, verify our verifications? In his essay "Of the Standard of Taste," David Hume offhandedly complained that nothing can be verified, and that the ostensibly "objective" truths of science are even more liable to change than those of aesthetics. Ptolemy's truths are dead, but Homer's truths survive. "Scientific conclusions which prevail in one age tend to explode in a subsequent age, when their absurdity has been detected…[and] nothing has been more liable to the revolutions of chance and fashion than these pretended decisions of science."

Two centuries later, Paul Feyerabend differed. Although he agreed that scientific conclusions are subject to overthrow and change, he argued against Hume that "there is no idea, however ancient and absurd, that is not capable of improving our knowledge. The whole history of thought is absorbed into science and is used for improving every single theory." For Feyerabend, philosophical discussions such as Hume's tend to be far removed from the untranslatable context of scientific practice. One of the most obvious historical patterns that skeptics like Hume neglect is the fact that science inevitably happens with incredible results. To philosophize concerning the nature of science is to ignore the crucial, living context that determines the meaning of every age's scientific advances.

Though intellectual virtuosos seldom agree on the nature and utility of scientific investigation, philosophies of science continue to describe and shape scientific outlooks. In celebration of all the disagreements within and about science, each of the books in this installment of What We're Reading relates a unique story about thinkers working together within a deeply shared yet mysterious context, exploring questions about scientific knowledge, its meaning for life, and its capacity to yield lasting truths.



AVIV BERGMAN
SFI External Professor & Professor, Albert Einstein College of Medicine

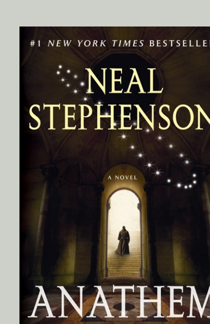
***The Knowledge Machine*, by Michael Strevens**

In this exploration of how scientific knowledge evolves "irrationally," Strevens provides a clear and engaging overview of the modern scientific method, offering numerous examples to illustrate his points. Although some sections may challenge audiences appreciative of the value of beauty and aesthetics in scientific endeavor, it is a rewarding read for anyone interested in contemporary philosophies of science.

KELLE DHEIN
SFI Complexity Postdoctoral Fellow

***Anathem*, by Neil Stephenson**

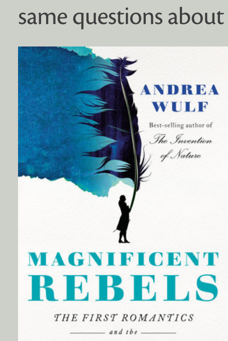
Anathem is a long but light sci-fi adventure story about a monastic community of intellectuals forced into the secular world. Philosophically, the book explores realist and nominalist views of abstract concepts. It also draws on Husserl's phenomenology in a spooky way that I found fun.



MIRTA GALESIC
SFI Professor

***Magnificent Rebels*, by Andrea Wulf**

The 18th-century Jena community of thinkers described in Andrea Wulf's book was not only similar to SFI, but was grappling with many of the same questions about how science should be done. Together we explore the interplay of science and art, empiricism and idealism, individual and collective thinking, and the role of stable funding for radical ideas, scientific cooperation and competition, and clear communication.



In memoriam: Herb Gintis

Herb Gintis (right) with longtime collaborator Sam Bowles in 1974. (image: Getty Images)

Herb Gintis, who drew on a variety of disciplines to study human society, passed away on January 5, 2023, in Northampton, Massachusetts, at the age of 82. He had been an SFI External Professor since 2001 and was a professor emeritus at the University of Massachusetts Amherst, where he had taught since 1974.

Gintis was a deep thinker — perpetually curious, widely read, and highly opinionated. He challenged orthodoxy and conventional wisdom, followed nontraditional paths, and was never afraid to change his mind when encountering new ideas. In the mid-1960s, as a young scholar close to completing his Ph.D. in mathematics at Harvard University, Gintis decided to take a break from academics to become a sandal maker. As he became actively involved in the anti-war movement and Marxist intellectual currents of the time, he felt mathematics was too disconnected from the real world. When he returned to Harvard, he switched his Ph.D. to economics and completed his dissertation, "Alienation and Power: Towards a Radical Welfare Economics," in 1969.

