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Parallax

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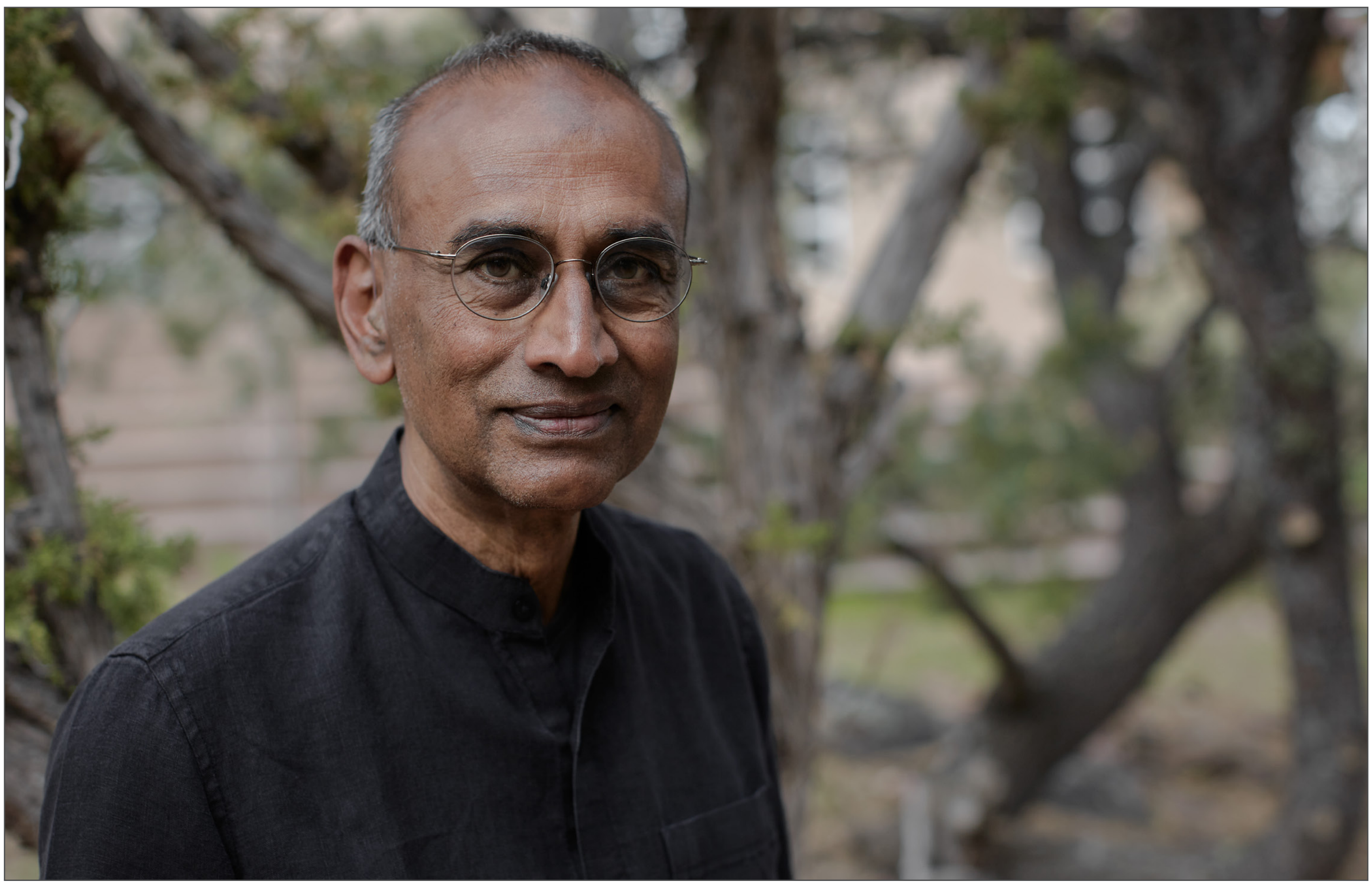


Venki Ramakrishnan, who won a Nobel prize in 2009 for his work uncovering the structure of the ribosome, joins SFI as Fractal Faculty. (image: Kate Joyce)

Venki Ramakrishnan joins Fractal Faculty

On a cold night in March 2000, a team of molecular biologists held their breath as they opened a dataset 30 years in the making. The group, led by the eternally restless and now exhausted Venki Ramakrishnan, had spent the previous 48 hours racing against time borrowed at Argonne National Lab's synchrotron, the Advanced Photon Source, bouncing x-ray beams off a frozen cell. The data they had collected would eventually reveal the complete structure and function of one of the two parts of the half-a-million-atom ribosome, the molecular machinery in every cell that translates mRNA into the proteins from which life emerges. Usually composed and humble, that night Ramakrishnan leaped from his chair, dancing as he shouted, "We're going to be famous!" Nine years later, Ramakrishnan and two other molecular biologists were awarded the 2009 Nobel Prize in Chemistry for solving the process that produced proteins out of genetic information.

In the decades that followed, Ramakrishnan received a dizzying assortment of accolades, wrote a book called *Gene Machine* that chronicled molecular biology's race to solve the ribosome's deepest mysteries, and served as the President of the Royal Society, the world's oldest scientific institution. He is currently founding a company, RNAvate, to use mRNA for therapeutics. He is also turning his gaze from reductionist, sub-cellular-level research to broader, systems-level questions. Ramakrishnan joined SFI's Fractal Faculty last year and is working on a new book about how and why we age and die. "You only have one life to live," he says. "Why not do the thing that actually matters most?"

Ramakrishnan found what mattered most to him early in his career. He left India for the United States in the late '70s at the age of 19 to get a Ph.D. in physics from Ohio University. But at age 23, recently married and with a doctoral degree in hand, he realized that he didn't want to be a physicist at all. Many of the big questions in physics had already been answered, and he couldn't see where the field — or his role in it — was going. But biology was in a revolution. It was "where the greatest advancements in 21st-century science could be made," he says. So Ramakrishnan packed up his physics career and moved with his wife and two young children to the Pacific coast to go to grad school again — this time in biology — at UC San Diego. He began by taking undergraduate courses along with pre-med students. From the outside, his

> MORE ON PAGE 5

Testing AI "intelligence" through visual analogies

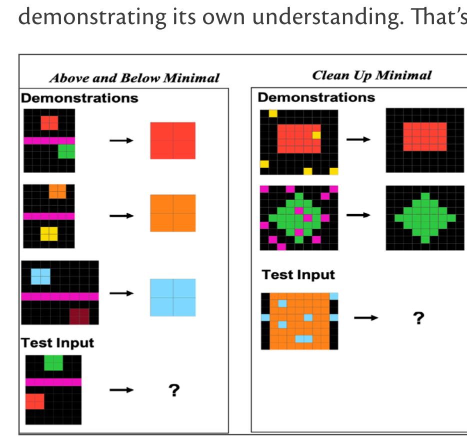
The field of artificial intelligence has long been stymied by the lack of an answer to its most fundamental question: What *is* intelligence? AIs such as GPT-4 have highlighted this uncertainty: some researchers believe that GPT models are showing glimmers of genuine intelligence, but others disagree.

