WINTER 2023-2024

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

Artwork by Jan Gerrit Schuurman is currently displayed at SFI's Cowan Campus. In describing his work to SFI, Schuurman wrote, "Each of my drawings and paintings is a renewed effort to extend oneself, to differentiate novel qualities. To rebel against conformity, to persist without fate — to disrupt the cycle, any cycle." (image: "Pregnant Light." charcoal, graphite, and pastel on canvas by Jan Gerrit Schuurman)

Modeling the UN's biodiversity goals

In 2015, the United Nations published its 2030 Agenda for Sustainable Development, setting aspirational and interconnected targets for economic, environmental, and health well-being to be met by 2030. The intent for these goals was simple: to "provide a shared blueprint for peace and prosperity for people and the planet, now and into the future." The agenda included 17 goals comprising 169 target conditions.

As we enter 2024, however, it is increasingly clear that the global community will fall woefully short of the U.N. targets. The numbers from a 2023 progress report paint a bleak picture: only 15% of the 169 targets are on track; half are at least moderately off-track while over one-third are stagnating or regressing. For a pair of SFI External Professors, the lack of progress on biodiversity goals is particularly troubling.

"We are concerned about the sloth with which the environmental agenda is proceeding — it is way too slow," says SFI External Professor Andy Dobson (Princeton University). Dobson is organizing a "Biodiversity Protection" working group at SFI alongside SFI External Professor Monique Borgerhoff Mulder (UC Davis). "People do not appreciate the magnitude of environmental damage and underestimate the speed at which things are changing," he adds.

The meeting, scheduled for February 12–15, will convene biologists, economists, and social scientists to explore the probabilities and consequences of falling short of the U.N. goals for biodiversity. The working group will use advanced statistics to model ecosystem and socioeconomic conditions — biodiversity, climate, vegetative cover, human behavior, and more — based on the magnitude by which each biodiversity target is expected to fail (e.g., 10%, 20%, 50% below expectation). The intent is to bring clarity to complex interactions among economic, social, and conservation forces. "Our model, or set of models, will assume a final ecological collapse," says Borgerhoff Mulder.

Based on their modeled outcomes, the participants will envisage scenarios representing varying shades of environmental dystopia resulting

> MORE ON PAGE 6

Quantifying the potential value of data

In an age of abundant information, one of the major questions to answer is how to quantify the value of this data. "The potential value of data is not just about the quality of the information contained in a dataset, but about what types of questions we can answer with it," says SFI External Professor Amos Golan (American University). "On one hand, this is a very philosophical question, on the other hand, we want to make it very empirical."

This April 2–3, researchers from around the world will meet at SFI for a two-day workshop, titled "The Potential Value of Data," to discuss methods for quantifying the potential value of specific datasets. "Information can appear to be useless until a model is constructed that renders it useful," says SFI External Professor John Harte (UC Berkeley), who is co-organizing the workshop with Golan and Min Chen, a professor at Oxford University.

The effort to quantify the value of data was prompted in part by recent efforts from government agencies to compile and maintain publicly available datasets. Given the enormous cost requirements of creating and maintaining these datasets, this creates a need to quantify the value of existing datasets and predict the value of future datasets.

"Usually when people talk about the value of data, they look at what people have already gotten out of a dataset, such as the number of papers published, but a more important issue is to think about the potential value," says Golan.

In addition to discussing ways of quantifying the value of existing datasets, they also plan to discuss methods for optimizing future datasets, which includes identifying specific high-value information that will increase the number of questions it can answer. "Thinking about the questions that you can answer with the data can help us in the practical sense, because then we can also evaluate what is the data that we wish we had, and what would be the cost of acquiring it," Golan says.

Sometimes the answer is very simple.

Physicists identify overlooked uncertainty in real-world experiments

The equations that describe physical systems often assume that measurable features of the system — temperature or chemical potential, for example — can be known exactly. But the real world is messier than that, and uncertainty is unavoidable. Temperatures fluctuate, instruments malfunction, the environment interferes, and systems evolve over time.

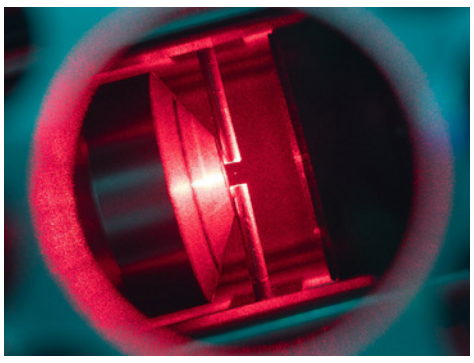
The rules of statistical physics address the uncertainty about the state of a system that arises when that system interacts with its environment. But they've long missed another kind, say SFI Professor David Wolpert and Jan Korbel, a postdoctoral researcher at the Complexity Science Hub in Vienna, Austria. In a new paper published in *Physical Review Research*, the pair of physicists argue that uncertainty in the thermodynamic parameters themselves — built into equations that govern the energetic behavior of the system — may also influence the outcome of an experiment.

"At present, almost nothing is known about the thermodynamic consequences of this type of uncertainty despite its unavoidability," says Wolpert. In their paper, he and Korbel consider ways to modify the equations of stochastic thermodynamics to accommodate it.

When Korbel and Wolpert met at a 2019 workshop on information and thermodynamics, they began talking about this uncertainty in the context of non-equilibrium systems.

"We wondered, what happens if you don't know the thermodynamic parameters governing your system exactly?" recalls Korbel.

> MORE ON PAGE 4



Optical tweezers, shown here trapping a nanoparticle, are among the systems impacted by a type of uncertainty that physicists have long missed. (image: Steven Hoekstra/ Wikipedia CC BY-SA 4.0)

BEYOND BORDERS

CONSTRUCTING SCIENCE

We might like to know what sets the speed of scientific discovery. And if we knew this, how to accelerate, cruise, break, and perhaps even stop. In the last couple of years, a great deal has been made of the high speed of progress in machine learning, many suggesting that we have achieved as a cultural mass, a dangerous momentum — Elon Musk, for example, warning that "If you're not concerned about AI safety, you should be." This is reminiscent of the fear of speed in the early ages of the automobile. In an article in the *Detroit Free Press* from 1914, there are dire warnings over the risks of driving at 40 miles an hour: "An automobile . . . rounded the corner from Labelle Avenue onto Woodward Sunday evening and turned turtle going at least 40 miles an hour." Admittedly the driver was in all likelihood intoxicated. But perhaps the same could be said of the legions of large language model users and their ghost-in-the-machine-written spam epistles.