"Herb was always interested in: How do we become the kind of person that we are?" says SFI Professor Sam Bowles, who completed his Ph.D. in economics in 1965 at Harvard where he met Gintis. "He wanted to know where our tastes and desires and norms and ethics come from. They may seem a mixed bag, but those are all things that determine whether we prefer one state of the world or another. His dissertation was a powerful critique of the then-standard economic models."

Their collaboration began in earnest when, in 1968, Gintis and Bowles received a set of questions about economics and inequality from Dr. Martin Luther King, Jr., who was organizing the Poor People's March, just before he was assassinated. Shocked to realize that their training in economics left them unprepared to answer Dr. King's questions, the pair resolved to change the direction of economics education. After a battle to get approval from Harvard, they co-taught a course called "The Capitalist Economy: Conflict and Power."

Gintis wanted to know what drove people's values and desires; Bowles was focused on economic injustice. Those questions paired well, they thought, and together, they launched a collaboration and friendship extending over almost half a century.

"Herb was like my brother," says Bowles. "We spoke every day."

In 1974, they were hired by the University of Massachusetts Amherst. Two years later they published their first of several books. *Schooling in Capitalist America* received wide attention around the world and was reprinted in several languages. The idea for what would have been their second book, however, floundered as they wrote it — they realized after years of research that the premise was incorrect.

"It's exciting to find out that you are wrong," says Bowles. "It means science has moved on."

That willingness to revise his thinking was a hallmark of how Gintis interacted with other researchers. "Herb loved a vigorous debate and would push against ideas as a way of testing them," says SFI External Professor Eric Beinhocker (Oxford University). "But he was never dogmatic, and was constantly bouncing ideas off of others, learning, listening, and evolving his own thinking."

He also read widely and shared his opinions of the books he read, leaving more than 350 detailed reviews on Amazon. He readily incorporated new ideas into his own work as he encountered them. "Herb was incredibly wide-ranging in his knowledge and interdisciplinary in his scholarship," says Beinhocker. "He had a perpetual curiosity that kept him constantly exploring for new and better ideas."

In 1986, Gintis and Bowles published their second book, *Democracy and Capitalism*, a critique of both philosophical liberalism and Marxism as inadequate foundations of democracy.

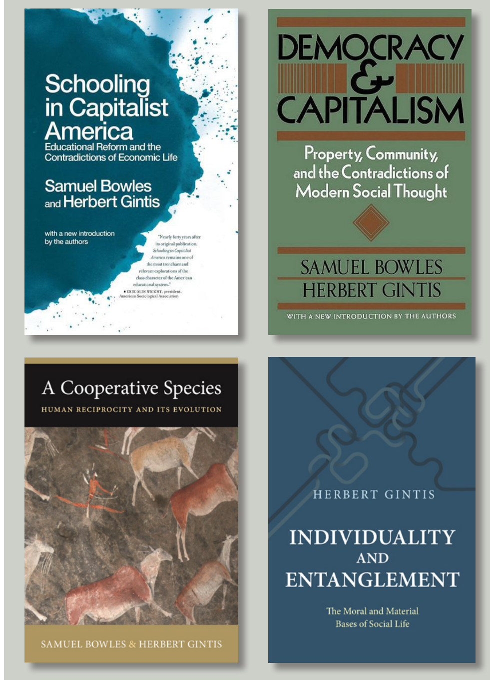
Their third book, *A Cooperative Species: Human Reciprocity and its Evolution*, published in 2013, took a new approach to sociobiology. Its aim was to explain human cooperation and altruism. Contrary to popular wisdom in both economics and biology, they suggested, cooperation in humans doesn't stem solely from self-interest. It also comes from our "better angels" — our predisposition, genetically and culturally evolved, to value fairness and collaboration toward a common goal.

