WINTER 2022-2023

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

Kyle Harper (image: Kate Joyce)

Kyle Harper joins SFI Fractal Faculty

Roman historian Kyle Harper is using technological leaps in the natural sciences to revitalize the study of human history. A tidy example of his approach comes from a 2018 project. Harper, who calls himself a "heretic of the humanities," had for years been studying the Nazareth Stone, a two-foot tall, one-foot wide gray marble slab inscribed around the first century with a brief Greek decree that can be summed up as "Leave This Tomb Alone!" Historians had long thought the Nazareth Stone might be the earliest physical trace of Christianity.

That fall, Harper, a 2013 Guggenheim Fellow, wrote in a piece for the *LA Review of Books* that, "The original circumstances behind the Nazareth inscription may remain forever beyond our grasp." But that winter, Harper called a geology colleague and asked if isotope analysis might decipher the stone's origin. A few months later, their cross-disciplinary collaboration had "put the nail in the coffin" of a century-old historical debate. The Nazareth Stone came from the Greek island of Kos — not Nazareth — and didn't reference Christ but the tomb of a fallen tyrant. "It's a seductive story," says Harper. And worthwhile research, but it's also far narrower in scope than the big questions he believes a new approach to history can solve.

Harper, a 42-year-old historian at the University of Oklahoma, joined the Santa Fe Institute's Fractal Faculty in 2022. He is a part of a group of historians trying to move their field beyond the study of "the narrow slice of time when humans produced documents." E.O. Wilson called this approach "consilience," a conversation between disciplines. "Why do physicists get the Big Bang? Geologists get Earth history? Biologists: evolutionary history? The sacred model of history confines historians to the study of writing and states," Harper says. "That's a very arbitrary way of divvying up the past." Nor is it one he feels is well-suited to answering the big questions: questions of the cosmos, climate change, humanity's future.

Harper is the author of four books. His past two, *The Fate of Rome: Climate, Disease, and the End of the Empire* (Princeton; 2017) and *Plagues Upon the Earth: Disease and the Course of Human History* (Princeton; 2021), demonstrate how the hard sciences can forge novel perspectives on historical questions. "Sometimes new

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Thirty years of undergraduate research

In the summer of 1993, seven undergraduate students from colleges across the U.S. came to Santa Fe for a 10-week immersive research experience. They began a tradition of bold and rigorous summer undergraduate research that has evolved and grown over the past 30 years. Since that first summer, more than 250 undergraduates have explored complex systems during their summers at SFI, gaining essential skills and a unique perspective to inform their scientific and professional futures.

"My summer at SFI was amazing: the environment was small, welcoming, and vibrant. I was exposed to ideas across many fields, ranging from economics and anthropology to biology and mathematics, each with their own technical languages albeit with common concepts and ideas," recalls Mahesh Mahanthappa ('95), professor of chemical engineering and materials science at the University of Minnesota. "This forced me to learn how to communicate across disciplines and by using analogies (sometimes anthropomorphic) — a skill that I value to this day."

While undergraduates had conducted research at SFI prior to the establishment of a formal program, Research Experiences for Undergraduates (REU) — later renamed the Undergraduate Complexity Research (UCR) Program — was a step toward a structured training path for early-career researchers at SFI. The UCR program provides an entry point to SFI research. Many students remember their summer at SFI as the first time they found a scientific "home," an intellectual environment where they were not forced into one or the other disciplinary silo. Others credit their SFI mentors and colleagues as having transformative effects on their careers.

"I would not be a research mathematician now if I had not met Professor Nancy Kopell from Boston University, a mathematical biologist, at the Santa Fe Institute during the summer that I was there as an undergraduate," says Megumi

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Lou Schuyler Internal Grants fund new postdoctoral research

In December 2022, SFI opened applications for its Postdoctoral Fellows to apply for funding through the Lou Schuyler Internal Postdoctoral Research Grant Fund. Now in its second round, the fund offers SFI Postdoctoral Fellows up to $15,000 per grant to explore new areas of research or expand the scope of their current projects.

Finding money to fund their work is a perennial challenge for academic researchers. Much of the scientific funding in the U.S. comes from federal agencies like the National Science Foundation and the National Institutes of Health, but both competition for available funds and the cost of conducting research have grown in recent years. "Money has remained relatively flat, but the number of applicants has really grown," says Susan Carter, SFI's Director for Research Development and Sponsored Research. Many institutions have launched internal funding programs to help early-career academics further their research and learn the grant-getting process.

SFI postdocs, whose research questions often span disciplinary boundaries, face an additional challenge: funding agencies are cautious about sponsoring projects outside a researcher's proven area of interest. "If a topic isn't on your CV, people think it's just a hobby," says SFI Complexity Fellow Mingzhen Lu, an environmental ecologist who received an internal grant in the fall of 2022 to explore a question related to industrial ecology and waste.

But it was exactly those boundary-pushing questions that drew Lou and Hank Schuyler to SFI. As longtime friends of the Institute, Lou and Hank enjoyed attending community lectures and interacting with SFI researchers — and particularly with Postdoctoral Fellows. "One of the things that Lou loved most was hearing the postdocs talk about their projects," says Hank.

SFI's Postdoctoral Fellows play an important role in engaging the broader community beyond academia. In the past year, five current SFI

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Lou Schuyler (image: InSight Foto)

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BEYOND BORDERS

THE BABEL ALGORITHM

In his 1901 essay, "Mathematics and the Metaphysicians," Bertrand Russell suggests that George Boole, the autodidactic son of a cobbler, was the discoverer of pure mathematics in his work, *An Investigation of the Laws of Thought* (1854). Russell argues that Boole was "mistaken in supposing he was dealing with the laws of thought" — that in fact the book is concerned with "formal logic, and this is the same thing as mathematics." In case one supposes that it was Aristotle who invented logic, Russell dispatches such quaint historicism, observing that "in each decade since 1850 more has been done to advance the subject than in the whole period from Aristotle to Leibniz."

