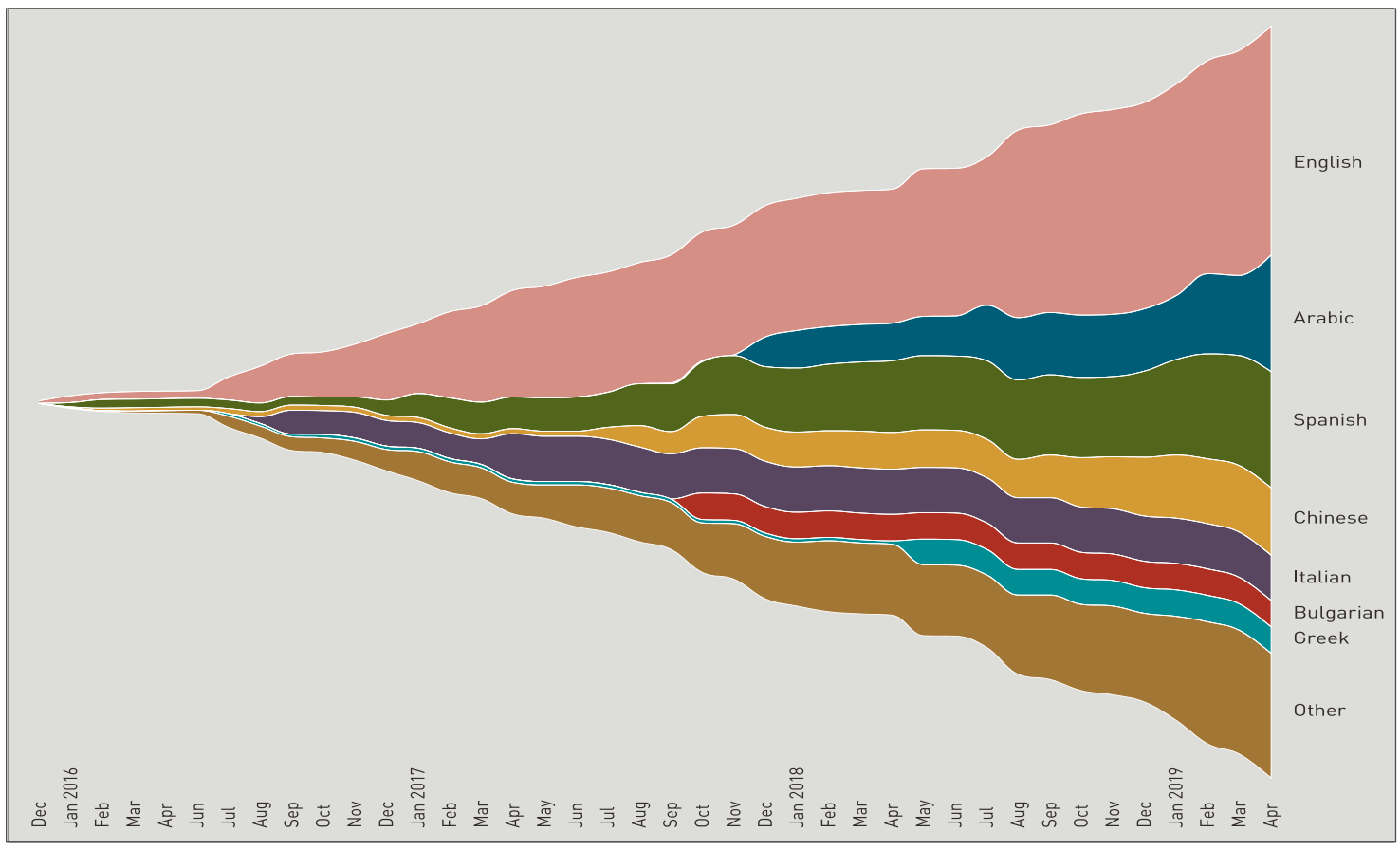
Summer 2019

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE



Cumulative number of courses translated over time, by language. Note—"Chinese" includes multiple dialects. (Image: Nicholas Rougeux)

Subtitle heroes speak complexity in many languages

They speak Bulgarian, Italian, Arabic, Mandarin, Greek, Farsi, and more. Together, they've put thousands of hours into making complexity research accessible to people around the world.

"Subtitle heroes," as they're known in the SFI education office, are a community of people worldwide who have dedicated their time to making SFI's online courses available in 63 languages to date.

Since its inception, SFI's online education platform, Complexity Explorer, has been dedicated to making complexity science accessible. While this mission initially involved keeping all core content free, it has expanded to offer language accessibility as well, with subtitles in multiple languages, including English. What most viewers don't realize is that these subtitles are provided by volunteers, many of whom are former students in the courses themselves who want to stay involved and give back to the community.

"If you can't donate, you can participate," says Linden Schneider, SFI's Online Education Coordinator. "It's a way for people to contribute to the platform. And they give us so much."