That book is one reason SFI Professor Mirta Galesic became interested in SFI. "I inhaled it," she says. "Among other techniques, they used agent-based models to understand cooperation in humans. It's so difficult to do clean and simple ABM, and they showed how to do it. It was very important for my own work."

> "They say that innovation happens at the edges. Herb had an instinct for where those edges were and how to bring them together."

Gintis loved a good debate, but he also made a point to share his praise of work he found inspiring, whether the work came from an established academic or an early-career researcher. "He would write to me saying how much he liked some of my ideas," recalls Galesic. "It meant the world to me."

SFI External Professor Suresh Naidu (Columbia University) reflects a similar sentiment. He was an undergraduate student in mathematics at the University of Waterloo in the early 2000s when he first encountered Gintis and Bowles' work. It "was a revelation, one of the things that made me resolve to do a Ph.D. in economics at UMass Amherst (without having taken a single economics class!)," he writes. "It was a chance to see the work process of a real genius. Only later would I realize how unique Herb's talents were even in a discipline filled with smart and eccentric people."



Gintis and Bowles co-authored three books over the course of their multi-decade friendship. Gintis' last book, "Individuality and Entaglement," published in 2003, was his third monograph and "his most important book," according to External Professor Eric Beinhocker.

In 2013, Gintis published a monograph — the third he'd written since becoming professor emeritus at UMass Amherst in 2003. *Individuality and Entanglement* uses research on gene-culture evolution, game theory, complexity science, and more to develop an analytic framework to unify behavioral sciences.

"In my opinion, it is his most important book," says Beinhocker. "They say that innovation happens at the edges. Herb had an instinct for where those edges were and how to bring them together."

After Gintis's passing, Bowles received hundreds of emails from Herb's colleagues and students. "People talk about how brilliant he was, of course, but there has also been this outpouring of affection," says Bowles. "He was very unusual — his brilliance, his thought, his willingness to try out quite improbable ideas. Herb spent a lifetime of scholarly passion against injustice and untruth, challenging the old and creating new ways of doing the many sciences of human behavior."

The complexity of human history

Things fall apart. That's a coarse interpretation of the wisdom in the second law of thermodynamics: Entropy increases over time. And yet, human societies have gotten ever more intricate, moving from small hunter-gatherer bands to a worldwide society with megacities. This paradox is fundamental to understanding human history, but historians have largely ignored it, instead focusing on particular, consequential personalities and events.

The March 15–17 working group "The Interactions of Information and Energy Propelling Human History" aimed to change that, drawing together historians, physicists, biologists, anthropologists, and computer scientists to analyze history in a whole new way. "We're bringing the tools and spirit of complex-systems science, along with SFI's spirit of boldness and lack of fences, to tackle human history," says Kyle Harper, an SFI Fractal Faculty member and a historian at the University of Oklahoma.

If entropy is disintegration, its opposite is information. Information theory, an approach from statistical physics, offers a useful lens on biology: organisms store information about the external environment in their genomes and continuously perform computations to stay away from thermal equilibrium.

The workshop aimed to bring this same lens to history. Modern societies will be viewed as a kind of supercomputer running "algorithms" acquired over the course of our history — how to turn grass seeds into edible calories; how to combust fossil fuels to do work; how to synthesize reactive nitrogen. These algorithms are the key to controlling energy flows, keeping the system out of thermal equilibrium and thus escaping the trap of the second law of thermodynamics.

From this perspective, human history is a series of information revolutions that created energy revolutions: fire, tools, agriculture, writing, money, empiricist science, fossil fuels, synthetic chemistry, computers. Each revolution has created an ever larger and more complex system, always under constraints, competing with dissipation.

"I think this could be a new and fundamental way to think of the place of human culture in the physical universe," Harper says.

Looking at history through the lens of physics, each "information revolution" of fire, tools, agriculture, and more has created an ever-larger complex system. (image: Landbouwinstrumenten, inzending van Busby op de Great Exhibition, Claude-Marie Ferrier (possibly), 1851/ Rijksmuseum)

BEYOND BORDERS *(cont. from page 2)*

requires a source of energy and as this increases the noisier (higher temperature) the environment. Landauer unites elements of Anderson and Shannon with thermodynamics, and in effect tells us that the longer a history (the more frozen accidents the Shannon information counts), the more energy needs to be expended.