What Russell's essay is really about is infinity, and through the work of Georg Cantor and others, the anchoring of mathematics in logic and logic in infinity. Although Russell did not yet see it, whereas ironically Boole already had, infinity is ultimately the constructive principle supporting knowledge and thought. As Boole puts it in "Constitution of the Intellect," the final chapter of *An Investigation of the Laws of Thought*:

> "When from a large number of observations on the planet Mars, Kepler inferred that it revolved in an ellipse, the conclusion was larger than his premises, or indeed than any premises which mere observation could give. What other element, then, is necessary to give even a prospective validity to such generalizations as this? It is the ability inherent in our nature to appreciate Order . . ."

It is order that empowers the archiving mind in finite time to operate in an infinite universe. And this permits in the words of Boole, "The necessary sequence of states and conditions in the inorganic world, and the necessary connexion of premises and conclusion in the processes of exact demonstration thereto applied, seem to be co-ordinate." Knowledge and reality converge through the right choice of system.

Perhaps too much has been written about Jorge Luis Borges' story, "The Library of Babel." But to my knowledge, much of this commentary has been aimed at scholarly futility and the impossibility of originality. The great power of infinity — as obtained through the ordering principles of Boole, Cantor, and Russell — is that like alchemy, it seems to transform discovery into creativity, or search into invention. When Borges writes that "The universe (which others call the Library) is composed of an indefinite and perhaps infinite number of hexagonal galleries" and that within these hexagons are all the books that could ever be written, he is suggesting that if there is a catalog or index to the library (a source of order), then knowledge is identical to intellection — to know where something is equates to its discovery. To know it all is to appear genius.

This last year has been full of know-it-alls. The artists have names like NightCafe, DALL•E 2, and Stable Diffusion, and the writers, GPT-3 and Bloom. They are Babel

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SFI IN THE MEDIA

Although the National Climate Assessment paints a dire picture of how climate change will impact the U.S., **Dan Schrag** told CNN, "there is no point where you throw up your hands and say, 'Oh, we lost!' . . . It's never time to give up."

Jenna Bednar shared her insights on voter behavior and the mid-term election results in Michigan with publications from *The Guardian* to *Michigan Daily* to *The New York Times*.

In a story about how business leaders can address inequality, *Rolling Stone* cited **Mahzarin Banaji** and her work on implicit bias.

Sean Carroll examined the theory of relativity — and its roots before Einstein "provided the capstone for a theoretical edifice" — in an essay for *Quanta*.

In *The Guardian*, **Eric Beinhocker** and Nick Hanauer wrote about how trickle-down economics has failed in the U.S., U.K., and other nations. Eric also offered an alternative — "middle-out economics" — on CNBC.

The Intercept featured research co-authored by **Andrew Dobson** about how addressing biodiversity loss requires more than simply addressing climate change.

In a story in *Forbes*, **Ricardo Hausmann** shared a nuanced perspective of what is driving Venezuelans to leave their country and head to the U.S.

Brandon Ogbunu wrote an essay, "Confronting the Ghosts of Science Past," for *Undark*, as well as "What Does Elon Musk's Ownership Mean to Black Twitter?" for *The Atlantic*.

In an essay for *Quanta*, **Melanie Mitchell** asks what it means to align AI with human values. *The New York Times*, *Bloomberg*, and CBC News also spoke with Melanie about the promise and peril of ChatGPT and other writing bots.

Pablo Marquette co-authored an op-ed in *La Tercera*, Chile's daily newspaper, about how COP15 offers a new opportunity to protect biodiversity.

Forbes cited **Geoffrey West**'s book *Scale* in their article "How The Quantum Computing Industry Can Ask Necessary Questions."

Sam Scarpino spoke with *STAT News* for their story, "What most surprised experts about the Covid pandemic."

Publications including the *LA Review of Books*, *The New Yorker*, *London Review of Books*, and *Harpers* featured **Cormac McCarthy**'s latest books and SFI's influence on his recent work. Relatedly, **David Krakauer** wrote an essay for *Nautilus*, sharing his reflections in "The Cormac McCarthy I know."

"Will We Know Alien Life When We See It?", a story in *Nautilus*, includes commentary and research by **Sara Walker**, **David Kinney**, and **Chris Kempes**.

Manfred Laubichler was interviewed by *The Arizona Republic* on what the evolutionary history of both nature and knowledge might teach us on how to live our best future.

Big Think asked **Sean Carroll** if free will violates the laws of physics.

2022 CSSS Journalism Fellow **Laura Spinney** wrote about innovation for *The Guardian*, featuring research by **Heyjin Youn**.

Why are sustainable practices often elusive?

For at least 200,000 years, humans have been trying to understand their environments and adapt to them. At times, we have succeeded; often, we have not. When we get it wrong, the results can be disastrous. However, in both success and failure, humans can learn from our past experiments and adapt.

Buried machinery in barn lot in Dallas, South Dakota, United States during the Dust Bowl, an agricultural, ecological, and economic disaster in the Great Plains region of North America in 1936. (image: USDA image no. oodio971)

"Our ability to respond to a future disaster is only as good as our ability to remember past challenges and to care about the future," explains SFI Complexity Fellow Stefani Crabtree (Utah State University). Crabtree is the lead author of a new study, "Why are sustainable practices often elusive? The role of information flow in the management of networked human–environment interactions," in the journal *Global Environmental Change*.

In the study, Crabtree led a team of researchers that grew out of SFI's ArchaeoEcology working group. Their goal was to measure how spatial, temporal, cognitive, and cultural limitations affect humans' understanding of their environments. The group, which is funded by the Coalition for Archaeological Synthesis, comprises experts from archaeology, anthropology, ecology, informatics, and other sciences.