To address these arguments, we need concrete tasks to pin down and test the notion of intelligence, argue SFI researchers Arseny Moskvichev, Melanie Mitchell, and Victor Vikram Odouard in a new paper in *Transactions on Machine Learning Research*. The authors provide just that — and find that even the most advanced AIs still lag far behind humans in their ability to create abstractions and generalize concepts.

The team created evaluation puzzles — based on a domain developed by Google researcher François Chollet — that focus on visual analogy-making, capturing basic concepts such as above, below, center, inside, and outside. Human- and AI test-takers were shown several patterns demonstrating a concept and then asked to apply that concept to a different image. The accompanying figure shows tests of the notion of sameness.

These visual puzzles were very easy for humans: For example, they got the notion of sameness correct 88 percent of the time. But GPT-4 struggled, only getting 23 percent of these puzzles right. So the researchers conclude that currently, AI programs are still weak at visual abstract reasoning.

"We reason a lot by using analogies, so that's why it's such an interesting question," Moskvichev says. The team's use of novel visual puzzles ensured that the machines hadn't encountered them before. GPT-4 was trained on large portions of the internet, so it was important to avoid anything it might have encountered already, to be certain it wasn't just parroting existing text rather than demonstrating its own understanding. That's



In a new paper, SFI's Arseny Moskvichev, Melanie Mitchell, and Victor Oudouard test "intelligence" using visual-analogy tasks (image: from Appendix A in "The ConceptARC Benchmark: Evaluating Understanding and Generalization in the ARC Domain," published in Transactions on Machine Learning Research in August 2023)

> MORE ON PAGE 3

Collective adaptation for a turbulent world

Humans are social creatures. We coalesce into families, tribes, cities, and countries, and we create structures and pathways to govern ourselves. Throughout history, we have introduced institutions — religions or new forms of government, for instance — to help us adapt and overcome population growth and technological advances. However, we currently lack the systems to adapt to modern technology, particularly social media and artificial intelligence, that are threatening the accepted beliefs, norms, and behaviors that underpin modern societies.

"In the last 20 years our social networks have evolved, and our individual behaviors are now maladapted," says SFI Vice President for Applied Complexity Will Tracy. "The world has changed and we have not been able to shift our behavior anywhere near the speed at which our network structures are changing."

To respond to these changes as a society, we first need a better understanding of how groups alter their decision-making strategies and beliefs to cope with emerging problems. Enter Tracy and SFI Professor Mirta Galesic, who hosted an interdisciplinary workshop September 12–14, 2023, to advance collective adaptation research and build cohesion among the research community. The meeting, part of SFI's CounterBalance Series and funded by Siegel Family Foundation, convened scientists from a range of biological, social, and physical sciences. Also attending were senior representatives from civic organizations and the tech industry, who shared real-world experiences and insights to inform future research questions.

"Technology has changed the way we organize and synthesize information," says Galesic. "In a flash, we can integrate information from thousands of people, and social norms are changing because it is easier to deceive and defraud people."

In a recent article published in the *Journal of the Royal Society Interface*, Galesic and

> MORE ON PAGE 5

INSIDE: SFI welcomes new postdocs . . . Human behavior in public health crises . . . Digital twins . . . . . . MORE

BEYOND BORDERS

MIRRORS OF THE WORLD

Arthur I. Miller subtitled his parallel biography of Einstein and Picasso *Space, Time and the Beauty that Causes Havoc.* The upheaval to which Miller alludes is nothing less than the assault on our intuitive beliefs about space (cubism) and time (relativity). Put differently, familiar representations used to encode regular patterns in the world are, in fact, conventions. At a certain point these are deemed insufficient, or rather boring, and replaced. It is like the experience of touring through the Metropolitan Museum in New York City by starting in Greece with a Balsamarium decorated in lion skin, ambling through the Pacific past an Asmat ancestor, hastening through the Middle Ages fleeing from its terrifying two-handed swords, and coming to a stop at the inevitable lion in a Rousseau painting. They are different means of seeing not progressively but of encountering alternative depictions of reality.

The overall effect is to wonder at the multiplicity of descriptions of very similar objects and events. In 1781 Immanuel Kant made the question of "representation" the foundation-stone of a theory of knowledge. Kant kicks us off with his section on "Metaphysical Exposition of this Conception" in the *Critique of Pure Reason*:

> "What then are time and space? Are they real existences? Or, are they merely relations or determinations of things, such, however, as would equally belong to these things in themselves, though they should never become objects of intuition; or, are they such as belong only to the form of intuition, and consequently to the subjective constitution of the mind . . ."

When are we entitled to call a representation objective (O) and when subjective (S)? There is a reasonable, operational form of naive realism that makes S mind and O sensation. Start with S_1, O_1: Ptolemaic astronomy (S_1) viewed through the naked eye (O_1) and replace it with S_2, O_2: Newtonian mechanics (S_2) constructed from telescopic observations (O_2). In this way, the accumulation of exact knowledge is the sequence $S_i, O_i \rightarrow S_{i+1}, O_{i+1}$. And there is of course an evolutionary counterpart to epistemology — the sequence of adaptive steps mapping successive traits onto environmental factors described through a lineage.

Let's just say that reality lies somewhere between the relatively simple history of science and life and a complex day trip to the Metropolitan Museum. What is striking is that in both cases — Miller's central point in his biography — is that we must think of life and cognition as systems of reflection. This fact is what establishes, or delimits, what we call complex reality. Physics and chemistry have no need of S, O pairs, but we cannot begin to talk about biology, culture, or technology, without some version of this duality.

John Holland and Murray Gell-Mann made the S, O pair the centerpiece of their definitions of complex systems,

> MORE ON PAGE 4

CREDITS

EDITOR: Katherine Mast

CONTRIBUTORS: Kyle Dickman, Anthony Eagan, Abha Eli Phoboo, William Ferguson, Sienna Latham, Stephen Ornes, Julie Rehmeyer, Aaron Sidder, Paul Stapleton, Neema Tavakolian, Shafaq Zia

DESIGN & PRODUCTION: Laura Egley Taylor

COPYEDITORS: Abha Eli Phoboo, Sienna Latham

VP FOR SCIENCE: Jennifer Dunne

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Information flow and human societies

The word "computation" doesn't only apply to today's laptops, phones, and other devices. It can describe almost any machine or system that uses energy to transmit, store, or transform information of all kinds. Living systems, from cells to organisms to ecosystems, can be seen as carrying out computation.