The metaphor of the automobile, or machine more generally, is fitting in more ways than one. The science of science has at various points emphasized the idea that fundamental science, unlike statistical science, is slowing down. It could have run out of fuel (new ideas), been hindered by too much friction (institutional inertia), excessive congestion on the roads (too many researchers on a project), a paucity of streets and highways (conservative ideas about where science should go), and bad driving (poor educational foundations). And there is ample empirical evidence for every one of these factors. In a recent meeting at SFI on "Accelerating Science," many of these topics were discussed and everything from the conservative forces operating within large teams to the economics of risk aversion were covered.

I would like to take a stab at relating these ideas to what the physicist David Deutsch has called Constructor Theory. According to Deutsch, the theory seeks to renovate physics, or what he has called the "prevailing conception," and to provide a rigorous, consistent framework for talking about possible and impossible transformations. My sense is that the true value of Constructor Theory is the way it allows us to talk about possibility and less for what it has to say about physics. The theory builds on John von Neumann's Universal Constructor argument for the origin of life, and adds details from what we know about enzyme kinetics (EK).

Von Neumann pointed out that a non-trivial lifeform requires far more than replication; it requires programmable development. His argument was reminiscent of the current AI Paperclip Apocalypse, where an algorithm might determine that its objective function is to saturate the universe through the endless replication of a trivial function. A simple replicator likewise might fill the universe with a single bit of information. Von Neumann understood that complex organisms require a means of replicating information, which provides a blueprint for "constructing" a functional machine. As the evolutionary theorist

> MORE ON PAGE 4

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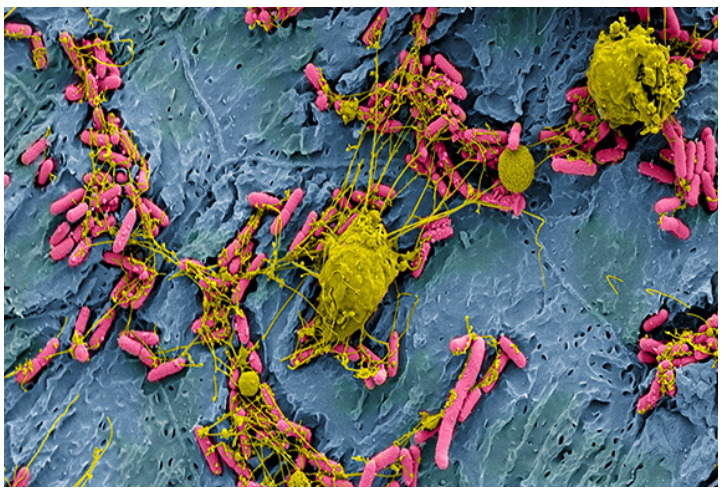
Study: New insights into antibiotic resistance & fitness landscapes



White blood cells fight an Escherichia coli infection in a mouse bladder. (image: U.S. National Institutes of Health/Flickr)

E. coli bacteria may be far more capable at evolving antibiotic resistance than scientists previously thought, according to a new study published in *Science* on November 24, 2023.

Led by SFI External Professor Andreas Wagner (University of Zürich), the researchers experimentally mapped more than 260,000 possible mutations of an *E. coli* protein that is essential for the bacteria's survival when exposed to the antibiotic trimethoprim.

Over the course of thousands of highly realistic digital simulations, the researchers then found that 75% of all possible evolutionary paths of the *E. coli* protein ultimately endowed the bacteria with such a high level of antibiotic resistance that a clinician would no longer give the antibiotic trimethoprim to a patient.

"In essence, this study suggests that bacteria like *E. coli* may be more adept at evolving resistance to antibiotics than we initially thought, and this has broader implications for understanding how various systems in evolutionary biology, chemistry, and other fields adapt and evolve," says Wagner.

Besides uncovering new and potentially worrisome findings about antibiotic resistance, the researchers' work also casts doubt on a longstanding theory about fitness landscapes. These genetic maps represent how well an organism — or a part of it, like a protein — adapts to its environment.

On fitness landscapes, different points on the landscape represent different genotypes of an organism, and the height of these points represents how well each genotype is adapted to its environment. In evolutionary biology terms, the goal is to find the highest peak, which indicates the fittest genotype.

Prevailing theory regarding fitness landscapes predicts that in highly rugged landscapes, or those with multiple peaks of fitness, most evolving populations will become trapped at lower peaks and never reach the pinnacle of evolutionary adaptation.

However, testing this theory has been exceedingly difficult until now due to the lack of experimental data on sufficiently large fitness landscapes.

To address this challenge, Wagner and colleagues used CRISPR gene editing technology to create one of the most combinatorially complete fitness landscapes to date for the *E. coli* dihydrofolate reductase (DHFR) protein.

What they found was surprising. The landscape had many peaks, but most were of low fitness, making them less interesting for adaptation. However, even in this rugged landscape, about 75% of the populations they simulated reached high fitness peaks, which would grant *E. coli* high antibiotic resistance.

The real-world implications are significant. If rugged landscapes like this are common in biological systems, it could mean that many adaptive processes, such as antibiotic resistance, may be more accessible than previously thought.

The result could ultimately lead to a re-evaluation of theoretical models in various fields and prompt further research into how real-world landscapes impact evolutionary processes.

"This has profound implications not only in biology but beyond, prompting us to reevaluate our understanding of landscape evolution across various fields," Wagner says. "We need to shift from abstract theoretical models to data-informed, realistic landscape models."