Worldwide accessibility — facilitated by a global, cooperative network — also has added resonance in today's political climate.

"In this moment, the international reach of Complexity Explorer feels more important to us than ever," says Dave Feldman, SFI's interim Vice President for Education. "That reach includes those living in countries whose governments are at odds with ours."

As of this year, the top non-English languages offered as subtitle options are Arabic, Spanish, and Mandarin. However, offering captions in English is also a core piece of the project, as it makes courses accessible to those who are non-hearing as well as those for whom English is a second language. A good English transcription can also speed up the process of subtitling in other languages, since subtitlers have a textual foundation from which to work.

In 2014, when the subtitling project was launched by then-Interim VP for Education, Melanie Mitchell, much of the organization of subtitling was painstakingly in-house with a small team of volunteers. Now, the Education team works with the subtitling platform Amara, a branch of the Participatory Culture Foundation, to help recruit volunteers, coordinate assignments, and monitor the accessibility of individual courses. All subtitling is done on a volunteer basis, though individuals who subtitle 120 minutes or more receive a free Complexity Explorer T-shirt as a gesture of thanks.

"What [the pro-level Amara platform] allowed us to do was to open it up completely to any-

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Wanted: Algorithms for quantum computing

The first theoretical framework for a quantum computer was proposed in 1982 by Richard P. Feynman, and in less than 40 years science and tech have rushed to build quantum machines. Today's quantum computers sustain temperatures approaching absolute zero and are designed to solve problems that would require millions of years for even the world's best supercomputers.

However, the rate of hardware development is seemingly outpacing the growth of algorithms that can leverage the phenomena of quantum mechanics.

Or to put it another way: "Everyone is trying to build these [quantum] machines, but we don't know how to use them in many application domains," says Helmut Katzgraber, a Principal Research Manager at Microsoft and an External Professor at SFI. "The number of quantum algorithms we have is limited, and most of them don't really have any practical value," he adds.

Quantum computers today excel at solving small toy problems for a select subset of disciplines, such as chemistry and physics, but the lack of practical algorithms limits their widespread application. And without useful algorithms, many fields will continue to rely on classical, silicon-based computers and potentially miss out on the revolutionary potential of quantum machines.

To address this shortage of algorithms, Katzgraber and his colleagues Maliheh Aramon (1QBit) and Jon Machta (the University of Massachusetts and SFI) are convening a working group this summer at SFI, from July 30 to Aug. 2.

During the workshop, an interdisciplinary team of attendees will consider several themes posed as questions. The considered topics will touch on which domains classical and quantum algorithms are likely to thrive, problems facing quantum computing, and recent developments in hardware, to name a few. The group will also discuss and develop algorithms for optimization, sampling, and machine learning.

"The main reason for the meeting is to think about

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Looking for entrenchment in all the right places

Over the last few years, molecular biologist Ashley Teufel has begun to notice an emerging trend in high-profile papers on protein evolution. In particular, researchers are reporting on entrenchment, a phenomenon in which a single event can have a widespread effect on an entire system. For a protein, a genetic mutation that occurs at one point in time may help determine the way the molecule evolves later.

Teufel, an SFI Complexity Postdoctoral Fellow, realized that entrenched systems occur elsewhere. "This can't just be a weird thing that happens to proteins," she says. "There must be an overarching, larger concept."

Entrenchment speaks broadly to the idea that the history of a system determines its current behaviors. That idea is similar to hysteresis, a phenomenon in which a change in one part of the system can change its behavior later in time (often observed in magnetic systems). Entrenchment is also similar to the concept of evolutionary contingency, which suggests that random accidents shape the future course of a living system. The first plant seeds to land on a new volcanic island, for example, may determine its future vegetation.

Evidence for entrenchment can be found in biology, ecology, computer science, and elsewhere. People's ideas and feelings can even become entrenched over time.

"What are the requirements that all these systems share?" asks evolutionary ecologist Luis Zaman, a Collegiate Fellow at the University of Michigan. To find out, Teufel and Zaman have organized a working group titled "The Point of No Return," to be held at SFI in October. Invitees include researchers from disparate fields, including ecology, network theory, atmospheric science, and even sociology. Their goal is to identify the underlying properties driving entrenchment, and find ways to infer, predict, or even control it.

The diversity of interests in the working group will fuel new insights and collaborations about how entrenchment works, says Teufel. "One of the strengths is having so many people from different fields collaborate on this to build some larger framework," she says.

Ohia seedlings sprout in lava cracks. (Photo: Alvis Upitis / Alamy)

BEYOND BORDERS

MURRAY GELL-MANN : THE METAPHYSICAL DETECTIVE

How to describe someone for whom a narrow list of his passions would include the life of birds, the collapse of ancient societies, the common roots of world languages, pre-Columbian pottery, the symmetries of space and time, and *New Yorker* cartoons?