Researchers at SFI and beyond have long explored ways that both biological and physical systems compute at a range of magnitudes. At the smallest scales, information about survival drives the machinery of individual cells. Zooming out — in terms of size and complexity — can reveal computational processes where information shapes social animal behavior and even the dynamics of evolution.

Human societies, too, have been shaped by the exchange, flow, and transformation of information, say SFI Professor David Wolpert, a physicist, and Fractal Faculty member Kyle Harper, a historian at the University of Oklahoma. But understanding how those mechanisms work remains something of an open question.

Wolpert and Harper are organizing a working group, to be held December 11–15, 2023, that focuses on how the interaction of information and energy, through computing, shapes social systems. The meeting follows a March 2023 working group that laid the groundwork for this emerging area.

"Human societies have tended to increase in complexity over time," says Harper. Two thousand years ago, the global population was about 300 million. Last November, it likely passed 8 billion, according to the United Nations. That growth has led to complex societies and an uptick in energy consumption, interwoven with increasing computational abilities.

> Systems that arise from dynamic human interactions are also, in a sense, computers.

The physical and biological environments that humans interact with can be modeled as computers, says Wolpert. Similarly, systems that arise from dynamic human interactions are also, in a sense, computers. "Human society uses computational processes," says Wolpert.

During the working group, researchers will explore the idea that the storage of information in human culture, and its transformation, drive its complexity. They'll use the tools of information theory, which was born in telecommunications in the late 1940s and has yielded deep insights in other living, computing systems.

But those tools only characterize transmission, a small part of how living systems engage with information. "If we were only engaged in transmission, we could scoop out our brains and put in fiber optics," said Wolpert. Living systems — and human societies — also store and transform information, and that process gives rise to complexity.

Harper said this line of inquiry naturally attracts diverse researchers who may enter the conversation speaking about the same ideas but using different scientific terms. "Once we try to work in the same language," he said, "we can see what new insights might be possible."

"Shoulao, God of Longevity, with his attendants in the heavens." Zhang Liu. 16th Century. (image: Shanghai Museum)

Workshop explores lifespan across scales

It would seem that one of the few certainties about life — and a fundamental fact of any complex system — is death. The second law of thermodynamics dictates that all systems tend toward disorder. Institutions can last only as long as they reflect the needs and values of the mortal individuals they serve, cities and civilizations eventually collapse, and stars implode and swallow their planets.

But is immortality necessarily impossible?

A September 27–29 workshop, the Complex Time General Conference on Immortality, will meet to explore general patterns for lifespan across scales, from organisms, the mind, and behavior, to civilizations and star systems. The organizers hope to challenge preconceptions about immortality and, eventually, develop a general theory of longevity.

"Entropy would almost insist that there is no such thing as immortality," says Caitlin McShea, SFI's Director of Experimental Projects and co-organizer of the workshop. "But we are bringing in the idea that life might approach immortality at the level of emergent phenomena that come from living systems — things like ideas or technology or culture."

Immortality isn't all it's cracked up to be. (illustration: Adam Copeland/SFI)

Among the workshop's several dozen participants will be researchers who led topical-track meetings over the past five years under the Aging, Adaptation, and the Arrow of Time theme, which is funded by the James S. McDonnell Foundation Complex Time Grant. The meetings have explored questions about time and aging as they relate to single-celled aging, infectious diseases, cognitive health, regeneration, and more.

"We have an understanding of how time works in the universe, but it doesn't actually describe the world we are occupying. The experience of living matter is, far and away, different from the experience of an inanimate particle. At SFI, we've been trying to probe that difference for a long time, and it's hugely important as we begin to engineer new systems or interventions for making the systems we have even better," says McShea. "We have here the potential for something like a general theory of living matter, and that's deeply coupled to how time functions in our universe."

Throughout the workshop, organizers of the topical-track meetings will give "thunder talks" — a longer, more informative variation on "lightning talks" — on insights from their earlier meetings. New participants, including physics- and theory-minded representatives, will broaden the expertise of the group to help identify general patterns observed across these various systems' lifespans. And while there are no specific outputs expected from the workshop, organizers hope it will serve as a jumping-off point for new focused meetings in the future.

CDC awards funds for disease-prediction research

External Professors Lauren Ancel Meyers and Samuel Scarpino, who both spent time at SFI as early-career researchers, are among the recipients of funds from the Centers for Disease Control and Protection to advance disease-prediction science. (image: InSight Foto)

The Centers for Disease Control and Prevention (CDC) has committed more than $250 million to become better prepared for disease outbreaks like COVID-19 — and they're turning to two SFI researchers, Samuel Scarpino of Northeastern University and Lauren Ancel Meyers of the University of Texas at Austin (UT), to help make it happen.

The CDC is building a network of 13 centers for forecasting and analyzing infectious diseases. Meyers will lead a project receiving $27.5 million, while Scarpino's EPISTORM Center, led by Professor Alessandro Vespignani, will receive $17.5 million.

Meyers and Scarpino each did research early in their careers at SFI, and both have since participated in and organized many workshops at SFI, including recent ones on "Digital Disease Surveillance" and "Simulation Games for Pandemic Preparedness."

"The many SFI workshops I have organized and attended over the last 25 years have fostered my innovative and interdisciplinary approaches to building models that elucidate the human, biological, and environmental drivers of epidemics," Meyers says.

In the early 2000s, Meyers (together with SFI's Mark Newman) applied network theory to epidemiological modeling for the first time, showing that people's patterns of interactions enormously influence the way some pathogens spread. Meyers and Scarpino expanded this powerful toolkit to many types of pathogens, and when COVID-19 appeared, these tools allowed both researchers to quickly produce models that the virus posed. Throughout the pandemic, Meyers led a large consortium of researchers from UT, SFI, and other institutions worldwide to build models to forecast hospitalization rates and design effective mitigation strategies. She received a Key to the City from the Mayor of Austin, Texas for designing the city's COVID-19 staged alert system and providing expert guidance that helped Austin to maintain COVID-19 death rate far below that of most other cities in the U.S.

The new grant will allow Northeastern's EPISTORM center, where Scarpino's group works, to build tools for predicting surges in hospitalizations for respiratory infections by combining wastewater and case data with high-resolution cellphone mobility data using artificial intelligence. They will design these tools to meet the needs of rural hospitals, which are often neglected, as well as urban ones. Meyers' new project will build on current COVID-19 models to better prepare U.S. public health agencies for future pathogen threats. Her team will also develop innovative educational resources, including pathogen wargames, to train public health officials to use these models during public health emergencies.