The problem with the Landauer bound is that while it places a lower bound on the cost of information, it tells us nothing about the cost of the decision the information encodes. By analogy, Landauer might say opening and closing a door requires more energy than flicking a switch, but ignores the fact that the door provides access to meager calories in a pantry, whereas the switch turns on a monstrous hydroelectric dam. As Shannon and Weaver wrote in 1964, "information must not be confused with meaning" such that for two equally informative messages, one is "heavily loaded with meaning and the other . . . is pure nonsense". As David Wolpert puts it, we are less often worried about the cost of a bit and more interested in "the bang per bit."

One of the keys to understanding the cost of the meaning of information is to explore more carefully how the information is used — how an algorithm or procedure takes an input and processes it into an output that we would describe as the "correct" solution to a local problem. This goes beyond moving a message around in space or time to consider how the message is transformed into something useful — how a message is computed. This is the problem that Charles Bennett tackled in his 1988 paper "Logical Depth and Physical Complexity." Bennett showed that a principled measure of complexity can be calculated as the running time of the fastest computer making use of the shortest instruction set (the Kolmogorov complexity) to achieve a desired solution.

The Harper–Wolpert meeting sought to take these foundational insights and ponder how they might be extended by considering recent progress in the non-equilibrium thermodynamics of computation. This in brief builds on a profound connection between energy dissipation and non-reversible transitions between metastable states described by a Markov process. It is not clear how this will be done. What is clear is that measures of history bear a very close resemblance to measures of complexity. And that as Murray Gell-Mann and Seth Lloyd showed us in their work on "Effective Complexity," anything complex must have a long history. History should not be confused with time but identified with the steps of social procedures. History does not flow like a river but clicks like a wheel, and whereas in some centuries it is cacophonous in others it is barely audible.

— David Krakauer
President, Santa Fe Institute

Information architectures in an era of change

In just a few decades, our information architectures — the ways in which we communicate and consume information — have changed dramatically, with significant implications for society. An SFI working group takes on some of the big questions surrounding the impacts of these changes and related governmental policies. (image: Manuel Pena/Unsplash)

In 1990, three-quarters of Americans got their news from thin sheets of paper printed with ink, delivered to their doors and sold on street corners nationwide. It took just 20 years for the internet to surpass the newspaper — and television and radio — as our primary source of information and news. In just a blip of evolutionary time, humanity has seen seismic shifts in the way we create, disseminate, incorporate, and regulate the flow of information.

"The world has changed very, very rapidly changed," says SFI External Professor Paul Smaldino. Technologies and cultures intersect in unprecedented ways. We have more access to more information than in any previous time, which means "we are more uncertain than ever before about what information is relevant to us, what information is trustworthy, what to believe, and what kinds of behaviors to adopt or not," he says.

Researchers use the term "information architectures" to describe the rules and norms that govern the spread of information, and they hypothesize that these architectures serve as a dominant force shaping society, its interactions, innovations, and ideologies. But we lack a comprehensive vocabulary for these phenomena. Our rich theories of cultural evolution were developed with pre-industrial societies in mind, and say little about social change in the era of smartphones and social media.

"We need a new language for talking about the structure of society that encapsulates the way information is transmitted, the way people have access to information, the way certain kinds of information is constrained," says Smaldino.

It's a prompt for the SFI workshop he is co-organizing ("Information Architectures as Sociotechnical Competitions," May 9–11) with more than 20 participants from diverse disciplines — sociology, anthropology, biology, cognitive and political science, physics, and engineering — to address a host of emerging questions: What is the most useful definition of information architecture? How do structures with top-down constraints on information (e.g., China) compare with those with minimal regulation (e.g., the United States)? How do we build theoretical models of social change and cultural evolution that take into account modern complexity — including massive inequality?