In a profile of the editor of the *New Yorker* cartoon section, Emma Allen, Andrew Goldstein wrote, "It's an article of faith in literary circles that the proper way to read the *New Yorker* is to start with the cartoons and then place the magazine atop a neat pile of older issues and wait for nuclear winter to free up time to read the rest."

It struck me that this is exactly the kind of satirical observation that Murray would have relished. And Emma Allen says: "I actually have an aversion to any idea of the rules of *funny*, because if I've learned anything over the past five and a half years, it's that the things that are the funniest defy the rules." She goes on to describe her latest favorite cartoon: "Recently I got a submission that I loved of a croissant lying in the desert, with the caption, 'The driest croissant in the world.'" I am not entirely sure why, but I am confident Murray would have loved that cartoon.

It seems to me that Murray achieved that point Cervantes did with *Don Quixote*, namely, finding a means of subverting reality in order to uncover its ubiquitous and hidden rules. And this is a subterranean tunnel to founding SFI — not aimed at recreation or endorsement of the establishment, not a recapitulation of a reputation-obsessed academy, but a spirit vehemently opposed to the cowardice of the status quo that militates against human discovery and well-being. Murray, with all of his merit badges, medals, accolades, and prizes, did what Quixote did in later life — he went in pursuit of dragons. And he accomplished what Quixote could not — he found them.

One of the books that Murray and I discussed was Gregory Bateson's *Naven*, published in 1936. Bateson himself was one of the dying breed of polymaths who was drawn to a precursor of complexity — cybernetics — as a framework that might integrate — and in some way make sense of — the great diversity of his interests.

Bateson is best known for his book *Steps Toward an Ecology of Mind*, published later in 1972. *Naven* was written while Bateson lived in New Guinea with Margaret Mead, studying with the Iatmul people of the middle Sepik River. "Naven" is the name of a ritual practiced by the Iatmul; it is performed to congratulate members of the tribe on the completion of heroic deeds, where homicide ranks highest followed by genderless sexual experimentation. From the outside Naven looks impossibly opaque and baroque — with its apparent jumble of elements drawn from nature, society, mythology, development, and warfare.

Over the course of the book, Bateson explores a detailed exposition of the Iatmul approach to each of these particular elements. By the end, without Bateson explicitly explaining it to you, you have come to understand the Naven ceremony — and more surprisingly — gained the key to Iatmul cultural life.

Murray told me on several occasions that this approach of Bateson's — to investigate the whole rich, perplexing phenomenology, and then carefully delineate its elements — reveals the essence of understanding. An approach that you will be familiar with from his physics. I think that SFI was for Murray in part the application of the insights of the Iatmul Naven ceremony: an effort to make sense of the labyrinthine complexities of the adaptive world through an exploration of sufficient diversity and richness to make sense of it. And to do so with the all the power of mathematics and computation that are the legacy of our own post-enlightenment scholarly ceremonies.

I was recently re-editing with the SFI Press staff David Pines' proceedings of the founding meeting of SFI and was writing a new introduction with Geoffrey West. We included the transcripts of all

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Parallax is published quarterly by the Santa Fe Institute. Please send comments or questions to Jenna Marshall at marshall@santafe.edu.

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SFI IN THE NEWS

Nobel prize-winning physicist and SFI co-founder Murray Gell-Mann passed away on May 24, 2019 at age 89. Best known for his contributions to particle physics, Gell-Mann also wanted to understand the "chain of relationships" that connected the universal laws of physics to complex systems like economies and human cultures. He life was celebrated in more than two dozen publications following his death, including *The New York Times*, *Nature*, *the BBC*, *Scientific American*, *The Guardian*, and *The Washington Post*.

Roughly 30 years after its founding at SFI, complexity economics was featured in *The Economist* (April 4), following a March 19 op-ed in the *Boston Review* by External Professors and affiliated researchers Eric Beinhocker, Brian Arthur, Robert Axtell, Jenna Bednar, Doyne Farmer, Ricardo Hausmann, Alan Kirman, Scott Page, and others.

Professor Mirta Galesic helped the BBC's *Why Factor* understand how humans might be hardwired to understand stories (April 8).

External Professor Steve Strogatz was quoted along with other science-of-synch pioneers in an April 4 *Quanta* feature about new patterns of synchronization.

On March 25, *The New York Times* reviewed Matthew Jackson's book, *The Human Network: How Your Social Position Determines Your Power, Beliefs, and Behaviors*.

Nature reviewed External Professor Stuart Kauffman's book, *A World Beyond Physics: The Emergence and Evolution of Life* (May 1).

External Professor Tim Kohler talked with the *Christian Science Monitor* about what we can learn from connecting climatic shifts with civilizations changes, and the challenges to making those connections for a March 28 story.

SFI Science Board Co-Chair and External Professor Melanie Mitchell's essay "How do you teach a car that a snowman won't walk across the road?" ran in *Aeon* on May 31.