Meyers and Scarpino helped pioneer a powerful approach to incorporating complex human behavioral dynamics into epidemic models using advanced tools from math and computer science they learned at SFI. "It's rare for someone at a postdoc level to learn in a deep fundamental way new things, and that's a lot of what happens at SFI," Scarpino says. "I would not be here if it weren't for my time in Santa Fe."

Predicting human behavior in public health crises

With the astonishingly fast creation of highly effective COVID-19 vaccines, science seemed to have saved us from the pandemic. But many people refused vaccination as scary stories spread through social media. Thousands of people continued to die every day. Science, it seemed, wasn't enough when humans wouldn't cooperate.

> "Can we build predictive intelligence to explain human behavior around pandemics?"

But Lauren Ancel Meyers argues we shouldn't give up — we just need to strengthen pandemic science by understanding, and planning for, the particularities of human behavior. And she believes that advances in the social sciences are making that possible in groundbreaking ways. She's bringing together a wide array of experts to more deeply understand, predict, and influence people's behavior during a pandemic. The workshop, "Understanding, Tracking, Predicting, and Influencing Social, Emotional, and Behavioral Dynamics During Public Health Crises," will be held at SFI November 8–9.

Throughout the COVID-19 pandemic, people were describing what they were thinking, feeling, and doing all over social media. And that fire hose of chatter, in Meyers' eyes, is "a goldmine of data." New methods have been developed to extract information from messy data like Reddit posts or tweets, allowing scientists to, for example, measure the real-world impact particular public health messages or news reports had, with far more nuance than simply, say, tracking vaccination rates in its aftermath.

The next step will be to incorporate this understanding of human behavior into epidemiological models, improving their accuracy. And the final step will be to learn the most effective ways of influencing behavior to protect the community as a whole. "Even today, we haven't come up with effective strategies for combating vaccine hesitancy," Meyers says. But with data-informed models, she believes, "we can design policies that people are going to want to adhere to."

"It's a call to action," Meyers says. "Can we build predictive intelligence to explain human behavior around pandemics?"

VISUAL ANALOGIES *(cont. from page 1)*

why recent results like an AI's ability to score well on a Bar exam aren't a good test of its true intelligence.The team believes that as time goes on and AI algorithms improve, developing evaluation routines will get progressively more difficult and more important. Rather than trying to create one test of AI intelligence, we should design more carefully curated datasets focusing on specific facets of intelligence.

"The better our algorithms become, the harder it is to figure out what they can and can't do," Moskvichev says. "So we need to be very thoughtful in developing evaluation datasets."

THE COLOPHON: UPDATES FROM THE SFI PRESS

New editions of iconic books celebrate Murray Gell-Mann

In 2019, SFI President David Krakauer shared an early proof of Worlds Hidden in Plain Sight with SFI Co-Founder Murray Gell-Mann. (image: Cecilia Lowenstein)

SFI Co-Founder and Nobel laureate Murray Gell-Mann wore many hats at the Santa Fe Institute. He was there at the its earliest formation, and he contributed to the very first SFI Press volume. He was also one of the first people to see the new edition of *Emerging Syntheses in Science* when, in 2019, SFI Press Editor-in-Chief David Krakauer visited Gell-Mann at his home and read from an advance copy. This affordable, revised version of a classic publication incorporated never-before-shared transcripts of SFI's founding workshops, which Gell-Mann had attended in 1984.

Synthesis was at the heart of those early conversations about the still-forming Santa Fe Institute. The 28 attendees, spanning the sciences and including policymakers, sought to create an institute that fostered interdisciplinarity, collaboration, and creativity, sidestepping the common pitfalls of colleges, universities, and other more traditional institutions. As Gell-Mann put it in his keynote lecture, "Our compartmentalization of learning is becoming more and more of a grave hazard."

He envisioned in SFI a place that would bypass the usual dichotomy of Apollonians versus Dionysians — of logical analysis versus qualitative intuition — in favor of Odysseans: scientists drawn to both perspectives. An institute where "really exciting people with broad interests are at the core," he said at the time, would allow ideas and connections "to develop or evolve that you hadn't planned on."

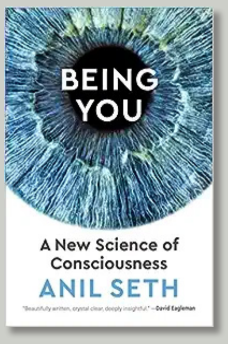
Now, nearly four decades after the founding workshops, the SFI Press reflects on the Institute's history by celebrating Gell-Mann, the consummate Odyssean. Later this fall, the SFI Press will republish two works — one *by* Gell-Mann and another *about* him. A fresh edition of *The Quark & the Jaguar* marks the first time Gell-Mann's 1994 science-focused memoir will be available in ebook format. It is paired with a newly updated edition of *Strange Beauty*, an insightful biography of Gell-Mann by author and science journalist George Johnson. Together, these works communicate the astonishing breadth of Gell-Mann's curiosity, persistence, and passion for understanding the world across scales. Physicist, linguist, nature-loving birder, collector (and corrector) of restaurant menus, he exemplified the qualities shared by so many who have been drawn to SFI — people with myriad interests, inexhaustible curiosity, and, above all, a drive to learn and to make a difference.

What we're reading

Books chosen by SFI scholars on Individuality

In his influential book *The Quark & the Jaguar*, soon to be re-released by the SFI Press, Murray Gell-Mann renews the perennial question of what constitutes an individual — that is, an object, animate or inanimate, with its own particular history. Although the question has been examined by philosophers, poets, and logicians since the origin of human inquiry, Gell-Mann puts a new spin on it by attempting to embrace the mystery more scientifically than before. To get at the matter, he had to apply his knowledge of and innovations in the study of particle physics. He writes, "Walking through the forest near Chan Chich, I was pondering how quantum mechanics can be used in principle to treat individuality, to describe which pieces of fruit will be eaten by parrots or the various ways in which a growing tree can shatter a piece of masonry from a ruined temple."

Each of the books recommended below shares similar concerns with individuality — albeit with an array of different techniques and starting points. How does contingency play a role in our unique development? Why do individuals age differently from one another? To what degree is the individual shaped by genetics, and to what degree by chance? How is each unique person being manipulated by mysterious external forces, other consciousnesses, or internal conflicts? And how is it possible that, from the same essentially universal hardware of the human brain, such distinct and discrete consciousnesses can emerge to produce the richness of our biological panorama?