The authors delve into archaeological and historical data from history's "completed experiments" to analyze how information flows from ecosystems to the societies inhabiting them. The resulting conceptual model, called Environmental Information Flow and Perception (EnIFPe), drew from case studies in Eastern Polynesia, the North Atlantic, and the American Southwest. The model yields a quantitative measure of information flow that can help distinguish when decisions have a sound basis in environmental knowledge versus when it's a shot in the dark.

"Of all the social sciences, archaeology is unique in its breadth and time range," says Jeff Altschul, the President of the Coalition for Archaeological Synthesis, which funded the research. "As such, it can detect signals in human behavior that other sciences with shallow historical reach cannot."

The research provides a framework to assess how societies — both in the past and those in present-day — interact with their environments for good or for ill. This framework can guide environmental decision-making, emphasizes Jennifer Dunne, a contributing author and SFI's Vice President for Science. With current environmental issues like climate change, pandemics, and biodiversity loss, the study's findings are relevant for questions of sustainability and stewardship.

"Societies that remember ecological information tend to adapt better," concludes Crabtree. "We need to be aware of the limits of our understanding so we can make better decisions and avoid catastrophe."

"Sparsification" could speed up epidemic modeling

Simulations that help determine how a large-scale pandemic will spread can take weeks or even months to run. A recent study in *PLOS Computational Biology* offers a new approach to epidemic modeling that could drastically speed up the process.

The study uses sparsification, a method from graph theory and computer science, to identify which links in a network are the most important for the spread of disease.

By focusing on critical links, the authors found they could reduce the computation time for simulating the spread of diseases through highly complex social networks by 90% or more.

"Epidemic simulations require substantial computational resources and time to run, which means your results might be outdated by the time you are ready to publish," says lead author Alexander Mercier, a former Undergraduate Research Fellow at SFI and now a Ph.D. student at the Harvard T.H. Chan School of Public Health. "Our research could ultimately enable us to use more complex models and larger data sets while still acting on a reasonable timescale when simulating the spread of pandemics such as COVID-19."

For the study, Mercier, with SFI researchers Samuel Scarpino and Cristopher Moore, used data from the U.S. Census Bureau to develop a mobility network describing how people across the country commute.

Then, they applied several different sparsification methods to see if they could reduce the network's density while retaining the overall dynamics of a disease spreading across the network.

The most successful sparsification technique they found was effective resistance. This technique comes from computer science and is based on the total resistance between two endpoints in an electrical circuit. In the new study, effective resistance works by prioritizing the edges, or links, between nodes in the mobility network that are the most likely avenues of disease transmission while ignoring links that can be easily bypassed by alternate paths.

"It's common in the life sciences to naively ignore low-weight links in a network, assuming that they have a small probability of spreading a disease," says Scarpino. "But as in the catchphrase 'the strength of weak ties,' even a low-weight link can be structurally important in an epidemic — for instance, if it connects two distant regions or distinct communities."

Using their effective resistance sparsification approach, the researchers created a network containing 25 million fewer edges — or about 7% of the original U.S. commuting network — while preserving overall epidemic dynamics.

"Computer scientists Daniel Spielman and Nikhil Srivastava had shown that sparsification can simplify linear problems, but discovering that it works even for nonlinear, stochastic problems like an epidemic was a real surprise," says Moore.

While still in an early stage of development, the research not only helps reduce the computational cost of simulating large-scale pandemics but also preserves important details about disease spread, such as the probability of a specific census tract getting infected and when the epidemic is likely to arrive there.

New book from SFI Press explores origins of sociality

Earth is full of examples of social behavior. When individual bacteria, insects, primates, and even self-driving cars make productive choices about their interactions with other individuals, that's sociality. We can trace social behavior back to the unicellular organisms that became the building blocks for life on our planet. And humans, by becoming social, gained a great advantage in the evolutionary race for survival. If we could rewind Earth's clock, would social behavior emerge yet again, and could we expect to find it elsewhere in the Universe? "Probably yes," concludes a new book from SFI Press.

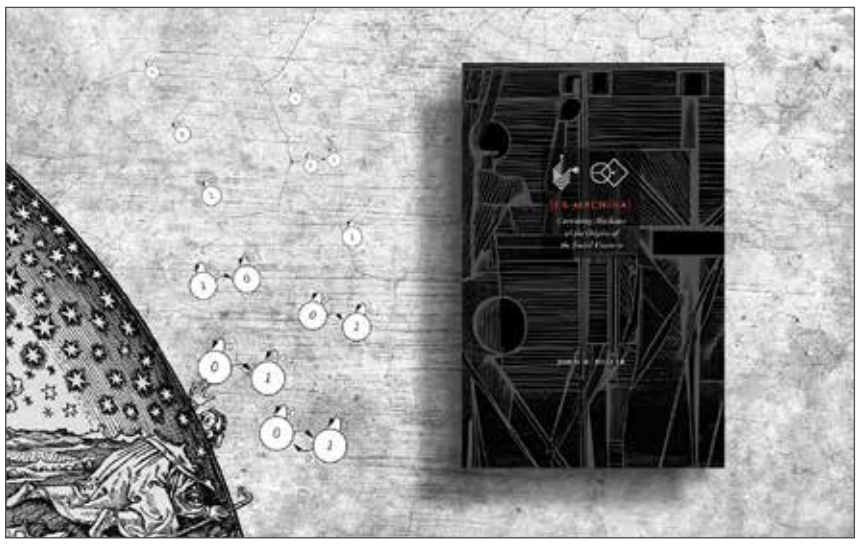
In *Ex Machina: Coevolving Machines & the Origins of the Social Universe*, SFI External Professor John H. Miller (Carnegie Mellon University) melds ideas from the study of games, the fundamentals of computation, and Darwin's theory of evolution to look at dynamic social systems through a computational lens. This novel approach, he writes, is like a time machine that allows us to observe and analyze the advent of social behavior — a question that cannot be answered using knowledge from one field alone.