Accuracy of 2005 financial economics model confirmed

Investors in stock markets trade by submitting orders to buy or sell. The mainstream view that markets are efficient would naively suggest that the sequence of new buy or sell orders entering the market should be random. But, as discovered in 2004 by (then) SFI postdoc Fabrizio Lillo and Resident Professor J. Doyne Farmer, the sequence of new buy and sell orders is far from random. Instead, a buy order is much more likely to be followed by more buy orders, and a sell order is much more likely to be followed by more sell orders. This presents a challenge for the theory of market efficiency, raising the question of whether the non-randomness in order arrival is also reflected in prices.

This persistence in the arrival of new orders, which has now been observed in stock markets throughout the world, is appropriately termed "long-memory," and lasts for days, weeks, and even months. To explain why this happens, Farmer, Lillo, and Szabolcs Mike published a paper in 2005 in *Physical Review E* postulating the cause for long-memory in markets. This past November, their theory was strongly confirmed by a paper in *Physical Review Letters*.

The model that Lillo, Mike, and Farmer put forward, now known as the LMF Model, postulates that long-memory in stock markets is due to extreme inequality in investor size.

> MORE ON PAGE 5

Embodied intelligence & a sense of self

Generative AI has garnered widespread attention over the last year with the viral success of ChatGPT. Those selling the hype and doomers alike suggest that these AI models will soon be conscious or self-aware. Cognitive scientists, however, are not convinced.

"A key feature that is currently missing in AI is the causal understanding of the world that we as humans have," says SFI External Professor Nihat Ay (Hamburg University of Technology). This is in contrast to humans who understand the cause and effect of their interactions with the physical world.

The difference between the two is embodied or extended intelligence. The human brain offloads some of the computation to the body and environment. Among other ways, it shows up as the feeling in your gut and why some people think better when walking.

Embodied agents bring this kind of intelligence to the world of AI. Think of robots or virtual assistants that interact with the physical world. As with humans, the mental constructs of these agents are shaped by their bodies.

But can these technologies become conscious one day?

Ay and his graduate students Carlotta Langer and Jesse van Oostrum are organizing an SFI working group, scheduled March 11–15, that will focus on the possibility of embodied agents gaining an awareness of what it is like to be. The meeting is inspired by recent research on the free-energy principle, a concept that posits that the brain uses internal models to reduce uncertainty in any situation.

According to the principle, an embodied agent leverages its understanding of its body to pick the most optimal option from a pool of choices. It considers the physical consequences of its actions, including on itself. During the working group, researchers will explore the link between how embodied agents make choices and what subjective experiences they can gain, including a sense of self.

Ay says that the behavioural patterns resulting from embodied intelligence are more interesting than those traditionally studied in reinforcement learning, a type of machine-learning approach that places an agent in a highly simplified world. This could pave the way for the development of truly artificial intelligent systems that are closer to human intelligence than existing AI models.

(illustration: Adam Copeland/SFI)

Writing the genealogy of complexity science

This spring, as SFI celebrates 40 years as the headquarters of complex-systems science, the SFI Press will release a four-volume collection of *Foundational Papers in Complexity Science*. Edited by David Krakauer, these books compile more than 80 papers originally published between 1922 and 2000, each of which played an essential role in the emergence of boundary-defying complexity studies. Researchers from across the SFI community have "adopted" the papers, contextualizing their significance with introductions and annotations. The project spans past, present, and future, articulating a genealogy of complexity.

Included papers range from Norbert Wiener's cybernetics to Elinor Ostrom's governance of the commons, from Claude Shannon's mathematical theory of communication to Mikhail Budyko's examination of the impacts of solar radiation. "The point," Krakauer says, is to familiarize readers "with the history of key ideas in complexity, and the community's interpretation of why those papers were consequential."

These diverse papers are unified by four underlying concepts — entropy, evolution, control, and computation — characteristic of all complex systems, whether living or nonliving, engineered or evolved. While the papers represent a twentieth-century vision, their roots extend much deeper. They build on the work of eighteenth- and nineteenth-century thinkers such as Ludwig Boltzmann, Rudolf Clausius, Charles Darwin, Thomas Malthus, and Adam Smith. Indeed, complexity stands in relation to the Industrial Revolution and the new science of machines as modern physics and chemistry do to the earlier Scientific Revolution.

In complexity science, Krakauer sees nothing less than a Kuhnian paradigm shift, during which new connections are made in a body of knowledge, and old connections broken.

In pursuit of the genealogical ontology of complexity, Krakauer is tracing the chain of citations connecting them, noting omissions alongside both influential and forgotten references. "What these foundational papers show clearly through their acknowledged predecessors is an ongoing and focused engagement with the interconnections," he says.

Many of the important discoveries documented in this collection would not have been possible without computation. Edward Lorenz's numerical weather prediction, for instance, built on the nineteenth-century work of Ada Lovelace and Charles Babbage and the creation in 1945 of ENIAC, the first programmable, electronic, digital computer. Computation emerged as a powerful tool for studying complex systems when the analytical methods of physics fell short, offering new methodologies and frameworks.

In complexity science, Krakauer sees nothing less than a Kuhnian paradigm shift, during which new connections are made in a body of knowledge, and old connections broken. "Revolution in some people's eyes implies speed, like the French Revolution, but, actually, scientific revolutions can be subterranean and slow," he says. *Foundational Papers* documents this (r)evolution in complexity with a veritable chorus. "It's the whole community writing it — it's very much a complex system in itself."

SFI Press publishes updated editions of Murray Gell-Mann books

In November, the SFI Press released two updated books — The Quark & the Jaguar and Strange Beauty — by and about SFI co-founder Murray Gell-Mann. (image: SFI Press)

The opening lines of Homer's *Odyssey* describe its eponymous hero as *polytropos*, a man of many turns. It's no coincidence that SFI co-founder Murray Gell-Mann invoked Homer's crafty, long-voyaging hero when he envisioned the pinnacle of the scientific endeavor.

"Murray described his ideal scientist as an 'Odyssean,' one who lives somewhere between the analytical Apollonian and the intuitive Dionysian, one who loves to simplify yet is equally enamored of complication," says David Krakauer, SFI President and Editor-in-Chief of the SFI Press. "Over the course of Murray's life, he realized this ideal in his own journey from reductive particle physicist to complexity scientist."