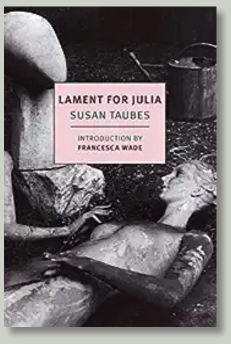


CARLOS GERSHENSON
Departing SFI Sabbatical Visitor

***Being You*, by Anil Seth**

Consciousness is more controversial and undefinable than complexity. This is because of the multiple uses of the word, but also due to its inherent subjective nature.

Nevertheless, the scientific study of consciousness has achieved various advances. Anil Seth excels at integrating recent results and open questions, as well as differentiating consciousness from intelligence.

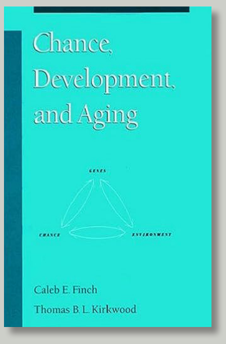


SIMON DEDEO
SFI External Professor (Carnegie Mellon University)

***Lament for Julia*, by Susan Taubes**

If Cormac McCarthy has Alicia, the tormented mathematical genius of his final book, *The Passenger*, Susan Taubes has her unnamed operator — a neurotic, manipulative, and condescending spirit, incarnated within the body of the earthy, sexual Julia Klopp.

As Julia matures from a whimsical childhood into early adulthood, her operator — a Jungian animus or contrasexual unconscious — struggles with the tantalizingly out-of-reach consciousness that runs alongside his own.



SUSAN FITZPATRICK
SFI Science Board

***Chance, Development, and Aging*, by Caleb E. Finch and Thomas B. L. Kirkwood**

Certain books create dividing lines; there is a before and there is an after. Once read, there is no going back. I read *Chance, Development, and Aging* twenty years ago (by chance) and return to it often. It is a mind-blowing antidote to textbook biology. Chance events profoundly affect events across the lifespan. We dismiss accounting for them at our peril.

SFI welcomes new postdoctoral fellows

SFI postdoctoral fellows are selected from around the world for their intellectual curiosity, quantitative and qualitative rigor, and multi-disciplinary creativity. At the institute they enjoy exceptional freedom to pursue new research questions and collaborate with foremost researchers in our international research network as they prepare to become tomorrow's scientific leaders. All fellows participate in a unique training program designed to develop their scientific, communication, and leadership skills. Most go on to hold faculty positions at major universities and research institutions, where they serve as lifelong ambassadors for the philosophies and methodologies of complexity science.

This fall, SFI welcomes four new Omidyar Fellows, one Complexity Fellow supported by the James S. McDonnell Foundation, and two Applied Complexity Fellows working with SFI's Applied Complexity Network.

KERICE DOTEN-SNITKER

Throughout history, minority racial and ethnic groups have often faced oppression from local majority groups within various geopolitical states. Medieval Germany can serve as a valuable model when studying the social construction of race and ethnicity; it exemplifies the competition that arises from state formation, which often has a negative impact on minority communities. In medieval Germany, it was Jewish communities that suffered.

Omidyar Postdoctoral Fellow Kerice Doten-Snitker, who completed her Ph.D. in sociology at the University of Washington, explores how the formation of states and institutions paves the way for the social constructs of race and ethnicity to emerge. She uses quantitative, geospatial, and historical methods to study how those constructs arise and how they affect societies and individuals. Her dissertation illustrates how social boundaries, such as cultural differences and class hierarchy that resulted from competition, were intertwined with political development, institutional change, and the facilitation of opportunistic exclusion and violence. "The expulsion of Jews from medieval German cities was legislated by the government," she says. "This is something we can use to learn about other times in the past and in contemporary politics."

While at SFI, Doten-Snitker hopes to build on her existing research. "When we think about inclusion and exclusion as part of social change, concepts regarding complexity science easily flow into that," she explains. She also hopes to finish creating the most comprehensive spatial database on medieval and modern Germany and dive into studying witch trials in medieval and modern Europe as well. Doten-Snitker joined SFI in August.

ANNA GUERRERO

From illustrations to diagrams to photographs, images help scientists record their observations and communicate their findings. Those images often spark new theories or research questions which, in turn, are captured through new images.

Complexity Postdoctoral Fellow Anna Guerrero recently completed her Ph.D. in biology from Arizona State University. She uses a historical and philosophical lens to document how biologists use that concept-to-image cycle to learn about the physical world. Guerrero is also an accomplished scientific illustrator whose exhibits have been on display at the Harvard Forest Fisher Museum and the Marine Biological Laboratory.

"Every image, even a scientific image, is shaped by the choices scientists make, and those choices are shaped by past images," she says. "Learning about choices scientists made in the past can help us understand the choices scientists make in the present, and help them make better choices going forward." At SFI, she plans to approach her research through a more quantitative lens, eventually building software that can help researchers study the interplay between concepts and images in biology. "This final product would be applicable to any research question involving roles of images in complex systems," she says. Guerrero joined SFI in July.

SEUNGWOONG HA

Machine-learning tools have powerfully accelerated the process of doing science. They can sort through and analyze vast sums of data, revealing insights and connections about the world never before possible. But could we ever fully automate the scientific process? Could we make an AI physicist? It's a question that captured Seungwoong Ha, an incoming Applied Complexity Fellow, as a student at Korea Advanced Institute of Science and Technology (KAIST) where he completed his B.S. and integrated M.S. and Ph.D., all in physics.

The basic roadblock is an AI's ability to comprehend. "You can't command a computer, 'find something interesting.' But humans can find it. We understand what 'interesting' means," says Ha. However, if we ask an AI a more specific question — for instance, does a dataset shows internal symmetry or a conserved quantity? — our machines could point toward something "interesting."

Ha now wants to apply the powerful pattern-finding abilities of machine-learning systems on complex-systems questions. And while many of his previous research questions have been rooted in physics, Ha is turning his attention toward social systems, "the hardest complex system," as he says. During his two-year fellowship, Ha will work closely with SFI Professor Mirta Galesic and External Professor Henrik Olsson on their belief dynamics project, using machine-learning tools and natural language models to explore how people behave and influence one another in online spaces. Ha began his fellowship in July.

HARRISON HARTLE

The study of mathematical models can provide insight into the structure and function of complex systems. However, even simple models can often be quite difficult to analyze, and meaningfully connecting models to real-world data is more challenging still. Omidyar Postdoctoral Fellow Harrison Hartle's research expertise is in mathematical and computational modeling. He is interested in advancing the study of generative models for complex systems with the goal of constructing practically applicable and meaningfully interpretable models for real-world data.