"This work, at its core, embraces SFI's way of doing science," says Miller, who is an economist and social scientist. "The most interesting and important scientific questions are often found in between traditional fields."

But when working across disciplines, even seemingly simple things — like defining social behavior — can be challenging, says Miller. "Different scholars have very different notions about whether it can occur across species, if it requires special forms of intelligence, and so on." His ultimate definition was fairly general — "a relief to dog owners everywhere," he says — and it allows the possibility that social behavior could have emerged early in the history of life on Earth.

> If we could rewind Earth's clock, would social behavior emerge yet again, and could we expect to find it elsewhere in the Universe?

To answer questions about the emergence of sociality, Miller uses finite automata, which are simple computing machines that can respond to the inputs produced by other automata and evolve inside of a computer. The computations captured by the finite automata illustrate how much interaction and "thought" it takes for a system to become social, providing rich insights into the complex and multifaceted nature of social behavior. Miller began working on the core ideas presented in the book at SFI when he was a postdoc — the Institute's first — more than thirty years ago. But only recently, aided by dramatic advances in computer power, could he realize the project.



The book became his path to discovery: a way for Miller to explore and understand, with a deeper vision, what it takes to make a system social. It also provided an opportunity to answer questions about the origins of social behavior, which Miller had raised in his 2007 book with Scott Page, *Complex Adaptive Systems.*

This new project offers readers unique and technical insights into the emergence of social behavior in a system. His work reveals that systems can change from asocial to social, or vice versa, as they cross certain thresholds.

"If agents are very limited in their ability to process information — to make choices or be 'thoughtful' — or in how much they interact with one another, the system falls into asocial outcomes," says Miller. "Surprisingly, even though these systems are driven by small evolutionary changes, the movement from asocial to social (and back again) can happen very quickly — revolutions by evolution."

Understanding these thresholds of social behavior might not only explain how social life came to be, but also give us insights into social upheavals such as political movements and revolutions, the rapid acceptance of new social norms, and even the emergence or collapse of an entire social order. Such events can lead to profound and rapid transitions that ultimately define our collective future.

From pathogens to fads: Interacting contagions

Most people think of a disease outbreak when they hear the word "contagion." But it's a concept that extends beyond pathogens. It could be an infectious disease, a fad, an online meme, or even a positive behavior in a population.

"From the mathematical perspective, a contagion is just a thing that spreads," says Laurent Hébert-Dufresne, a former SFI Postdoctoral Fellow, now an associate professor in computer science at the University of Vermont.

In April, Hébert-Dufresne and Juniper Lovato, who was a former director of education at SFI, now the director of partnerships and programs at the University of Vermont's Complex Systems Center, will organize a workshop titled "Dynamics of Interacting Contagions." At the three-day event, around 25 experts from diverse fields, such as psychology and vaccine science, will make presentations and engage in brainstorming sessions to explore the science behind the complex interplay of contagions. SFI Professors Mirta Galesic and Sidney Redner will also be a part of the organizing team.

Many disciplines use the paradigm that "one pathogen equals one contagion" to study how things spread. However, this framework fails to capture phenomena such as outbreaks and misinformation. For example, multiple pathogens are responsible for making people sick during a flu season, explains Hébert-Dufresne.

Similarly, a lot is going on with social contagions, too. Lovato says that several factors determine the impact of a rumor, such as its content and people's ability to either debunk or get duped by it. The organizers hope the discussions at the event will yield a scientific publication, among other outcomes.

While the pandemic did not inspire the workshop — it was supposed to be held in 2020 and was postponed because of the public health emergency — Lovato believes understanding how different contagions interact can help us untangle large-scale outbreaks. For example, anti-vaccination sentiments can influence the rate of disease spread during these crises.

> Understanding how different contagions interact can help us untangle large-scale outbreaks.

Currently, researchers don't fully understand the mechanisms of contagion spread. "If we want to study a world where there are hundreds of millions of pieces of misinformation online and hundreds of pathogens that pose a danger in the real world, we just don't have the right tools to do it," Hébert-Dufresne says.

The workshop will be a starting point for discussing what these research tools could look like in the future. "I'm pretty confident we can build the framework that's needed to study interactions between contagions in a more systematic way," says Hébert-Dufresne. "And I think we have the right group to do it."

ACHIEVEMENTS

External Professor **Seth Blumsack** (Penn State University) was awarded a grant from the Alfred P. Sloan Foundation to study the U.S. electric grid.

External Professor **Orit Peleg** (University of Colorado Boulder) recently received an NSF CAREER Grant for her project titled "Principles of Firefly Rhythmic Synchronization."

Seth Blumsack

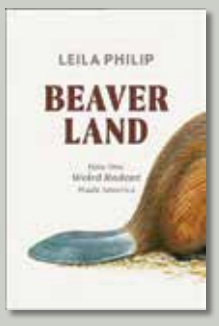
Orit Peleg

What We're Reading

Books chosen by SFI scholars on the theme of Capitalism

In his book *The Weird and the Eerie*, Mark Fisher says of capital that it is "at every level an eerie entity: conjured out of nothing, capital nevertheless exerts more influence than any allegedly substantial entity." For Fisher, eeriness surfaces when events occur without any indication of a guiding, conscious agent — a negative elaboration of Adam Smith's metaphor of the invisible hand. While Smith believed that the free market would lead to individuals acting in ways beneficial to their own societies, Fisher believed that capitalism more or less deprives individuals of any agency and is in the process of bringing about an end to history and innovation. Whatever one's opinion of capitalism, it has become increasingly evident that adequately complex alternatives to our current situation will be far superior to ideological impositions from above — where the hand is visible, oppressive, and far worse than eerie.

With a nod to SFI's new research theme on emergent political economies, this installment of What We're Reading focuses on books in which capitalism plays a significant role. How has our history been shaped by strange forms of labor and trade, and how, in turn, does capital shape our personal relationships, communities, infrastructure, and even our aesthetic judgments? Each author devotes a subtlety to these questions, which might occasion a sense of both the detriments and benefits of capitalism, along with inspiration for new frameworks that may transcend any political disposition.