"We're not going to solve this problem with this workshop," Smaldino says, but it's a starting point for exploring emerging needs in this uncertain new world of information. "Are there actionable ways to make things better? I don't know if the answer to that is yes," Smaldino says, "but I want to try to find out."

COVID DECARCERATION *(cont. from page 1)*

prisoners were released in response to the pandemic. But in most states, the released prisoners were not disproportionately white. Instead, the primary driver of the disparity was more subtle. With fewer prisoners coming in over the course of the pandemic and with white prisoners disproportionately serving shorter sentences, the population skewed Black and Latino.

"These disparities in sentencing have long been the object of criticism, and this shows how such problems can ramify in unexpected ways," Brandon Ogbunu says. "It has a lot of consequences and ripple effects through the criminal legal system."

In addition, with the courts closed, prosecutors pushed hard to get pre-trial plea deals so that cases could be completed anyway. Studies show that plea deals result in a disproportionate number of Black defendants spending time in prison.

"You had a lot of individuals who were left behind in prison and thus had a higher chance of being infected by COVID during the pandemic," Ogbunu says. "That means this is also a public health issue, and even a human rights issue. The pandemic acted like a stress test for the criminal legal system, and that stress test revealed these disparities."

A third dynamic played a role too: While Black and Latino individuals continue to be incarcerated at higher rates than whites, that disproportion has been steadily falling over the last ten years, with a greater percentage of whites being incarcerated. So, while Blacks are overrepresented by a factor of six in the general prison population, they are only overrepresented by a factor of two in new admissions. Decreasing the flow of new admissions thus increased the non-white population.

> "The pandemic acted like a stress test for the criminal legal system and that stress test revealed these disparities."

These deep structural problems are particularly urgent at this moment, says co-author Brennan Klein (Northeastern University). "There is, right now, a large backlog of cases in the criminal legal system still left over from the delays during the early stages of the pandemic. It forces us to immediately consider the disparities in sentencing in our legal system and work towards reforms that bring a more equitable and just system."

Because most prisons don't automatically make their data public, "the data curation aspect is really one of the great marvels of this project," Ogbunu says. The team scoured websites from around the country and filed reams of Freedom of Information requests for prison records from 2018 through 2021. They've made the data public so that other teams can look for additional patterns within it.

"The dream for this is that people will actually be released from prison," says Scarpino. "Of course, that's going to require lawyers to make the case and judges to decide. But we demonstrate that sentencing is unjust, and that means that there are people who are incarcerated who would not be if they had a different skin color. My expectation and hope is that this will inspire a growing movement around doing these population-level analyses to begin to remediate this kind of racial injustice in mass incarceration."

Simulations for pandemic resilience

In 2015, Bill Gates said, "If anything kills over 10 million people in the next few decades, it's most likely to be a highly infectious virus." Though his words were prescient — COVID-19 has now killed seven million people and rising — Gates wasn't a psychic. He was guided by a series of simulation exercises he'd helped fund, gathering pandemic response specialists to play out how a pandemic might go.

But if SFI Science Board member and External Professor Lauren Ancel Meyers (UT Austin) is right, simulation games can teach us far more. She and her colleagues organized a workshop at SFI May 17–18 to reimagine how pandemic simulation games can help us prepare for the superbugs to come, bringing together epidemiologists, military war game specialists, officials from the Centers for Disease Control and Prevention, and experts in human behavior, cognitive science, and artificial intelligence (AI). "In the military, simulation games have proven powerful tools for learning about and advancing human decision-making," Meyers says. "To equip the globe for future pathogen threats, we need to bring the state-of-the-art into public health preparedness."

Pandemic simulation games can accomplish a variety of goals, from advancing our understanding of human behavior to designing robust strategies to combat future threats and training the decision-makers of tomorrow.