The models that Hartle plans to work on range from the very simple to the relatively complex, including both null and mechanistic models. Null models can be used to detect nontrivial patterns in data. Simple mechanistic models may exhibit qualitatively realistic behavior but serve primarily as abstractions. More intricate and data-driven models can produce quantitative predictions pertaining to specific real-world systems. Hartle wants to create models that can be applied to areas such as origins-of-life research, immunology, criminal legal systems, and international relations. By working to advance both theory and application, he intends to contribute toward strengthening the theoretical foundations of complexity science and help bridge the divide between the understanding of models and of real-world phenomena.

Hartle studied physics at the University of Alaska, Fairbanks, and holds a Ph.D. in network science from Northeastern University. He has worked on fluid dynamics, nonlinear oscillator systems, and probabilistic network modeling. He joins SFI in October.

SAVERIO PERRI

In a complex system, small, local changes can create a cascade of unexpected consequences in other parts of the system. Choices that seem immediately prudent might prove less ideal in the long term. Applied Complexity Fellow Saverio Perri is interested in the unexpected ways that sustainability transitions might impact both social and ecological systems.

Perri holds an M.A. in environmental engineering from the University of Palermo and a Ph.D. in interdisciplinary engineering from Khalifa University. His dissertation focused on how degraded, salty soils impact plant communities across spatial and temporal scales. During a recent postdoctoral fellowship at Princeton University, he expanded his research into managed ecosystems by studying the dynamics of the global food system.

During his fellowship at SFI, Perri plans to explore biophysical constraints like water availability and soil fertility within our food systems and the negative consequences of exceeding those limits. "If we can better understand the constraints, we can maximize productivity without having to further increase land use or inputs such as water and fertilizer," he says.

He also wants to better understand individual and collective perceptions of climate change adaptations. "Most people know that climate change is happening, and governments have agreed that we need to do something," he says. "I want to know why we are not doing what's needed and identify governance and behavioral scenarios to sustain the transition to sustainability targets." Perri began his fellowship in August.

ANDREW STIER

How much do city environments constrain human behavior? What aspects of a city's organization affect the psychology and mental health of its inhabitants? Scientific theories anchored in psychology that explain how city spaces shape human behavior are sparse. Omidyar Postdoctoral Fellow Andrew Stier works at the intersection of psychology and urban science to build theoretical models that examine how individuals and large groups adapt to and design city spaces. He holds a Ph.D. in integrative neuroscience from the University of Chicago, where he also earned a Master's in psychology and a B.A. in mathematics and physics.

"I want to extend the models of cities to neighborhoods in urban spaces," says Stier. "Cities are important to us, and they are useful places to learn about human behavior scientifically. However, can we take these tools and apply them to neighborhoods? That could give us a better understanding of human social interactions."

While at SFI, he wants to used collaborative research to build theoretical frameworks that examine the nexus of the physical and social environment, human psychology and implicit biases. Stier starts his fellowship at SFI in October.

KATRIN SCHMELZ

In the East German village where Omidyar Fellow Katrin Schmelz grew up, a pair of barbed-wire fences, a minefield, and guarded watch towers separated her from the West Germans she could see across the border. "I always wondered who I would be had I been born just a few kilometers to the west," she says.

That question led Schmelz to complete a Master's program in psychology, followed by a Ph.D. in economics at the Max Planck Institute of Economics in Jena. Her early research explored how people from West and East Germany who had lived through different levels of state control responded to other restrictions throughout their lives. In three recent papers published in *PNAS*, Katrin showed that those same populations responded differently to COVID regulations, in particular vaccine mandates.

More recently, she has been studying how individual behaviors and values co-evolve with societal institutions and policies. She asks how mandates like those designed to address climate change or public health emergencies can backfire if they compromise peoples' sense of autonomy. "We know that in the climate crisis, voluntary actions aren't sufficient, but we have also learned that mandates can destroy people's prosocial motivations." Schmelz began her fellowship in August.

A new era of personalized modeling through digital twins?

If a digital copy of your heart or another organ were stored on a hospital supercomputer and could evolve alongside changes in your actual health, a doctor could use this type of personalized model to make custom-tailored decisions about treatments in real time. This "digital twin" could help you prevent diabetes, cardiovascular disease, or even cancer.

While researchers are on the cusp of creating computer models for entire organs, precision healthcare applications using digital twins are still theoretical. Karen Willcox, an SFI External Professor and University of Texas aerospace engineer, is helping to convene a National Science Foundation-sponsored workshop at SFI, October 12–13, to make this new type of modeling technology a reality.

What sets digital twins apart from conventional models and simulations is the dynamic interaction of data between the physical and virtual environments. Sensor data or remote sensing from the physical system is assimilated into the virtual model, causing it to evolve and adapt. The updated virtual model can then provide recommendations on how to improve the physical system. This feedback loop creates a continuous cycle of optimization, which could ultimately be used to improve everything from airplane fuel efficiency to natural disaster forecasting and personalized medicine. In fact, since NASA coined the phrase "digital twin" in 2010, scientists have found a variety of ways to put the technology to use in improving drones, spacecraft, and other mechanical systems.

An October workshop at SFI explores the research still needed before we can develop digital twins for computationally intense activities. (image: Adolfo Félix/Unsplash)

"The scientific community has been building mathematical models and simulations of complex systems now for decades and it has really changed our understanding of engineering systems, the natural world, and medical outcomes," Willcox said. "What digital twins now enable us to do is personalize these models in a way that has never been possible before."

However, several barriers impede the realization of digital twins for more computationally intense activities. Our computing capabilities and modern algorithms are nearing the ability to model an entire human organ, but they remain distant from modeling complete human beings or planetary ecosystems.

Additionally, uncertainty and trust on the part of decision-makers and other stakeholders are pivotal concerns when deploying digital twins, particularly when informing critical decisions involving things like human healthcare and urban infrastructure.

Willcox said her hope is that the workshop, "Crosscutting Research Needs for Digital Twins," will help to start addressing these challenges by combining mathematical and modeling expertise from the wide array of subject matter experts.

Maya identity in Mesoamerica

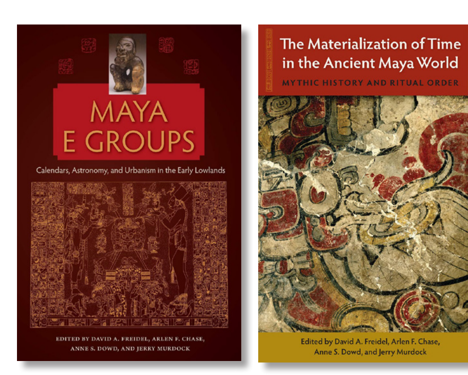
For several years, the Maya Working Group at SFI has brought together dozens of researchers from many disciplines to explore what it means to be Mayan, and what those insights say about modern culture. Those collaborations have yielded two books, and this November, the group will reconvene to start talking about a third. The working group will be organized by archaeologist David Freidel at Washington University in St. Louis and SFI Trustee Jerry Murdock, who co-founded Insight Partners.