LAURENCE GONZALES
Former Miller Scholar

***Beaverland: How One Weird Rodent Shaped America,* by Leila Philip**

In searching for a ray of ecological hope, I stumbled on a hole in my learning: I knew nothing about beavers. I recently corrected that with *Beaverland*, the fine new book by a Guggenheim Fellow. The book opened my mind to beavers' tremendous importance to the health of ecosystems — as well as to American history and economy, and even transatlantic trade.

DANIEL MURATORE
Complexity Postdoctoral Fellow

***Our Aesthetic Categories: Zany, Interesting, Cute,* by Sianne Ngai**

Ngai outlines contemporary capitalism as a cultural system through three modes aligning with the physical triumvirate of matter, information, and energy: the cute, the interesting, and the zany. Spanning the fine arts, television, and literature, Ngai describes the drive to protect and destroy our objects simultaneously (the cute), the effort to promulgate information without internalizing it (the interesting), and the urge to preoccupy ourselves with business accomplishing nothing in particular (the zany).

RENÉE TURSI
Manager, Office of the President

***Trust*, by Hernan Diaz**

Diaz's absorbing novel, with its story-within-a-story structure that upends our trust, features a consistent central figure: money. Steeped in a contemporary form of Henry James's and Theodore Dreiser's moral realism, the book opens with a man transfixed by the "ciphers of the ticker tape" that, as his "form of communion," supplant human connection. We go on to question how worlds are shaped by forces that remain abstract and analogous — like stocks, or novels — but are still acutely felt.

UNDERGRADUATE RESEARCH *(cont. from page 1)*

Harada ('95), professor of mathematics at McMaster University (Canada). "She was the first female mathematician I had ever met, and for the rest of the summer and for the full academic year that followed (which was my last year as an undergraduate), she kindly served both as a superb female role model as well as a generous and compassionate (informal) advisor."

What students valued then as now is the independence afforded by SFI's program, the lack of hierarchy at SFI in general, and the chance to discuss ideas with everyone. "Back in 1992, I first read about complexity science and the Santa Fe Institute in a science magazine and was immediately intrigued. I wanted to do science like that!" recalls Jean Czernicki Ortega ('93), senior engineer at Google. "I got a desk and a Mac in an office that was inhabited by a professor who was simulating economies. We had many informal discussions about how simulations could expand the boundaries of knowledge beyond what mathematical proofs could show."

The students' research projects in the early years tended toward mathematics and computer science, with significant interest in the then-emerging field of machine learning. Today, project themes still reflect those foundations but also include a generous representation of evolution and ecology as well as social systems and institutions. The backgrounds of participants have likewise diversified over time, with a broader range of fields of study and colleges represented.

What is next for undergraduate research at SFI? "We want to reach students who might not use the terms 'complexity science' or 'transdisciplinary' but who are drawn to SFI's approach to understanding adaptive, hard-to-predict systems," said SFI Director for Education Carrie Cowan, "even if they don't know it yet." Under the guidance of UCR program directors and SFI Professors Chris Kempes and Melanie Mitchell and the dedicated mentorship of SFI researchers, undergraduate researchers will continue to bring new ideas and talent to SFI.

SFI's REU/UCR program has been supported over the past 30 years through a combination of funding from the NSF REU program, faculty grants, institutional funds, and several significant donors.

Undergraduate Complexity Research students at SFI, summer 1996. [L-R] Terence Kelly, Scott Rifkin, Sean Mooney, Catherine Grasso, Josh Berman, and Brandon Weber.

KYLE HARPER *(cont. from page 1)*

perspectives come from new evidence like DNA, tree rings, and isotopes," he says. "And sometimes from new or better models of complex systems that help us understand really hard problems."

Harper was first exposed to how technology can reveal historical secrets while getting his Ph.D. at Harvard. It was the early 2000s, and Harper, who had a long interest in physics and biology but chose to go to graduate school in history, had just met Michael McCormick, a medieval historian that Harper calls another "maverick against the forces compartmentalizing knowledge."

McCormick was working on the Plague of Justinian, a medieval pandemic that erupted in 541 AD and is often seen as the Black Death's predecessor. But was it the plague, the same disease caused by the bacterium *Yersinia pestis*?

On a hunch, McCormick asked doctoral candidate Harper and a microbiologist to go into the Harvard medical school to scrape the dental cavities of a possible plague victim buried sixteen hundred years earlier. They ran flecks of the ancient remains through a PCR machine and the results solved exactly no mysteries. The technology needed another decade to mature enough to confirm that the Plague of Justinian and the Black Death were in fact caused by the same germ. But for Harper, the damage was done. He'd been infected with a passion for diseases ("Plague is near and dear to my heart," says Harper, unironically) and an awareness that the natural sciences held the keys for answering questions once thought lost to history. "Genetic data is a historical archive for historians who are paying attention," Harper says, adding to that idea every other scientific discipline that looks at change through time.

His latest book builds on those themes. *Plagues Upon Earth* explores why the human disease pool is far richer and nastier than any other species'. From humanity's chimpanzee-like ancestors to present, the book spans thousands of years of pandemics. Harper knew that conventional historical research wasn't equipped to answer the big questions. Could dendrochronology help explain whether climate change helped trigger the Plague of Justinian? Could DNA analysis of *Yersinia pestis*'s different genetic strains help clarify how and why this disease spread, mutated, and haunted humanity for centuries? What did economics say about how globalization made our species more vulnerable to pandemics like COVID-19?

> The sacred model of history confines historians to the study of writing and states. That's a very arbitrary way of divvying up the past.