Two November releases from the SFI Press illuminate that journey. A new printing of Gell-Mann's *The Quark & the Jaguar: Adventures in the Simple & the Complex* (originally published in 1994) will appear in the SFI Press Compass series alongside the second edition of George Johnson's acclaimed biography *Strange Beauty: Murray Gell-Mann & the Revolution in Physics* (originally published in 1999).

As both books attest, Gell-Mann was a complicated figure, renowned as much for his divisive personality as for his unwavering belief in interdisciplinarity. His life story in many ways parallels the emergence of complexity science, including the founding of the Santa Fe Institute in 1984 as a haven for fellow "Odysseans."

The voyage was sometimes tortuous. Amidst other challenges, the same virtuosity that animated Gell-Mann's forays from physics into linguistics, antiquities, and ornithology also made writing an agonizing trial.

For Gell-Mann, "every word was hovering with connotations and etymology in a quantum haze," says Johnson, an award-winning science journalist. *Strange Beauty*, which was shortlisted for the Royal Society Science Book Prize, chronicles the years of writer's block, fired ghostwriters, and missed deadlines that preceded *The Quark & the Jaguar.*

The ironies of revising a biography of a challenged writer are not lost on Johnson, who relished the chance to revisit *Strange Beauty* after two decades. Though the core of the biography remains the same, says Johnson, "I never expected that I'd get such a wealth of new material that wasn't available when the book was first written."

Among this "treasure trove" are the transcripts of the 1969 Nobel deliberations and a diary Gell-Mann kept before and after the announcement of his prize, as well as reports from the FBI's investigation into Gell-Mann during the Cold War paranoia of the mid-1950s. The new edition also adds a foreword by cognitive scientist Douglas Hofstadter and a new chapter that covers Gell-Mann's life up to his passing in May 2019.

The thoughtful design of the new SFI Press editions — available at an affordable price made possible by the Miller Omega Program — honor Gell-Mann's "many turns," from physicist to conservationist, dedicated reductionist to champion of diversity in academic disciplines and wildlife species alike.

The central image in *The Quark & the Jaguar* captures the duality of the book's title and, perhaps, its author. "The quark," Gell-Mann wrote, "is a symbol of the physical laws that, once discovered, come into full view before the mind's analytical eye, so the jaguar is, for me at least, a possible metaphor for the elusive complex adaptive system, which continues to avoid a clear analytical gaze, though its pungent scent can be smelled in the bush."

For more, visit **www.sfipress.org**.

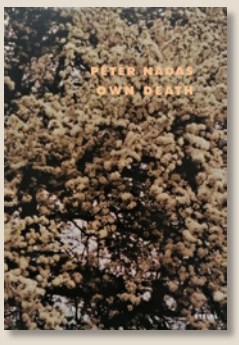
What we're reading

Books chosen by SFI scholars on Immortality

Last quarter, the James S. McDonnell Foundation funded an SFI workshop entitled "The Limits of (Im)mortality," an eclectic, three-day meeting devoted to the possibilities of life extension, longevity, and deathlessness. In addressing these themes, the speakers also considered the degree to which immortality is a desirable aim for complex living systems. Attendees were asked to consider the shared characteristics of all long-lasting systems, the extent to which biology, technology, and culture are entangled in the quest for longer lifespans, and how we should understand the idea of immortality, "whether as a theoretical limit, an achievable reality, or an idea with mostly negative consequences," as David Krakauer put it.

The unanswerable metaphysics of immortality have enthralled virtually every known culture. And a definitive conviction concerning what comes after death forms the basis of almost every religious or moral scheme. Some of the greatest thinkers, from Homer, Buddha, and Plato, to Dante, Newton, and Spinoza, have taken inspiration from the mystery of whether or not consciousness continues after death in some form or another. In this edition of What We're Reading, we invited contributors to recommend books from across cultures that touch on the problem of (im)mortality. For regardless of our ceaseless speculation and differences on these matters, perhaps it is as Simone Weil put it in *Gravity and Grace* when she wrote that merely by contemplating this perpetuity, "we are snatched away into eternity."

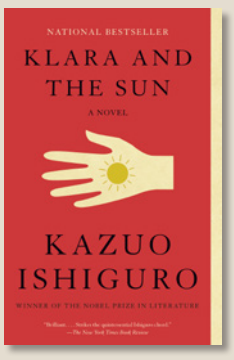
A definitive conviction concerning what comes after death forms the basis of almost every religious or moral scheme



OLIVIER DEL FABRO
SFI Visitor, ETH Zurich

***My Own Death*, by Péter Nádas**

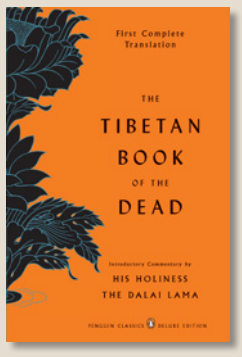
In this compelling autobiographical piece, Péter Nádas describes how, after enduring a heart attack, he wanders on the boundary between life and death. Having traveled through infinite space and time, towards a shining light, Nádas believes he has been only steps away from rebirth. A must-read for all those interested in literature about transgression, death, and the thresholds of life.



MIRTA GALESIC
SFI Professor

***Klara and the Sun*, by Kazuo Ishiguro**

Ishiguro's "Artificial Friend," Klara, the novel's narrator, imagines a future where embodied AI can understand and feel emotions, navigate relationships, develop superstitions and hallucinations, and even replace our deceased human family members by assuming their personalities and physical characteristics. At the same time, the novel depicts how artificially enhanced humans are approaching the uncanny valley from the other side.



DANIEL MURATORE
SFI Postdoctoral Fellow

***The Tibetan Book of the Dead*, edited by Graham Coleman and Thupten Jinpa**

This 2007 edition of *The Tibetan Book of the Dead*, based on Gyurme Dorje's translation, combines philosophy with lyric prayer and prose, providing an account of the metaphysics of death and reincarnation in the Tibetan Buddhist tradition. The text details various stages of dying — including liminal transience in the 'bardo' realm prior to beginning a new life — in parallel with the stages of early development and consciousness, reinforcing a cyclical understanding. This systems-level view suggests a model of immortality that is completely separate from longevity instead embracing the persistence and stability of the processes of life and death as a form of immortality in itself.