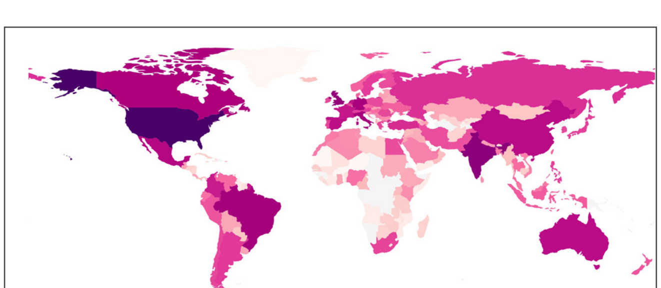
For example, designers might create a game to help build an AI-enabled decision support system, collecting data on how players perceive information and make decisions to train the AI. Games can also help to hone surveillance systems or public communication strategies by collecting data on how people make decisions based on different types of information.

Alternately, a game can be used to train decision-makers, giving them experiences in a safe, controlled environment so that they can better assess risks, cope with uncertainty, and predict outcomes of decisions. At the workshop, Meyers will demonstrate just such a game that she and her team are building for the city of Austin. The game will help city managers improve their command and coordination plans, testing decisions such as: When should they set up an emergency operations center when a new pathogen emerges? Who should be part of it? What authority and resources should it have?

"By building games that force players to confront unprecedented pathogen threats and the cascading interdependencies between our health, social, political, and environmental systems," Meyers says, "we can help to overcome the failures of imagination that left us unprepared for COVID."

COMPLEXITY EXPLORER *(cont. from page 1)*

ComplexityExplorer.org has also helped advance one of SFI's earliest and most central goals, says Richardson, who interviewed for her position in 1986 with then-president George Cowan. "When Cowan explained his vision for the Institute, it was clear it transcended a simple elite endeavor," she says. "George thought SFI's work could create a more scientifically informed citizenry capable of meeting world challenges."



Since its launch in 2013, ComplexityExplorer.org has drawn learners from 146 countries around world. (image: Carrie Cowan/ SFI)

The platform has grown to engage learners across the world; participants have registered from 146 nations, including 31 of the U.N.'s least developed economies. While the U.S. leads in overall numbers, Brazil, Canada, England, Germany, India, and Italy all have large audiences. Recent years have seen growing participation from Africa and Southeast Asia.

To meet learners' diverse interests, SFI researchers have created more than 20 courses, tutorials, and lectures. The offerings include everything from fundamentals like SFI President David Krakauer's lecture "What is complexity?" to more specialized and technical topics such as tutorials on machine learning and computation theory. Generous donations and grants allow SFI to offer most courses at no cost to learners.

"I'm incredibly proud that we have made so much world-class course material accessible to so many people," says Mitchell. "Complexity science is a niche area, one that is not well-represented at most universities, so I think Complexity Explorer has a centrally important role to play in getting many of these ideas out there, for anyone to engage with."

The need to bring a complex-systems approach to thinking about the world's big problems is perhaps more evident now than in 2013 or in 1986. SFI plans to continue expanding the content, subject matter, and faculty represented on ComplexityExplorer.org, says Leah Brennan-Magidson, SFI's Manager of Online Education Programs. "We will continue to prioritize making complex-systems science and the methods and techniques developed at SFI accessible to all, while finding new and innovative ways to engage with our community of learners."

The development of the ComplexityExplorer.org platform was supported by a grant from the Templeton Foundation. Course development has been supported by grants from the National Science Foundation, National Endowment for the Humanities, and private donors.

ACHIEVEMENTS

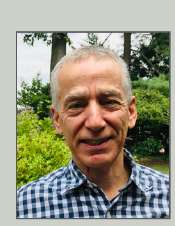
External Professor **Eleanor Power** (London School of Economics) was awarded a Research Leadership Award from The Leverhulme Trust, which will fund a new four-year project on reputational poverty traps and social inequality.

External Professor **Wendy Carlin** (University College London) received the inaugural RES Medal for Services to the Economics Profession from the Royal Economic Society.

External Professors **Amos Golan**, (American University) **Matthew Jackson** (Stanford University, SFI Science Board) and **Doug Erwin** (Smithsonian National Museum of Natural History) were elected to the American Association for the Advancement of Science (AAAS).