Over the three years that COVID raged, Harper thought about parasites deeper than most of us. Viruses and bacteria are parasites that need energy and host cells to thrive. What better source than humans? There are cities of 20 million people; 8 billion of us on Earth — each individual an irresistible target for microparasites. Harper began to see each pandemic in relation to contemporaneous technological advances that "let us extract more energy from the environment and make more of us." Domesticating the horse. Trans-oceanic sailing. Germ Theory. Fertilizer. Antibiotics. Six million people on 100,000 flights every day. Technology detonated Paul Erlich's population bomb and then tied every person on Earth together in one big interconnected knot. We're a parasitic feast.

"Humanity is the architect of its own misery. It's the paradox of progress," Harper says. "Only it isn't an ecological paradox at all. Our story is also the story of our parasites."

With *Plagues Upon Earth* published last fall (*Forbes* called it a "sweeping masterpiece"), Harper has turned to a related question: How has human success depended on and shaped biodiversity? And what does the historical relationship between humans and biodiversity say about our species' chances of surviving Earth's ongoing sixth mass extinction event? Harper started his research for his new book in the University of Oklahoma library. At the Santa Fe Institute, where he'll spend time with scholars transcending the conventional boundaries between fields of knowledge, he'll continue it through conversation.

LOU SCHUYLER FUND *(cont. from page 1)*

Mingzhen Lu, Helena Miton, and Yuanzhao Zhang, SFI Postdoctoral Fellows, each received a Lou Schuyler Internal Grant in the fall of 2022. (photos: Katherine Mast and Doug Merriam)

postdocs presented flash talks at SFI's fall symposium, and four current and former postdocs shared longer presentations at SFI's 2022 end-of-year donor appreciation event.

After Lou died in 2021, sponsoring the internal grant and propelling the work of early-career researchers felt like a natural way to honor her legacy, says Hank.

Lou and Hank met during high school while attending a National Science Foundation Summer Program in Mathematics and Science at Brown University. Lou went on to receive a degree in applied mathematics from Brown and a Master's degree in operations research from Columbia University. After retiring, she became a volunteer at University of New Mexico's Maxwell Museum of Anthropology, cataloging a collection of Tijeras jewelry. She also wrote five volumes that were published through the Maxwell Museum's Technical Series. "What she did was the first step in the process of moving from data toward knowledge," says Hank. She also dove into textiles, creating her own garments through weaving, knitting, and sewing. And, she engaged her lifelong love of math and science by participating in SFI events.

"It's comforting to me if I can help out in a small way that helps the postdocs do what they need to," says Hank. "They are doing incredibly sophisticated science, and the questions they are asking are astounding. This is the kind of thinking that the world desperately needs." Helping SFI postdocs to fund creative projects felt like "a perfect match," he says. "Lou was very creative — always pushing the boundaries of what could be done."

SFI VP for Science Jen Dunne describes the fund as a kickstarter. "Each grant provides a relatively small amount of funds, but they are important for developing interesting new lines of research."

SFI postdocs who wanted to apply could meet with Carter and the Sponsored Research office for guidance on the application process. "I was pleasantly surprised by the number of applications we received in the first round," says Carter.

In addition to Mingzhen Lu's industrial ecology project, the first round of funding is also supporting projects on historical exchange networks, led by Complexity Fellow Helena Miton, and on visualizing basins of attraction in high-dimensional landscapes, led by Complexity Fellow Yuanzhao Zhang.

"I'm pivoting from studying cultural evolution at rather micro scales (e.g., collections of individual paintings) to getting into larger historical dynamics, which is a bit different and also means that usual funders do not see me as an expert on the topic," says Miton. "This grant allows me to produce a first high-impact, proof-of-concept paper to start demonstrating my competence in this new line of research."

Zhang's project builds on work he started with former SFI Postdoctoral Fellow Tyler Millhouse and summer UCR student Katherine Li. The grant will allow him to purchase more powerful computers and help the researchers reconvene. "Having this money will make this project much easier," he says.

Carter expects this second round of funding to attract a variety of novel proposals. "There's a tremendous need and these are high-quality applications," she says.

Lou and Hank Schuyler at SFI in 2011 (image: InSight Foto)

BEYOND BORDERS *(cont. from page 2)*

Algorithms, accumulating limitless hexagons of online information, where every artist born and unborn is somewhere in the endless permutation of what came before. And the search index seems to provide the necessary order to turn mere facts into fancy. It is a challenge for a dawning science to think through the implications of solving problems by exploiting practically searchable "effective infinities."

Boole had foreseen this utilitarian dilemma in a bygone configuration as well as its dire limits for the future:

"In the extreme case it is not difficult to see that the continued operation of such motives, uncontrolled by any higher principles of action, uncorrected by the personal influence of superior minds, must tend to lower the standard of thought in reference to the objects of knowledge, and to render void and ineffectual whatsoever elements of a noble faith may still survive."

— David Krakauer
President, Santa Fe Institute

Toward a theory of regeneration

Abraham Trembley, a mathematician from Geneva, Switzerland, first reported on biological regeneration in 1740 when he observed a bisected Hydra — a freshwater polyp — reconstitute itself. In the centuries that have followed, science has identified a host of species, from starfish to salamanders, with regenerative capabilities. But despite the years of study into the phenomenon, science still lacks a comprehensive theory of regeneration.

All biological complex adaptive systems, which range from multicellular organisms to ecosystems, will inevitably totter, either from aging cells or external forces like an out-of-control wildfire. In this moment of uncertainty, two paths emerge.

"If a system does not regenerate, it will fail," says SFI External Professor Manfred Laubichler (Arizona State University). "However, if we better understand regenerative dynamics, we may be able to steer distressed systems toward regeneration and away from failure."

Whether a system veers in the direction of regeneration or failure — death, in the case of cells or organisms, or system collapse, for ecosystems or communities — depends largely on its robustness, or its ability to remain stable in the face of disturbance.

In an era of unprecedented stress — from climate change, habitat loss, novel viruses, and more — science needs a theory of regeneration.