In Memoriam: Erica Jen

Erica Jen, former SFI Vice President for Academic Affairs and longtime SFI research collaborator, in 2007. (image: SFI)

Erica Jen, former SFI Vice President for Academic Affairs, passed away on November 12, 2023, at the age of 71. A mathematician by training, Jen was held in high esteem by all who knew her for her ability to bring together people from diverse backgrounds and disciplines.

As VP for Academic Affairs, Jen significantly broadened the scope of research collaborations in complex adaptive systems to include more social science and led founding workshops on robustness which eventually grew into an SFI research program. She was instrumental in bringing several key people to SFI, including formalizing Cormac McCarthy's relationship with the Institute.

"When I started at the Santa Fe Institute as President and was just learning about the Institute and meeting people, I kept hearing Erica's name," says Ellen Goldberg, who served as SFI President from 1996 to 2003. "People would talk about her and the wonderful work she was doing. When we finally met, we just clicked and I realized she would be such an incredible asset for the Institute." Goldberg offered Jen the Vice Presidentship, and she says, "Erica did an incredible job. It took a town to do what Erica did. We worked so well together to make SFI a success."

Jen held various official roles at SFI beginning with External Faculty, and later, Science Board member, VP for Academic Affairs and Resident Faculty. Since 2017 and until the time of her passing, Jen held the title of Science Board Fellow, an honorary appointment given by SFI's President to recognize researchers who have made significant contributions to the Institute via service on the Science Board.

Jen was a bold, eloquent speaker. While a young undergraduate at Yale, Jen accompanied her father, theoretical physicist Chih-Kung Jen, to China and asked the then-Chinese Premier, Zhou Enlai, if she could stay. She became one of the first Americans allowed to study in China after the Cultural Revolution. Excerpts of her conversation with Enlai and her character as a student are featured in fellow student Jan Wong's book *Red China Blues*.

> "We have lost exactly the kind of person that the world needs more than ever."

Jen returned to the U.S. two years later to pursue a Ph.D. in applied mathematics and became the first postdoctoral fellow at the Center for Nonlinear Studies at Los Alamos National Laboratory. Her main area of study then was cellular automata or computational models featuring grids of cells that change states over time.

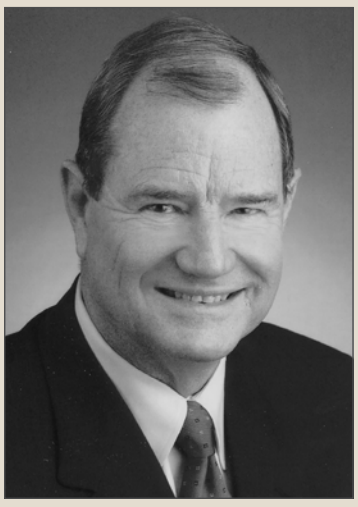
"We talked constantly about research," says SFI External Professor Stephanie Forrest (Arizona State University), who met Jen when they were both postdocs at Los Alamos. Shortly after, they both became SFI External Faculty. "She had one of those rare interdisciplinary minds that can synthesize across disciplines. In her quiet way, she had a huge impact on SFI and the scientific direction we took, always very involved and engaged in people's ongoing projects," says Forrest.

After seven years as an external professor and three more as a vice president, Jen had a child born with severe disabilities and decided to step down; Forrest took over as Interim VP of Academic Affairs. "She was always so giving, worked so hard to make sure the Institute would be a success, cared deeply about the science, and she did it all from an egoless place. When she had a child, she gave up her career and focused solely on her daughter. It's heartbreaking to know she's not with us anymore," says Forrest.

Jen stayed connected to SFI by continuing to attend workshops, and encouraging researchers. She was scheduled to visit SFI this fall for a workshop on emergent computation, celebrating Forrest's career, but a month before the meeting, emailed to cancel it. A few weeks later, she passed away.

"Erica was what I like to call an extraterritorial personality, effortlessly passing across boundaries, which in her case were both national and disciplinary," says David Krakauer, SFI President. "Erica's training in mathematics lent to her many interests an analytical perspective, which in combination with her family biography, provided a deep empathy for the itinerant imagination. Erica, in her role as VP for science at SFI, gave those who met her an opportunity to think about more or less anything, and I was a beneficiary of her largess, recollecting with gratitude the work we did together on how the complex world manages to endure and how it even achieves a surprising robustness. I feel that we have lost exactly the kind of person that the world needs more than ever."

In Memoriam: William Sick



Bill Sick, who served as a member of SFI's Board of Trustees for more than 20 years, passed away on December 8, 2023. (image: William Sick)

William (Bill) Sick, who served for nearly two decades on SFI's Board of Trustees, passed away on December 8, 2023. He was 88 years old.

Deeply curious with strong interests in technology and engineering, Sick was an active member of the SFI Board for two decades. He held a B.A. and a B.S. in electrical engineering from Rice University, and he used his degrees to fill several roles — from semiconductor engineering to executive vice president and director — at Texas Instruments before launching several businesses as a venture capitalist.

> "He did me and SFI a great service . . . We changed our whole approach to raising money."

Sick learned about SFI in the late-nineties through Robert Maxfield, who had joined the Board in 1992. The two were serving together on the Board of Rice University and shared common interests in SFI's multidisciplinary approach to science.

"We loved the same things about SFI," says Maxfield. "We were both curious and wanted to learn, and SFI scientists knew how to communicate in ways that a layperson could understand. I knew he'd be very interested, so I invited him to a Symposium." Sick joined SFI's board in 2000.

With his experience as a high-level executive, Sick brought to the Board a wealth of knowledge about management and an interest in coaching. "He didn't talk a lot in the meetings, but he never hesitated to make a call or contact people in person," says Maxfield.