Eleanor Power

Wendy Carlin



Amos Golan

Matthew Jackson

Doug Erwin

Upcoming Community Lectures

Join us at The Lensic Performing Arts Center, live-stream, or catch up later on YouTube. More details at www.santafe.edu/events.

May 23
A Vision for the Future of Physics
John Baez (University of California, Riverside)

June 20
Magnificent Rebels: The First Romantics and the Invention of the Self
Andrea Wulf (SFI Miller Scholar)

July 25
The Future of Artificial Intelligence
Melanie Mitchell (SFI)

August 23
How the Brain Makes You: Collective Intelligence & Computation by Neural Circuits
Vijay Balasubramanian (University of Pennsylvania)

Stanislaw Ulam Memorial Lecture Series
September 19 & 20
Evolving Brains: Solid, Liquid, and Synthetic
Ricard Solé (Universityat Pempeu Fabra, SFI)

October 18
Towards Collective AI
Radhika Nagpal (Princeton University)

RESEARCH NEWS BRIEFS

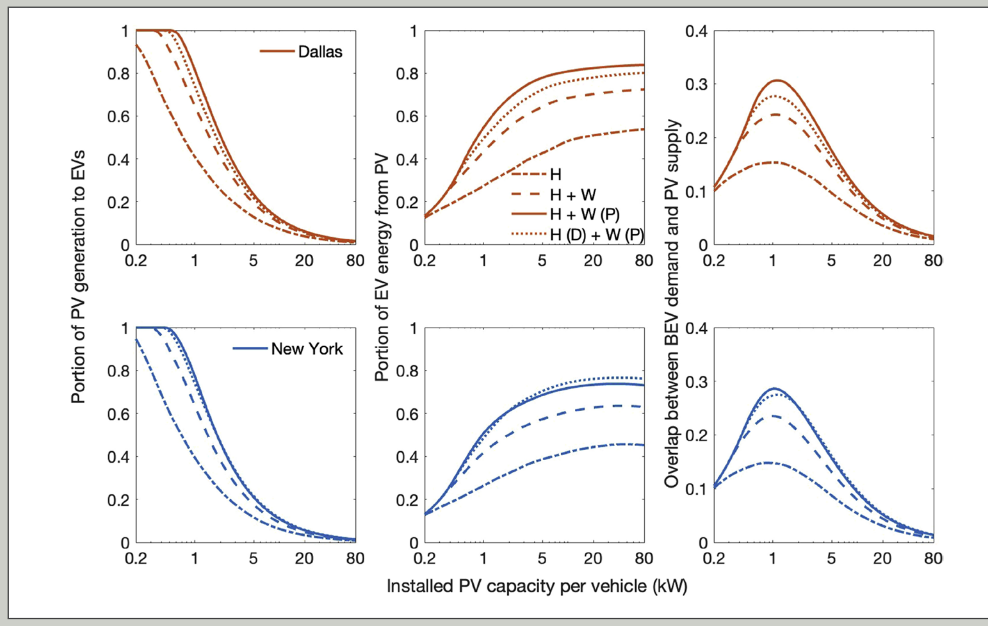


Figure 3 from "Strategies for beneficial electric vehicle charging to reduce peak electricity demand and store solar energy": Importance of relative adoption levels of PV and BEVs on marginal electricity supply/demand impacts. (image: PNAS)

STRATEGIES FOR MAKING EV CHARGING BENEFICIAL FOR THE POWER GRID

Cleaning up the transportation sector is key for meeting climate goals, but as we move to "green" up travel, we risk overstraining the electric grid or requiring costly power capacity additions. Most people tend to charge EVs at home, at night — the opposite of when the most solar power is generated. A March 15 paper in *Cell Reports Physical Science* co-authored by External Professor Jessika Trancik (MIT) says that travel behaviors are predictable and diversified in ways that can help. If we choose where to locate chargers based on these aspects of travel behavior, EVs can actually help the grid by distributing load more effectively.