The relationship between regeneration, robustness, and failure is the focus of an upcoming SFI working group scheduled for February 22–24, 2023. Laubichler is organizing the meeting alongside SFI Science Board Member Susan Fitzpatrick and Jane Maienschein (Arizona State University). The participants will discuss regeneration, robustness, and failure through the lens of an information-theoretic framework, which is an approach to understanding complex systems through mathematical representations.

"There is a certain amount of information that a system holds — an essential amount of information that is needed to regenerate," explains Fitzpatrick. "We want to know if that information can be quantified or measured."

Post-fire regeneration in Yosemite National Park (image: Cristofer Maximilian)

In an era of unprecedented stress — from climate change, habitat loss, novel viruses, and more — science needs a theory of regeneration. Such a theory would help managers or administrators address resilience, for human and ecosystem health. The working group hopes to take an important first step by quantifying what makes a system resilient and describing how that informs the system's ability to adapt and regenerate in response to disturbance.

Carlos Gershenson writes *Balance* on sabbatical

When political decision-makers confront the hardest problems that human communities face — climate change, political polarization, pandemics, for example — they often face challenges that emerge from complex systems. Yet many helpful conceptual frameworks from complexity science do not circulate in public forums. For SFI Sabbatical Visitor Carlos Gershenson, the time is ripe to bring complexity science to public life.

Gershenson, a research professor at the Universidad Nacional Autónoma de México, has come to SFI to finish work on a book ten years in the making. Called *Balance*, it will bring some of the most salient concepts from complexity science to a broader public audience.

Each of the book's 10 chapters will elaborate on one concept or framework from complexity science, including synchronization, antifragility, criticality, and the slower-is-faster effect.

To make these concepts accessible to a broad audience, Gershenson discusses them through familiar illustrations. For example, to describe the slower-is-faster effect, he invites readers to imagine runners in a marathon. If they start too quickly, runners will use up their energy, but if they go too slowly, they won't achieve their best times. Finding optimal speed is a matter of balance.

"By generalizing the slower-is-faster effect," Gershenson says, "scientists can apply the framework to problems in traffic flow, crowd control, and resource management."

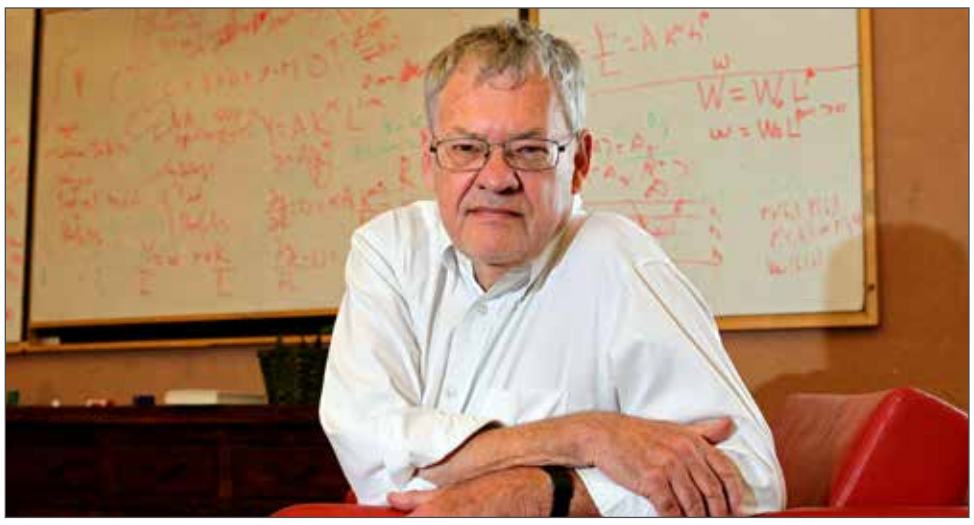
As he works on each of the chapters, Gershenson is offering seminars at SFI to engage with scientists and refine his explanation of each core concept.

So far, when he's had a chance to work with SFI scientists, Gershenson has found the process immensely helpful. Since he's interested more in testing presentations for the public than sharing new research, he anticipates that the community will "help tell the story by pointing out holes in the narrative or unnecessary detours."

Ultimately, Gershenson anticipates that his work will help "decision makers of the future take complexity into account in their decisions." He also hopes that, with the discussions at SFI, he will help scientists translate their work to the world.

Carlos Gershenson (image: Katherine Mast)

Charles 'Chuck' Stevens: mentor, man of science, generous soul



Charles 'Chuck' Stevens at SFI in 2011 (image: InSight Foto)

Charles Stevens, a preeminent neurobiologist who revealed fundamental architectures in the brain and whose experimental techniques paved the way for decades of molecular neuroscience, passed away on October 21, 2022, in San Diego, CA.

At the time of his passing Stevens, 88, was a distinguished professor emeritus at the Salk Institute for Biological Studies and a fellow of SFI's Science Board and External Faculty. He was also a long-time member of the National Academy of Sciences and the American Academy of Arts and Sciences.

"Chuck had a procedural curiosity like almost no one I have ever met before," says SFI President David Krakauer. "Rather than read about a topic from outside of his orbit he would dedicate a year to applying distant ideas and methods to a data set from his own work. And there was almost no area of inquiry that might not illuminate his subject, from feed-back control to information theory, compressed sensing to statistical mechanics."

When he first joined SFI in 1996 as a member of the Science Steering Committee, Stevens was revered in neuroscience circles for his foundational work in synaptic transmission Stevens' postdoctoral fellow, Erwin Neher, further developed this work and went on to win the 1991 Nobel Prize in Physiology or Medicine with collaborator Bert Sakmann.

A consummate man of science, and a mentor throughout his career, Stevens shared his methods with research collaborators and mentees. Among Stevens' many distinguished mentees is SFI External Professor Vijay Balasubramanian (University of Pennsylvania), who says Stevens helped him move from physics into computational neuroscience.