In an issue devoted to play, *Nautilus* magazine published an excerpt from External Professor Andreas Wagner's new book: *Life Finds a Way*.

The 2019 InterPlanetary Festival received pre-event coverage in local media including the *Santa Fe New Mexican*, *Albuquerque Journal*, *Richard Eeds Show*, and *Living on the Edge*, and was featured in international podcasts including *Interplanetary Radio* and *This Week in Science*.

Mendel— Gardens in the air" (Illustration: Anat Zeligowski)

Working group seeks 'Mendelian moment' for cultural evolution

Until Gregor Mendel came along, students of Darwin explored biological evolution without a mechanism to explain heredity. With his pea experiments, Mendel began to illuminate the genetic processes that underlie evolution — and eventually gave evolutionary theory a causal substrate.

According to former Complexity Postdoctoral Fellow Vanessa Ferdinand, now a cognitive scientist at the University of Melbourne, the field of cultural evolution is ripe for a Mendelian moment. Ferdinand hopes that in the next several years, theorists of cultural evolution will deepen their account of the mechanisms that underlie cultural replication — and give themselves the kind of causal clarity that Mendel gave to Darwin's beginnings. "Cognitive science," Ferdinand says, "is the Mendel of cultural evolution."

This summer, from Aug. 5-7, the Santa Fe Institute will host its second working group on cumulative cultural evolution. Along with Ferdinand, the event is led by longtime SFI External Professor Rob Boyd, who is also Origins Professor at Arizona State University's School of Human Evolution and Social Change, and Bill Thompson, a cognitive scientist at Princeton University and Berkeley's Computational Cognitive Science Lab.

Last year, Boyd and Ferdinand brought together a group to explore the meaning of cumulative cultural more broadly. The working group gathered scientists studying cultural evolution from a broad range of fields including anthropology, cognitive science, and philosophy of biology. Their task was to synthesize the ways that different fields understand cumulative culture.

By all accounts, workshop participants found the group exciting and fruitful — and their

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Postdocs get reckless in sixth group conference

Reckless Ideas will feature high on the agenda of the sixth Postdocs in Complexity Conference, the latest in a twice-yearly series held at SFI and generously funded by the James S. McDonnell Foundation (JSMF). The conference, to take place Aug. 27-30, brings together early career complexity postdoctoral fellows in a wide range of disciplines from institutions around the world.

The Reckless Ideas format encourages the participants to bring up untested propositions they would otherwise be reluctant to voice. Originally started in 2010 by SFI President David Krakauer (then the SFI Faculty Chair), past Reckless Ideas have included a notion of "selfish" neurons, presented by SFI External Professor Daniel Dennett, and apparently "telepathic" phenomena in social organisms, presented by former Omidyar Fellow Jeremy Van Cleve.

To encourage recklessness in presenters, audience members give feedback in the form of "yes, and . . ." statements, rather than the more critical "no, but . . . ." Presenters do their part by limiting themselves to no more than one slide, no matter how complex the topic.

All postdocs at the August conference will propose a reckless idea. They will then divide into smaller groups and choose four ideas for brainstorming and serious discussion.

"In the past, participants have consistently rated the research jam sessions and group discussion time as the best parts of the conference," said Hilary Skolnik, Program Manager of SFI's Postdoctoral Fellows Program. "So this is a novel way of incorporating group discussions so that participants can share ideas and collaborate with each other".

In addition to off-the-wall collaborative sessions, the participants will receive professional training, practice science communications through an improv session, and engage in social activities that include a mushroom hunt in the Santa Fe National Forest and a yoga session on the SFI beach.

From academia to industry and back: A case study in applied complexity

As a Texas Instruments researcher working on artificial neural networks and speech recognition in the early 1990s, SFI Science Board member Derek Smith (University of Cambridge) was applying science to real-world problems every day. But he wanted to dig deeper.

"It seemed to me that the work that I was doing on pattern recognition and speech recognition might be related to how our immune systems recognize different strains of pathogens," Smith explains, "so I started looking around to see where I might do such work."

An invitation from SFI External Professors Stephanie Forrest (Arizona State University) and Alan Perelson (LANL) to join Forrest's Ph.D. program at the University of New Mexico came with a suggestion: First, attend the Complex Systems Summer School at SFI.

One month later, Smith took a leave of absence from industry and began the summer program. The experience was transformative.

"The first morning, Mike Simmons, VP for Academic Affairs, talked about how at SFI there were no barriers between disciplines, and I was completely and utterly gobsmacked," Smith says. "I knew this was the place for me to explore my ideas."