Recent technologies have dramatically increased the volume of data available to the working group researchers, and others, who study resource utilization in Mesoamerica. Those tools include stable isotope analysis, which can be used to analyze diet and population patterns, and lidar, a remote sensing method that uses laser pulses to map an area — and can reveal structures hidden by dense jungle terrain.

"We've been able to analyze extremely precise data on resource utilization associated with Maya civilization and its collapse," says Murdock. "There are lessons for the current world we learn by looking at the past, and how we manage resources for the planet." The working group's first book focused on public, ceremonial architectural structures called E Groups that help researchers gain insights into how the Mayans regarded time and the cosmos. The book was published in 2017. Murdock says the book has invigorated a multidisciplinary approach to understanding this ancient civilization. The second book, to be published later this year, will offer an incisive survey of how Mayans apprehended time. That research supports the idea that the Mayans regarded time as something alive and nurtured by human activity.

"Being Maya means first and foremost being aware that the visible world is only one dimension of the world in which we exist and function," says Freidel. "They presume that the world they live in is as intelligent and sentient as they are."

For the November 30–December 1 working group, about 20 researchers will convene in person at SFI to launch new conversations about how to translate the themes and concept of their research that have emerged in the last few years into the new, third volume. It will largely follow on the other two, says Freidel, and dive even deeper into what it means to be Maya and Mesoamerican.



SFI's Maya working group has produced two books — "Maya E Groups," published in 2017 and "The Materialization of Time in the Ancient Maya World," which will be released this fall. They meet again in November to discuss a third volume.

VENKI RAMAKRISHNAN *(cont. from page 1)*

decision may have seemed rash, but Ramakrishnan says, "My life has been guided by pragmatism." Two years later, Ramakrishnan decided he'd learned enough biology and began a postdoc at Yale with Peter Moore where he used neutron scattering to see where pieces of the small subunit of the ribosome were located.

The biological revolution that inspired Ramakrishnan's research began in the early 1950s with James Watson and Francis Crick's discovery of DNA's double-helix structure where the instructions for an entire organism are packed into chains of amino acids. But DNA is an inert code that can't run without a cell, and a multistep process, to read it. The genetic information in DNA is first copied to a molecular messenger, mRNA, which in turn is read by a large molecular machine — the ribosome — to make fully functional proteins. Using the most advanced imaging techniques of the day, the ribosome was a mysterious black box of life made up of two non-distinct blobs. Could we ever see what the ribosome looked like and figure out how it worked?

This question intrigued Ramakrishnan and he pursued the problem over two decades at Brookhaven National Laboratory and the University of Utah. By 1999, technology had evolved to the point that a few teams were racing to solve the ribosome riddle. Ramakrishnan, then a full professor at the University of Utah, had a plan that could win the race. He would grow thousands of ribosomes into crystals, soak them in special atoms that scattered x-rays differently, deep freeze the entire batch to near liquid-nitrogen temperatures, then blast them one by one with x-ray beams that would produce the data from which he could construct an atomic model of the ribosome's full structure. But he had no idea how long it would take. Others had been working on the problem for 15 years. Britain's MRC Laboratory of Molecular Biology, the storied lab where Crick and Watson uncovered the structure of DNA, has a tradition of supporting scientists for long periods while they work on difficult but important problems. The caveat was that they could only pay about half the salary he was making at the University of Utah. Ramakrishnan didn't hesitate. "OK, maybe that decision was a bit romantic," he says. But it ultimately led to the discovery that had him dancing on a cold winter night inside an x-ray lab. Every step in the moonshot plan that had required moving his family five times and laboring in relative obscurity for three decades — it had all worked. The image his data produced looked like a rat's nest of rainbow confetti. To the few who could interpret, Ramakrishnan's was the first clear image that showed where mRNA entered the ribosome and where the proteins that birthed life emerged. "It felt like discovering an entire new continent," he says.

> "You only have one life to live. Why not do the thing that actually matters most?"

Ramakrishnan has spent his career as a reductionist scientist, viewing the world through the highly focused lens of cellular biology. "SFI represents almost the polar opposite of my career," he says. "I reduce big systems into a molecule. Here, they study everything from the point of view of the system: how do all the big players interact?" But in a different sense, joining the Santa Fe Institute is an ideological homecoming for Ramakrishnan. His uniquely clear cellular perspective will help researchers grapple with ideas about why life exists and the mechanism of death. Ramakrishnan's contribution to SFI will again ask that he step out of his comfort zone. He's glad for the opportunity. He likes to call it pragmatism.

COLLECTIVE ADAPTATION *(cont. from page 1)*

colleagues introduced the theoretical scaffolding that will guide the workshop. The authors' collective adaptation framework establishes links between social integration strategies, social environments, and problem structures, which shape how groups respond to dynamic situations. Workshop participants used the framework to explore the mechanics of collective adaptation, particularly as they relate to new technologies that open the door for large-scale information manipulation.

There are many foundational questions still to be answered about collective adaptation: Why do some technological platforms foster more or less beneficial adaptation? How do collectives adapt cognitive strategies and social networks to match emergent problems? And how do we handle the problems that online social environments present?

"We all have a big task to adapt to these new social environments, but we do not yet know how," said Galesic. "This was an opportunity to come together to tackle the problem and see what we are missing."

BEYOND BORDERS *(cont. from page 2)*

both describing the mirroring mechanism in the *S* as a schema of the *O*. For Holland a schema is a binary string whose fixed elements (as opposed to wild cards) define an equivalence class of coordinates encoding optimal solutions in adaptive landscapes. Complex systems are, for Holland, agents in possession of map-like schemata. For Gell-Mann, schemata, which he also called the IGUS (Information Gathering Utilizing System), are compressed rule systems capable of receiving inputs from history and environment in order to predict and act on states of the world. These span genomes, nervous systems, and even material culture.

Returning to Miller's interest in the revolutionary transformation in the representation of time and space, we find the late James Hartle formalizing the IGUS in order to explore the origin of what he described as the emergent concepts: present, past, and future. These are not, contrary to received opinion, physical properties but representational concepts. By placing an IGUS in Minkowski space, Hartle traced what he called their "subjective" world lines. And in this way connected complexity (life) to simplicity (physics). What Hartle, re-representing Gell-Mann, re-representing Kant, initiated is a new science that might make aesthetics a fundamental principle of complexity — a rigorous connection between life, mind, and matter.