SFI Professor Geoffrey West, who served as SFI's president from 2005 through 2009, benefited from Sick's behind-the-scenes approach. "I really enjoyed his support and positive criticism," he says. West was learning how to oversee an organization as he went, and he says, "Sick did one thing for me that was really important — it changed me forever."

Working one-on-one as was his fashion, Sick approached West to congratulate him on his achievements as President, and to suggest he needed a fundraising coach. He knew just the person — a well-regarded consultant who would mentor West in pitching the Institute, and his own research, with clarity, simplicity, and confidence. "He did me and SFI a great service," says West. "We changed our whole approach to raising money."

As the Institute grew and matured in its early decades, it needed a Board that could embrace its identity as a center for fundamental research. Sick was willing to adapt his understanding of the Institute, letting his interests shift from that of a pure technologist toward a more integrated view of how SFI could offer insights into the biggest challenges of the 21st century.

Those kinds of insights are at the heart of the discussions and presentations featured at SFI's annual Board Symposium, an event that Sick and his wife, Stephanie Sick, attended each year. "Since I first met him in the early 2000s until his health prevented him from traveling, I don't recall a time when he and Stephanie missed a Board meeting or Symposium," says West. "I think it was a reward for him. He was a man of broad interests."

SFI President David Krakauer recalls similar memories and sentiments. "Bill and Stephanie have been stalwarts of SFI support over the years and the source of much institutional history for me," he says. "I have always appreciated their support for a more expansive vision of SFI that connects the sciences with the arts. We are stronger than we have ever been and this ultimately comes down to the ideas and support of board members like Bill. We shall miss him."

UNCERTAINTY *(cont. from page 1)*

"And then we started playing around." The equations that describe thermodynamic systems often include precisely defined terms for things like temperature and chemical potentials. "But as an experimenter or an observer you don't necessarily know these values" to very large precision, says Korbel.

Even more vexing, they realized that it's impossible to measure precisely parameters like temperature, pressure, or volume, both because of the limitations of measurement and the fact that these quantities change quickly. They recognized that uncertainty about those parameters not only influences information about the original state of the system, but also how it evolves.

It's almost paradoxical, Korbel says. "In thermodynamics, you're assuming uncertainty about your state so you describe it in a probabilistic way. And if you have quantum thermodynamics, you do this with quantum uncertainty," he says. "But on the other hand, you're assuming that all the parameters are known with exact precision."

Korbel says the new work has implications for a range of natural and engineered systems. If a cell needs to sense the temperature to carry out some chemical reaction, for example, then it will be limited in its precision. The uncertainty in the temperature measurement could mean that the cell does more work — and uses more energy. "The cell has to pay this extra cost for not knowing the system," he says.

Optical tweezers offer another example. These are high-energy laser beams configured to create a kind of trap for charged particles. Physicists use the term "stiffness" to describe the particle's tendency to resist being moved by the trap. To determine the optimal configuration for the lasers, they measure the stiffness as precisely as possible. They typically do this by taking repeated measurements, assuming that the uncertainty arises from the measurement itself.

But Korbel and Wolpert offer another possibility — that the uncertainty arises from the fact that the stiffness itself may be changing as the system evolves. If that's the case, then repeated identical measurements won't capture it, and finding the optimal configuration will remain elusive. "If you keep doing the same protocol, then the particle doesn't end up in the same point, you may have to do a little push," which means extra work that's not described by the conventional equations.

This uncertainty could play out at all scales, Korbel says. What's often interpreted as uncertainty in measurement may be uncertainty in the parameters in disguise. Maybe an experiment was done near a window where the sun was shining, and then repeated when it was cloudy. Or perhaps the air conditioner kicked on between multiple trials. In many situations, he says, "it's relevant to look at this other type of uncertainty."

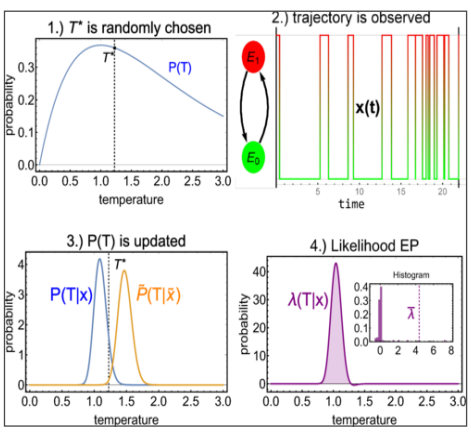


Illustration of the second law of inference on a two-state system with uncertain temperature. (image: fig. 5/ Korbel and Wolpert, 2024)

Postdocs in Complexity Conference XI

The 11th Postdocs in Complexity Conference participants at SFI's Cowan Campus. (image: Katherine Mast/SFI)

In January 2017, when SFI and the James S. McDonnell Foundation launched the first Postdocs in Complexity Conference, Elizabeth Hobson and Joshua Garland were only a few months into their postdoctoral fellowships at SFI. They were two of several dozen early-career complexity researchers gathered for what would become a biannual event — a unique opportunity for complexity postdocs to gain professional development, share insights from across their disciplines, and begin building deep and meaningful research networks.

Like all the other conference participants, Hobson and Garland were honing their research questions, and also wondering if anyone would ever hire them again to continue their work.

"Being a postdoc is an incredibly stressful time. Making connections with others in that same career stage can be really transformative in helping postdocs build their support networks," says Hobson, who is currently on a fast track for tenure at the University of Cincinnati, where she leads a lab studying sociality in animals.

This October, during the 11th Postdocs in Complexity Conference, Hobson and Garland returned to share insights they've gleaned and things they wish they had known as postdocs.

"The people who come to this conference are the leaders in the next generation of complex systems," says Garland, who is now directing the Global Security Initiative, Center on Narrative, Disinformation and Strategic Influence at Arizona State University. "This conference helps build connective tissue."

The most recent meeting brought together SFI's 15 postdoctoral fellows and 21 James S. McDonnell Foundation fellows who come from academic institutions around the globe. It also expanded this time to include three Neukom complexity postdoctoral fellows from Dartmouth College and one from the University of Cincinnati.