After his studies at SFI, Smith went on to work in industry at Popular Power to develop these ideas, worked closely with US public heath colleagues at the US Centers for Disease Control, and eventually ended up as a full

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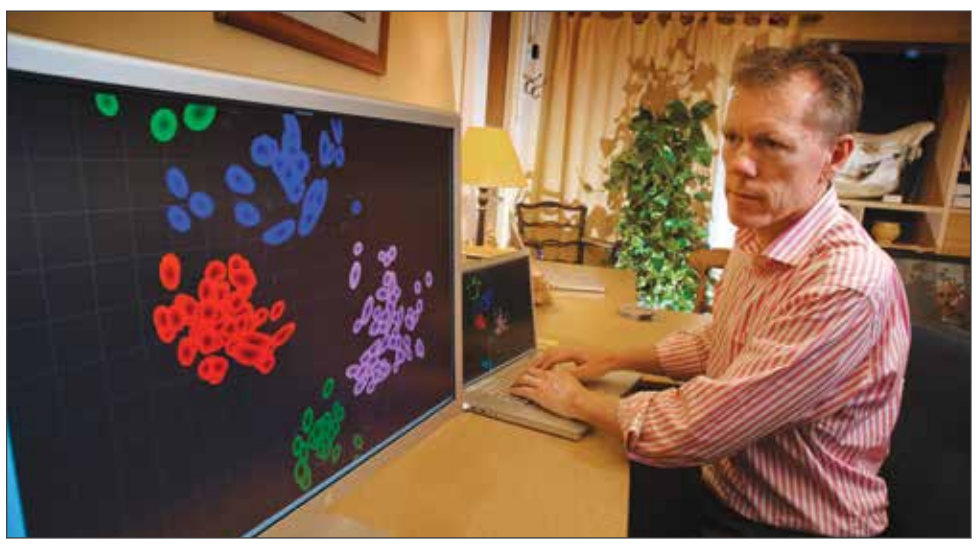


At right: Derek Smith (Photo: James King-Holmes)

Workshop: Do living things compute?

Biologists agree on many things that living organisms can do: They eat, they respire, they reproduce, they die. Many would also agree, implicitly or explicitly, that living things compute. But a trio of SFI researchers want to know: What does it mean for biological systems to carry out computations? The answer isn't clear.

"Biologists have a vague sense of what they mean by computation," says biologist Albert Kao, a SFI Complexity Postdoctoral Fellow. "At a certain point, if your definition is too loose, then anything can be computation. But if you make it too tight, then maybe nothing is computational in biology."

For three days this fall, biologists, physicists, neuroscientists, and computer scientists will come together for an SFI workshop to investigate the links between computational theory and biological systems. The workshop is the brainchild of SFI Professor David Wolpert, who leads the Thermodynamics of Computation project at SFI. It was co-organized by Kao and SFI Professor Jessica Flack, who runs the Institute's Collective Computation Group.

Flack says the workshop's goal "is to first establish a rigorous conceptual framework for studying biological computation so that the foundations of computation in adaptive systems can be identified and compared to those in synthetic computing systems."

Workshop participants will identify components of living systems that might look like elements of computation. They may have possible inputs and outputs, for example, or processes that look like algorithms. Researchers have also observed that the modular, hierarchical organization of biological systems resembles that of digital computers: A body is organized into separate organs, each containing cells that are organized into many separate organelles.

Finding links between computers and biological system has been a longstanding goal of researchers on the edge of both fields. "This topic has deeply puzzled scientists for decades," says Wolpert. "However, there have recently been breakthrough in other fields, like collective computation, coarse-graining dynamical systems, and non-equilibrium statistical physics, that we believe can help us make major progress on this topic."

The organizers say the benefits will run both ways: Insights from computer scientists will help guide new ways of thinking about biological computation, and biologists may help computer scientists find ways to build scalable, more robust machines.

"If you remove half of a school of fish, the remaining half can still do things," Kao says. "If you take away half a CPU, it's dead. What new ways of computing can we think of that compute scientists don't typically think of?"

SFI celebrates Thirty Years of Complex Systems Thinking

This August 21-22, SFI will celebrate Stuart Kauffman's contributions to complex systems science in a workshop: "Thirty Years of Complex Systems Thinking." The two-day workshop will cover new research linked to Kauffman's adventurous career.

Already a prestigious scholar by the 1980s, Kauffman moved to Santa Fe in 1986 after the Institute's first full-scale workshop on Complex Adaptive Systems. A MacArthur Fellow, and one of SFI's first resident researchers, he helped define the early science of complexity, developed new theories of the origins of order in biological and technical systems, and added various other tools and ideas like NK fitness landscapes and the "adjacent possible" to the complexity lexicon. Kauffman's scientific curiosity and desire to follow ambitious questions that disregarded the traditional boundaries between domains fit well within the nascent institute and formed a key part of its lasting culture.

Kauffman remembers those years of intense collaboration and recombinant ideas, "Probably the most thrilling ten-year period of my life. We thought we were onto something, but we didn't know what. It was like a Rorschach test…and it led to this sprawling, innovative learning from one another. I've never experienced it anywhere else."

Since his early years at the Institute, much has changed — "most of the rail has been laid down since then" for complex systems science, as he puts it.