Trancik and her colleagues analyzed data from two very different U.S. cities — New York and Dallas — about travel and charging behavior. They found that installing less expensive, slower charging stations at workplaces was an effective approach to utilizing solar power, and that combining workplace charging with low-tech, preprogrammed devices to stagger home charging during evenings can essentially eliminate the electricity demand peaks from EVs that would otherwise require power system capacity expansion.

Read the study "Strategies for beneficial electric vehicle charging to reduce peak electricity demand and store solar energy" at doi.org/10.1016/j.xcrp.2023.101287

GROUP THREAT, POLITICAL EXTREMITY & COLLECTIVE DYNAMICS ONLINE

When people feel threatened by an out-group, they focus their attention on a few voices in their own group rather than listen democratically to many different viewpoints — or so social scientists have believed. They've also thought that more politically extreme groups tend to be guided by a smaller number of influential voices. But no large-scale data backed up these theories — until now.

Former SFI Postdoctoral Fellow Gizem Bacaksizlar Turbic and SFI Professor Mirta Galesic tested these ideas, publishing their results in *Scientific Reports*. They compared the network structure of comments in four publications with varying political persuasions — *Mother Jones, The Atlantic, The Hill*, and *Breitbart News* — after seven major news events. And indeed, the more extreme publications had few, highly influential commenters, while in moderate ones, influence was more evenly distributed. Furthermore, events that made a group feel threatened, such as the election of Donald Trump, caused that group to focus its attention more narrowly to a few influential individuals.

Read the study "Group threat, political extremity, and collective dynamics in online discussions" at doi.org/10.1038/s41598-023-28569-1

SOCIAL COPYING & TIPPING POINTS

We've all observed social contagion in humans: When one person laughs, it's hard not to laugh too, or if someone screams "Fire!" in a movie theater, everyone stampedes toward the door.

The Adouin's gull discovered a particularly good beach for breeding in Spain in 1981, and within six years, half the world's population of the bird was breeding there, climbing all the way to 73 percent by 2006. But foxes discovered the birds. Although the foxes only killed a few adult birds, the population crashed as birds moved elsewhere. In 2017, only three percent of the world population bred at the beach.

External Professor and UC Davis professor emeritus Alan Hastings and colleagues analyzed the fluctuating population with a detailed mathematical model and found that it could be explained by the departure of a few individual birds influencing others to leave too, until only a few die-hard patriots of that particular beach remained.

Read the study "Social copying drives a tipping point for nonlinear population collapse" at doi.org/10.1073/pnas.2214055120

IMPLICATIONS OF NO-FREE-LUNCH THEOREMS

In the 18th century, the philosopher David Hume observed that induction — inferring the future based on what's happened in the past — can never be reliable. In 1997, SFI Professor David Wolpert with his colleague Bill Macready made Hume's observation mathematically precise, showing that it's impossible for any inference algorithm (such as machine learning or genetic algorithms) to be consistently better than any other for every possible real-world situation.

Over the next decade, the pair proved a series of theorems about this that were dubbed the "no-free-lunch" theorems. These proved that one algorithm could, in fact, be a bit better than another in most circumstances — but only at the cost of being far worse in the remaining circumstances.

These theorems have been extremely controversial since their inception, since they punctured the claims of many researchers that the algorithms they had developed were superior to other algorithms. As part of the controversy, in 2019, the philosopher Gerhard Schulz wrote a book wrestling with the implications of Hume's and Wolpert's work. A special issue of the *Journal for General Philosophy of Science* was devoted to Schulz's book, and included an article by Wolpert himself.

Read the study "The Implications of the No-Free-Lunch Theorems for Meta-induction" at doi.org/10.1007/s10838-022-09609-2

FOR MORE RESEARCH NEWS BRIEFS, VISIT **SANTAFE.EDU/NEWS**

E-PARALLAX

Sign up for our monthly e-newsletter at **www.santafe.edu/subscribe**

SPRING 2023

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

1399 Hyde Park Road
Santa Fe, New Mexico 87501
505.984.8800

www.santafe.edu