Professional development talks at this fall's conference ranged from how to apply for federal grants to writing for general audiences and, as always, prioritized time for participants to network. Research Jams provided space for brainstorming collaborative research questions that draw on the wide range of expertise in the group.

"Many postdocs who come to this conference are isolated at universities where it's hard to do interdisciplinary work," says Garland. "Interdisciplinary research can't happen without multiple disciplines in the room. This conference allows that to happen in a way that no other conference I know of allows." And the relationships that develop create colleagues for life — a network of people to call on for advice or insights into specific questions.

> "The people who come to this conference are the leaders in the next generation of complex systems"

Recently, the James S. McDonnell Foundation has been shifting its focus toward issues closer to its home in St. Louis, Missouri. As a result, the collaboration with SFI on this conference will be ending. In the first major gift of 2024, as part of the 40th Anniversary of SFI, The McKinnon Family Foundation and The Darla Moore Foundation are making significant contributions to education, the SFI postdoc program, and a newly formatted Postdocs in Complexity Conference. (Full press release forthcoming.)

"From the feedback that we receive following each conference, it is really clear that the meetings are extremely valuable for early-career complexity scientists," says Hilary Skolnik, Program Manager for SFI's Postdoctoral Fellows Program. "The new funding will allow us to make this conference open to a broader range of early-career complexity researchers."

Complexity Global School launches in India & South Africa

In December 2023, SFI's Complexity Global School for Emerging Political Economies brought together students from across South Asia and Africa to the Indian Institute of Technology Bombay (IITB) in India and the University of the Witwatersrand (WITS) in South Africa respectively. Early-career scholars and change-makers from civil society and private industry joined an intensive 12-day intercontinental program, engaging with the latest complex methods, models, and frameworks for thinking about economics and governance. Here are glimpses from [top row] IITB, [middle Row] WITS, IITB, WITS, and [bottom row] WITS. (Credits: Shobha Chhatri/IITB; Jamel Dugbeh, Carla Coburger, Anthony Ogbesor/SFI)

ACHIEVEMENTS

Melanie Mitchell

John Geanakoplos

John Geanakoplos and co-author Ana Fostel received the eighth Stephen A. Ross Prize from The Foundation for Advancement of Research in Financial Economics for their 2008 paper "Leverage Cycles and the Anxious Economy."

Melanie Mitchell received the 2023 Senior Scientific Award from the Complex Systems Society for her "outstanding contributions" in a variety of fields across complexity science, and for sharing her insights with broad audiences.

Andreas Wagner

Andreas Wagner's newest book, *Sleeping Beauties: The Mystery of Dormant Innovations in Nature and Culture*, published last May by Oneworld Publications, was named a 2023 Science Book of the Year by *The Times* and the *Daily Telegraph*.

ECONOMICS MODEL CONFIRMED *(cont. from page 2)*

Portfolio managers make decisions about what they want to trade, but then buy or sell to realize these decisions over an extended period of time. If there were many investors, all of the same size and acting independently, their decisions would average out under the law of large numbers, and the odds of a new buy or sell order would always be about the same.

But LMF assumed there are a few really large investors, for whom buying or selling based on a given decision can take many months; there are more fairly large investors, for whom this can take days or weeks; and there are millions of small investors for whom this takes less than a day.

LMF assumed the distribution of sizes of these different investors follows a "fat-tailed" power law, and showed that this can cause the observed long-memory behavior of the orders entering the market (which follows a power law in time rather than size). According to their theory, periods when there are a preponderance of buy orders entering the market are caused by a few large investors who happen to be buying at the same time, and similarly for sell orders.

The recent paper, published by Yuki Sato and Kiyoshi Kanazawa, used 9 years' worth of previously unavailable data from the Japanese stock market to test the LMF model. They showed unequivocally that the size of desired institutional trading follows the power law predicted by LMF, and that this explains the long-memory of orders entering the market.

The fact that LMF's precise prediction was confirmed in every respect demonstrates that financial markets can follow quantitative laws like those in physics. "It is particularly satisfying to see that our model has been proven to be true," says Farmer, who is now an SFI External Professor based at Oxford University's Institute for New Economic Thinking. "Successful quantitative predictions of this type are rare in finance and economics."

The long-memory of order arrival is interesting for its own sake, says Farmer, but notes that its implications for market efficiency are complicated. "Even though buy orders tend to push the price up, and sell orders tend to push it down, the size of the response in the price varies so that on average the resulting deviation from market efficiency in prices is relatively small," he says. Several papers have since shed light on how this happens, but the precise mechanism, says Farmer, remains to be clarified.

BEYOND BORDERS *(cont. from page 2)*

George Williams wrote, all of biology operates through both codical (replicating) and material (phenotypically interacting) domains. It is not a stretch to extend this idea to scientific knowledge, where our educational systems, funding sources, and risk-averse norms, all emphasize replication of existing ideas over the possible construction of new ones.

Within the Constructor Theoretic framework, there are elementary inputs to a machine, the constructor, and outputs that are new configurations of matter. As von Neumann first noted, simple replication can dispense with the constructor, but the constructor is where almost all the interesting affordances and constraints live. In ontology, gene regulatory networks play the role of constructors, and through phylogeny, natural selection is a constructor.

The process of knowledge creation — that is, epistemic causality — resides in constructor mechanics. And of course the constructor is a machine that obeys the second law, and so its contribution to the generation of knowledge (under reasonable assumptions) implies an equal contribution to the production of waste, possibly even misinformation. Moreover, since the constructor is a kinematic machine, it obeys the combinatorial laws of chemical kinetics. And these imply that the speed of reactions is governed by the unique interactions of elements with constructors, the free energy available for transformation, the population size of the inputs, the time delay during the construction process, and so forth. All of the necessary ingredients for a scientific theory of knowledge production.