Stuart Kauffman

New computational techniques have grown along with the adjacent possible to understand better the potent intuitions of the initial wave of research in more rigorous terms. Kauffman's impact can be felt around the world, both among scientists and in the broader public that was inspired by his many books on complexity.

"It's hard to imagine the early years of SFI without Stu's presence," explains workshop co-organizer John Miller, who became the Institute's first postdoc in 1988. The workshop, co-organized by Miller and Shannan Distinguished Professor and Past President Geoffrey West, brings in dozens of researchers, many of whom have co-authored with Kauffman. Their talks will span the broad panorama of Kauffman's research interests and contributions.

New books by SFI authors

The SFI Press publishes affordable, enlightening books on some of the most ground-breaking areas of complexity science, distilling scientific meetings and public-facing panels, as well as fresh takes on historical texts. In recent months, the SFI Press has released four new titles.

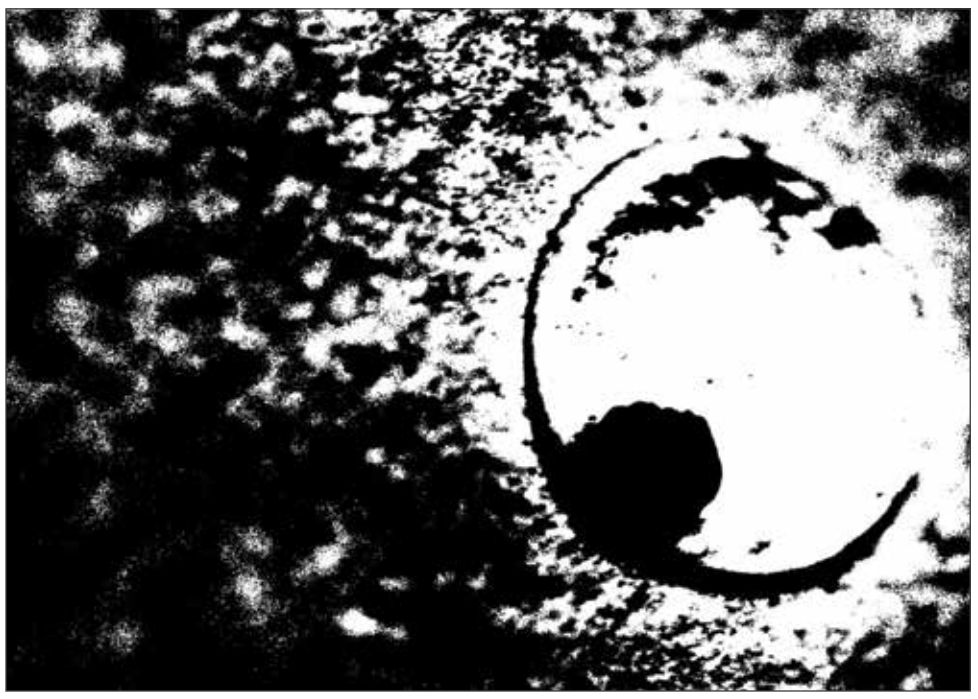
Worlds Hidden in Plain Sight, (SFI Press, Compass Series, 2019) edited by SFI President David Krakauer, is a collection of popular essays from the past thirty years of research by SFI scientists, offering a clear and accessible overview of the deepest challenges and insights of complexity science.

InterPlanetary Transmissions: Genesis, (SFI Press, Compass Series, 2019) edited by SFI President David Krakauer and Caitlin McShea, InterPlanetary Festival Director, is a record of the proceedings of SFI's first InterPlanetary Festival held in June 2018.

Law as Data, (SFI Press, Seminar Series, 2019) edited by External Professor Daniel Rockmore (Dartmouth College) and Michael Livermore, (University of Virginia Law School), explores the new field of computational legal analysis, which uses legal texts as data. This book introduces the legal world to a broad range of computational tools already proving themselves relevant to law scholarship and practice.

The Energetics of Computing in Life and Machines, (SFI Press, Seminar Series, 2019) edited by SFI's David Wolpert, Chris Kempes, Peter Stadler, and Joshua Grochow, explores the fundamental physical laws governing the relationship between the precise computation run by a system, natural or artificial, and the amount of energy such computations require.

RESEARCH NEWS BRIEFS



"Sand" (Image: SFI Press)

THE DISCRETE-TIME PHYSICS HIDING INSIDE OUR CONTINUOUS-TIME WORLD

As scientists understand it, time is continuous rather than discrete; it "flows" rather than progressing in "chunks." Scientists successfully model real-world processes from folding proteins to evolving ecosystems as continuous-time "Markov processes," even though we observe the state of system only in discrete times. In a pair of papers published in *Nature Communications* and *New Journal of Physics*, SFI Professor David Wolpert, Postdoctoral Fellow Artemy Kolchinsky, and co- authors show that within seamless Markov processes are infinite hidden states and timesteps. The authors stumbled on the necessity of hidden states and timesteps while searching for the most energy-efficient way to flip a bit of information in a computer. Any biological or physical system that computes would conceal the same hidden variables.