— David Krakauer
President, Santa Fe Institute

SFI's new External Faculty

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

This year, eight new researchers joined SFI's External Faculty.

ROSEMARY BRAUN
Associate Professor, Department of Molecular Biosciences
Northwestern University

STEFANI CRABTREE
Assistant Professor, Environment and Society
Utah State University

JACOB FOSTER
Professor of Sociology
University of California, Los Angeles

LARS HEDIN
George M. Moffett Professor of Biology; Chair, Department of Ecology and Evolutionary Biology
Princeton University

LYNNE KIESLING
Research Professor in the School of Engineering, Design and Computing
University of Colorado Denver

DANIEL LARREMORE
Associate Professor in the Department of Computer Science and the BioFrontiers Institute
University of Colorado Boulder

LILIANNE MUJICA-PARODI
Professor Director of the Laboratory for Computational Neurodiagnostics
Stony Brook University, State University of New York

SERGUEI SAAVEDRA
Associate Professor of Contemporary Technology; Associate Professor of Civil & Environmental Engineering
Massachusetts Institute of Technology


Rosemary Braun


Stefani Crabtree


Jacob Foster


Lars Hedin


Lynne Kiesling


Daniel Larremore


Lilianne Mujica-Parodi


Serguei Saavedra

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505.984.8800
www.santafe.edu

ACHIEVEMENTS

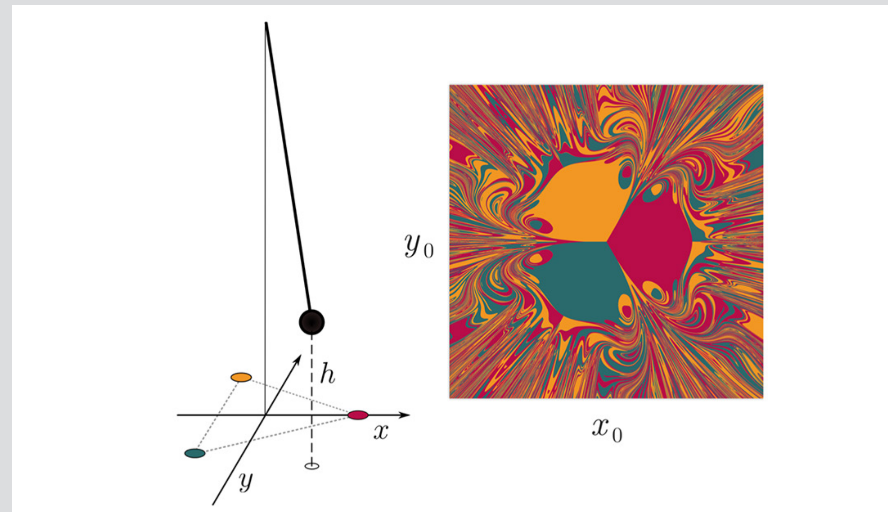
The Cognitive Science Society announced SFI External Professor **Alison Gopnik** as the 2024 winner of the Rumelhart Prize.

SFI External Professor **André de Roos** and Jasper Croll won the 2023 Outstanding Paper in Theoretical Ecology award by the Ecological Society of America.


Alison Gopnik


André de Roos

RESEARCH NEWS BRIEFS



Magnetic pendulum with three fixed-point attractors and the corresponding basins of attraction. ((fig. 1 from "Catch-22s of reservoir computing")

A CATCH-22 OF RESERVOIR COMPUTING

In the last two decades, researchers have reported success in modeling high-dimensional chaotic behaviors with a simple but powerful machine-learning approach called reservoir computing (RC). It's a nimble predictive model. More recently, next-generation reservoir computing (NGRC) has offered several advantages over conventional RC. Recent papers have reported that RC is effective in predicting the trajectory of chaotic systems after seeing very little training data. However, in a new paper in *Physical Review Research*, SFI Complexity Postdoctoral Fellow Yuanzhao Zhang and co-author Sean Cornelius identify limitations to RC and NGRC, suggesting a kind of Catch-22 that can prove hard to circumvent, especially for complicated dynamic systems.

Their results suggest that models built on NGRC cannot make accurate predictions unless key information about the system being predicted was already built in, and that models built on RC require a prohibitively lengthy "warm-up" time. Addressing these limitations in both RC and NGRC could help researchers better use this emerging computing framework.

Read the paper, "Catch-22s of reservoir computing," at https://doi.org/10.1103/PhysRevResearch.5.033213

SHARING VISUAL CATEGORIES THROUGH LANGUAGE

Category learning is a broad term that describes how people learn to classify things around them into various groups. We learn to visually distinguish between cats and dogs, for instance, or to identify specific dog breeds. As children, and we learn categories through visual examples, verbal explanations, or both, and are often guided by "teachers" — perhaps a parent or other adult. In contrast, academic research has primarily studied non-pedagogical learning where there is no active teacher, and learning based on visual examples, omitting verbal-based category learning.

A recent paper in *Cognition* by Arseny Moskvichev and co-authors aims to close this gap. The study investigates the differences between verbal, visual, and mixed-channel category communication. When teachers were free to generate as much educational material as they wanted, verbal- and example-based communication were equally effective, although the best results were achieved when teachers used both channels of communication to share their knowledge. When teachers were limited to a much smaller amount of educational material, talking was more reliable.

This work is an important step in understanding the differences between language and visual examples in how they are used to share knowledge.

Read the paper "Teaching categories via examples and explanations" at doi.org/10.1016/j.cognition.2023.105511

MODEL OFFERS INSIGHTS ABOUT AGING AND THE CIRCADIAN SYSTEM

It is well known that the process of aging is associated with sleep and circadian functions, but we still lack a systematic understanding of the complex interplays between them. A recent paper in *Chaos* by Yitong Huang (Northwestern University) and SFI's Yuanzhao Zhang and Rosemary Braun (Northwestern University) takes another look at mammalian circadian clocks and the effects aging has on them.

The authors build on previous work that tests the effects of jet lag through environmental cues like light exposure, feeding, and physical activity. They also built upon previously validated models to create a single mathematical model that can describe the hierarchical nature of the circadian system. In addition to a central clock, mammals have peripheral clocks that affect rhythm and respond to cues independently; aging causes more frequent disruptions in both the central and peripheral clocks.

The results from this paper suggest that circadian misalignment, or the disruption of the biological circadian rhythm, can be corrected with adequately timed food stimuli. The authors recommend that optimized meal schedules could help when trying to readjust circadian systems. "In the future, it would be exciting to test the predictions in experimental and clinical settings," says Zhang.

Read the paper "A minimal model of peripheral clocks reveals differential circadian re-entrainment in aging" at https://doi.org/10.1063/5.0157524

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