The historian Fernand Braudel, in the third volume of his *Civilization and Capitalism: The Perspective of the World*, writes of the "rhythms of conjuncture," meaning the variable rates of synchronous events throughout history required to transform the cultural world, and that "human life was subject to fluctuations and swings of periodic movements, which carry on in endless succession." And Jürgen Osterhammel, in his equally titanic *The Transformation of the World*, suggests that it was in the nineteenth century that what he calls "asymmetrical efficiency growth" accelerated, fueled by the increased mechanical productivity of labor, new sources of energy from new territories, and sequelae of conflict. The tempo of science is a microcosm of the rhythms of history, and as such, the outcome of intelligible construction processes realized at the global scale.

— David Krakauer
President, Santa Fe Institute

COMPLEXITY PODCAST

Complexity, the official podcast of the Santa Fe Institute, relaunches soon with Season One: Physics of Life. More at **www.santafe.edu/podcast**

UN BIODIVERSITY GOALS *(cont. from page 1)*

from significantly reduced biodiversity. With this inhospitable future mapped out, the group will reverse engineer development pathways and identify critical logistical problems in attaining the development goals.

"From these models, we can identify key junctures where action could or should be taken to avert these dire outcomes," says Borgerhoff Mulder.

Initially, the group will focus on a single geographic region as a case study, scaling to a global perspective once the concept is proven. Potential outcomes from the meeting include a short documentary about the proposed solutions, a series of podcasts, and a scientific publication, all geared to changing public perception of the environmental problem.

"The Santa Fe Institute is one of the places we can bring an eclectic mix of people together to address these questions," says Dobson. "Hopefully, we produce a different level of creativity that has been missing."

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RESEARCH NEWS BRIEFS

A recent paper in PNAS Nexus uses scaling theory to forecast future needs for electric-vehicle charging infrastructure throughout the United States. (image: Andrew Roberts/Unsplash)

HOW TO OPTIMIZE ELECTRIC-VEHICLE CHARGING LOCATIONS

Consumer interest in electric vehicles is rising, but the lack of charging stations is a continuing concern to potential customers. No U.S. counties currently have a charging infrastructure that can deliver power equal to gasoline stations; many counties have no public electric-vehicle charging infrastructure at all. To equal the power of the existing gasoline network, the U.S. would need 1.8 million charging stations. But where should they be built? A recent paper in *PNAS Nexus* provides a possible road map.

SFI Professor Christopher Kempes and co-authors used scaling theory to forecast future charging station needs. Their work relies on the infrastructure efficiency achieved for areas with higher population density and fewer stations per capita, and shows that areas with a lower population currently have a bigger charging-station gap. So, using simple population data to plan future charging stations could result in excess urban infrastructure and underserved rural communities. Prioritizing charging development using scaling analysis could help guide the distribution of charging stations needed for the widespread adoption of electric vehicles.

Read the paper "Scaling behavior for electric vehicle chargers and road map to addressing the infrastructure gap" at doi.org/10.1093/pnasnexus/pgad341

HOW THE FEMALE BRAIN DRIVES EVOLUTION

Evolutionary change can be strongly affected by choosing mates with particular characteristics, like a long, colorful tail or wide shoulders. However, it has been frustrating to match empirical data on mate choice to theoretical predictions, with animals sometimes using mate choice patterns that diverge from patterns they "should" be using according to theory.

To solve this problem, former SFI Postdoctoral Fellow Elizabeth Hobson (University of Cincinnati) and co-authors developed a mate choice mechanism called Inferred Attractiveness that was recently published in *PLOS Biology*. Using a theoretical model, they tested how male trait variability and female preferences for males would change over time if females acquired their preferences by watching what sort of males other females chose to mate with and unconsciously figured out — sometimes correctly and sometimes not — what distinguished them from other available males.

Inferred Attractiveness highlights not only the power but also the flexibility of female mate choice as a means of sexual selection. By casting the female brain as the central influence in breeding choices, Inferred Attractiveness captures the dynamic aspects of sexual selection and reconciles inconsistencies between mate-choice theory and observed behavior. The research paper is the result of two workshops organized by Hobson and funded by SFI Science.

Read the paper "Inferred Attractiveness: A generalized mechanism for sexual selection that can maintain variation in traits and preferences over time" at doi.org/10.1371/journal.pbio.3002269

WASTE SURVEILLANCE CAN HELP COMBAT CLIMATE-AGGRAVATED DISEASES

Traditional disease-monitoring systems are ill-equipped to handle the recent unprecedented outbreaks of climate-aggravated diseases. In a paper published in *Science Translation Dynamics*, SFI External Professor Samuel Scarpino (Northeastern University) and colleagues describe how comprehensive wastewater surveillance could pair with existing disease-surveillance systems to produce cost-effective, high-resolution health data and guide stronger public health interventions.

Wastewater testing, where sewage is strategically sampled and analyzed for health threats, can be used to detect and monitor established, emerging, and neglected pathogens in human waste. A single sample provides a comprehensive, high-fidelity snapshot of the health status of a large population. Scarpino calls for the global community to establish an ongoing multi-pathogen, climate-resilient surveillance system paired with traditional disease monitoring. Such a global initiative would leapfrog decades-old public health challenges in reducing preventable morbidity and mortality driven by climate change.

Read the paper "Wastewater surveillance facilitates climate change–resilient pathogen monitoring" at doi.org/10.1126/scitranslmed.adi7831

DEVELOPING A GLOBAL SUPPLY NETWORK

The world economy is astonishingly complex, relying on more than 300 million companies interconnected with about 13 billion supply chain links. SFI External Professors Doyne Farmer (Oxford University) and Stefan Thurner (Complexity Science Hub Vienna), with other colleagues, highlighted in a paper in *Science* the need for a comprehensive global map of these supply connections. Such a map would guide policymaking at national and international levels, and inform economic decisions to resolve critical business and societal challenges.

Presently, there are various national and supranational efforts to chart specific parts of the global supply network. Drawing a complete, trusted picture of international linkages would require integrating multiple datasets, developing analytical tools, and establishing secure infrastructure for storing and processing sensitive information. The only way to succeed would be for international organizations, individual nations, their public institutions, and the private and technical sectors to come together in an alliance to collaborate closely on such an overwhelmingly complicated enterprise.

Read the paper "Building an alliance to map global supply networks" at doi/10.1126/science.adi752

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