ILLUMINATING THE LIVES OF MAYAN COMMONERS

Each year, the *Annual Review of Anthropology* selects a senior scholar to write the lead chapter. This year, SFI External Professor Emeritus and Past President Jeremy Sabloff was selected. Combining an autobiographical perspective with an extensive literature review, Sabloff describes the changing nature of Maya archaeology, focusing on the role of settlement pattern studies in illuminating the lives of commoners. As he writes: "In retrospect […] scholars had, in effect, made a key sampling error by concentrating on the remains of the elite and, by and large, not paying much attention to those of commoners. Settlement pattern studies helped rectify this error." Sabloff also recounts his personal contributions to this new understanding of pre-Columbian Mayan societies.

IN SCHOLARLY SUCCESS, PEDIGREE IS NOT DESTINY

What matters more to a scientist's career success: where they currently work, or where they got their Ph.D.? It's a question that SFI External Professor Aaron Clauset (University of Colorado, Boulder), former Complexity Fellow Dan Larremore (University of Colorado, Boulder), and their co-authors tease apart in an April paper published in *PNAS*. Their analysis calls into question a common assumption underlying academia: that a researcher's productivity reflects their scientific skill, which is reflected in the prestige of their doctoral training. Rather, they found that "where you train doesn't directly impact your future productivity," says Clauset. However, they found that prestige of a researcher's early-career workplace has a strong impact on future success.

POSITIVE SELECTION IN OUR CHOICE OF WORDS

A puzzle of language is how speakers come to use the same words for particular meanings, given that there are many alternatives and seldom a connection between a word and its meaning. In a study published on April 9 in *PNAS*, External Professor Mark Pagel (University of Reading) and co-authors applied models of neutral drift and various forms of selection to explain word-use choices. What they find is that neutral drift alone is not adequate to explain shared vocabulary, but

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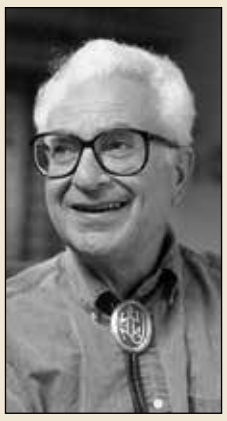
SFI remembers Murray Gell-Mann



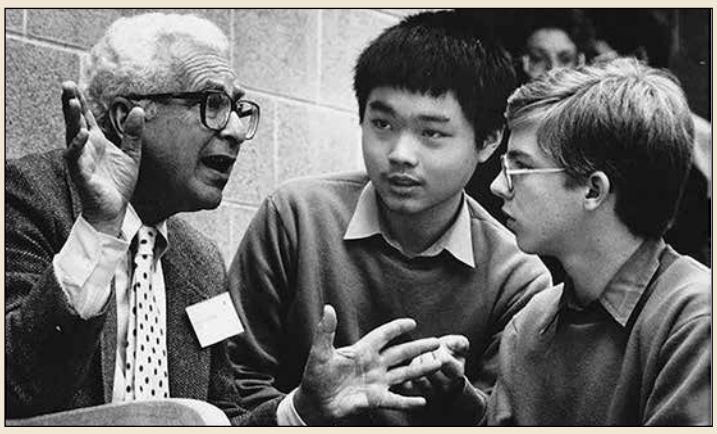
Murray Gell-Mann (1929–2019)

Murray Gell-Mann, a Nobel laureate who revealed symmetry and order in the world of subatomic particles and leveled his genius at complex mysteries of life and mind, died peacefully May 24, 2019. He was 89 years old.

Though he was best known for his contributions to particle physics, for which he won the 1969 Nobel Prize in Physics, Gell-Mann wanted to understand the "chain of relationships" that connected the universal laws of physics to complex systems like economies and human cultures. He described these two extremes of interest in his 1994 book, *The Quark and the Jaguar*, as "two aspects of nature . . . on the one hand, the underlying physical laws of matter and the universe, and on the other, the rich fabric of the world that we perceive directly and of which we are a part."

To enable a rigorous study of the latter aspect of reality — the fabric of the complex world around us — Gell-Mann co-founded the Santa Fe Institute in 1984, 15 years after winning the Nobel Prize in physics for his classification of elementary particles. At SFI he collaborated with economists, linguists, biologists, computer scientists, and with other physicists who shared his passion for finding fundamental principles in learning, evolving systems. **Gell-Mann's full obituary is available on santafe.edu.**

Here, we share some remembrances from his SFI friends and collaborators.