"He mentored so many people," says Balasubramanian. "He was just a generous soul. And he never tried to take credit. Chuck always had a focus on the intellectual depth and content of the things he thought about. That's what he really cared about."

Like many SFI scientists, Stevens' work bridged physics and biology. Moreover, he excelled as both an empiricist and a theorist, and made great strides toward understanding the fundamental architectures of the brain across a variety of animal species.

During his summers at SFI, he conversed with Geoffrey West, SFI Distinguished Shannan Professor, on the subject of scaling laws — the physical, quantifiable constraints that govern biological traits across species.

"He became intrigued by our work on scaling laws and we spent quite a bit of time struggling with what we might learn about the brain, and even cognition, by extending the ideas to neurological systems," says West. "He was one of my favorite people for talking science and for getting feedback on almost any issue."

Stevens and his colleagues at the Salk Institute went on to elucidate several fundamental scaling laws for the brain that revealed how brain structures can grow, adding more neurons, without having to re-organize.

"In order for evolution to work, neural circuits have to have what the computer scientists call a scalable architecture," Stevens told PNAS in a 2012 interview. "That means that you have to be able to make the computer more powerful just by making it bigger — you don't have the luxury of redesigning it; and so the question that I'm asking is: What are the design principles that brains use to give their circuits a scalable architecture?"

Many SFI colleagues recall Stevens' remarkable work ethic. He was known for his 10–12-hour workdays during his summer visits and, simultaneously, his willingness to engage with everyone he met around the institute. He often enjoyed a glass of wine with his lunch, and Balasubramanian recounts that Stevens spent many lunch breaks with his wife, Jane Stevens (née Jane Robinson), with whom he had three beloved daughters.

"Chuck and I were really in different fields, but his ability to translate difficult concepts into simple terms almost made me think we were in the same field," says SFI Science Board Member Simon Levin (Princeton University). "His writings were elegant, deep, and pedagogical, and I learned much from them. He was a giant in his field, and I always enjoyed our interactions at Santa Fe. He will be missed."

New Journal: Collective Intelligence

Collective Intelligence, a new online open-source journal, launched its inaugural issue in August 2022. The editors* hope the journal will help stimulate the discovery of the fundamental principles that underlie collective intelligence — a phenomenon found in complex systems, from swarms of ants and crowds of humans to bacteria in biofilms and networked computers. When these groups solve problems together, they often (but not always) make "smarter" choices than their individuals would if working alone.

As a phenomenon, collective intelligence has fascinated scientists and scholars since at least the 1700s. But as a field of study, it remains relatively underdeveloped when compared to other areas of research that inform complex-systems science.

The journal is dedicated to collective intelligence across scales and systems from "adaptive matter and physical systems, to molecular and neural systems, hybrid human-AI systems, sports teams, economies," and beyond, says SFI Professor Jessica Flack, one of the four editors-in-chief.*

The lineup of authors for the first issue illustrates the spectrum and ambition for the field, with high-profile contributors publishing on human, insect, and machine collectives, and trends in the field, such as the emerging influence of artificial intelligence.

As a society, we face several challenges — from pandemics to climate change — that require smart, nuanced responses "A richer understanding of collective intelligence offers the potential for better design of the systems we depend on to solve complex, shared problems," the editors write in their introduction to the first issue. "Starting a new journal . . . can accelerate our understanding of how to do better."

Flack is also organizing a Collective Intelligence Short Course & Symposium to be held in Santa Fe June 20–23, 2023. The Symposium & Short Course will search for unifying principles in collective intelligence by tackling its foundations, and explore radical ideas for harnessing collective potential.

**Collective Intelligence Editors-in-Chief: Jessica Flack, Panos Ipeirotis (New York University), Geoff Mulgan (University College London), & Scott Page (University of Michigan, SFI), with Founding Editor Thomas Malone (Massachusetts Institute of Technology)*

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RESEARCH NEWS BRIEFS

ECONOMICS IN NOUNS AND VERBS

In the last 50 years, economic theory has come to be based almost solely on mathematics. This brings logical precision, but according to a new paper by SFI economist Brian Arthur, it restricts what economics can easily talk about. Algebraic mathematics is "a language," Arthur writes, "that allows quantitative nouns only, but doesn't allow verbs — actions." So economics does very well with quantities, ratios, and prices but fails to properly deal with processes, formation, and creation.

With the advent of computers, new opportunities emerge to study that which cannot be contained in equations. Algorithmic models, Arthur points out, can easily include actions and processes, so the use of such tools can bring sorely needed verbs into the language of economics. Such a process-based economics would fill gaps in our understanding and help answer poorly understood questions: how economic actors navigate (and change) a fundamentally uncertain shifting landscape, how innovation works, how novel institutions form, and how economic development works.

Read the study: "Economics in nouns and verbs" at doi.org/10.1016/j.jebo.2022.10.036

COMPETITION FOR NUTRIENTS & INVASION RESISTANCE IN MICROBES

Does a diversity of species protect ecological communities from invasion? Recent work by SFI External Professor Andreas Wagner (University of Zurich) takes up this long-standing question for complexity science, at a microscopic scale. In his paper in Molecular Ecology, Wagner reports that microbial communities do indeed "become more species-rich, show higher biomass, and become more invasion resistant," as they develop in reaction to invading outsider species that compete for nutrients.

Because of the challenges involved in observing species at the microscopic scale, invasion amongst microbes has been relatively under-studied as compared to macroscopic ecological communities. To get around these challenges, Wagner used a computer modeling framework based on genome sequence data and extensive biochemical information for hundreds of microbial strains to explore, in-silico, how real-world microbes would react and grow. In addition to finding that microbial communities become more diverse in response to invasion, he also found that certain combinations of species occurred more often than chance would predict. This could mean that certain "attractor" communities do better than others at fending off invasions.

Read the study: "Competition for nutrients increases invasion resistance during assembly of microbial communities" at doi.org/10.1111%2Fmec.16565

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