From left: Murray Gell-Mann, unknown student, and James Tauber at the Fifth Marcel Grossmann Meeting on General Relativity (Photo courtesy James Tober)

REMEMBRANCES OF MURRAY GELL-MANN

In 1993, at SFI's second campus by the Old Pecos Trail, Stu Kauffman and I were heading out to lunch one day. In comes Murray Gell-Mann struggling with a large box of books for his office. He had many more in his SUV, and Stuart and I carried them in to his office. Murray beamed and thanked us. "Any time," said Stuart, "For someone like you." Murray looks at Stu with complete innocence. "But there is no one like me," he says. How true.

W. Brian Arthur, External Professor, SFI

Losing Murray is like losing the Encyclopedia Brittanica. *He knew more things about more things than anyone I've ever met.*

Cormac McCarthy, Author, SFI Trustee

In about 1998 I began having conversations with Murray about earthquakes and markets. As a result of that, I invited him to one of our meetings that was held in Maui, Hawaii during March 2000. He came with his wife Marcia. We all had a wonderful time. He went on a helicopter ride over the island, and attended all our sessions. One day we went on a whale-watching trip west of Maui. At one point, on the bow of the ship, he turned to me and began singing the famous Hawaiian song "Aloha Oe," all the verses in Hawaiian. What a treat to have a Nobel laureate do that! . . . He was always an elegant gentleman. We are indeed saddened at his passing.

John Rundle, External Professor, SFI

The task is not to see what no one else has seen, but to think what no one else has thought, about that which everyone else has seen. That is Murray Gell-Mann.

Jim Hartle, External Professor, SFI (at a 2014 ceremony where Gell-Mann was awarded the Helmholtz Medal)

Murray was called the Emperor of Theoretical Physics because when he was doing theoretical physics, nothing stirred without Murray hearing the nails falling down from far away. Murray was extraordinarily productive in this life, but Murray was also an extraordinarily warm human being. One of the warmest I have ever met . . . . I have lost more than a mentor and collaborator: we were like brothers, and he was "one of the great ones in science."

Juan Perez-Mercader, External Professor, SFI

Recently, a student and I spent several days at [Murray's] home in Santa Fe cataloging and documenting his astounding collection of ancestral Pueblo pottery. I couldn't help but notice the correspondences between his display and the periodic table — a prototypical example of every variety, arranged in rows and columns according to their colors and symmetries. It was a wonderful expression of his belief in the unity of complex systems everywhere you find them . . . I think it provides a lovely window into perhaps the most perceptive person I have been blessed to know.

Scott Ortman, External Professor, SFI

> I have lost more than a mentor and collaborator: we were like brothers, and he was "one of the great ones in science."
>
> **Juan Perez-Mercader, External Professor, SFI**

From left: Cormac McCarthy, Murray Gell-Mann, and Brian Arthur at the Santa Fe Institute circa 2012 (Image: SFI archives)

The world lost one of its highest geniuses in science, and I lost a dearest friend. We will forever miss his joy of life and of knowledge.

Constantino Tsallis, External Professor, SFI

Because of Murray's interest and urging, many innovative archaeologists are on the Science Board and External Faculty. They have been intimately involved in research projects at the Institute on the evolution of specific culture areas, as well as the more general evolution of human social and cultural complexity. The archaeological practitioners at SFI have used the science of complexity to address pressing questions that underlie the evolution of human behavior.

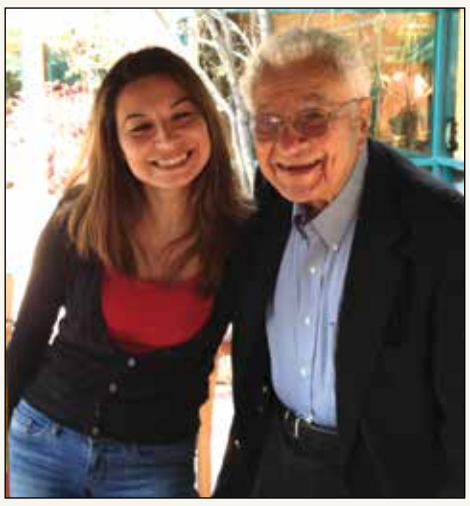
Perhaps one of the most interesting things is that this one individual could generate an entire research program that would produce an understanding of the evolution of human behavior. Thank you, Murray, for introducing me to an organization that has changed my life.

George J. Gumerman, External Professor, SFI

Working with Murray Gell-Mann is one of the most priceless treasures in life for a scientist. Every memory that I remember from Murray Gell-Mann's conversations forms a precious piece of history and philosophy of science.

I am deeply saddened by the loss of my unique mentor and collaborator and invaluable friend. He lives in my heart forever.

G. Cigdem Yalcin, Faculty of Sciences, Istanbul University



Cigdem Yalcin and Murray Gell-Mann at SFI (Photo: courtesy Cigdem Yalcin)

There's nothing more satisfying to a physicist than to find the hidden order beneath all the chaos. And he was better than anyone in the world at doing that.

Sean Carroll, Research Professor, Caltech

A great loss to humanity!

Aviv Bergman, External Professor, SFI

Murray helped make SFI so special from its founding to the days when he was at the Institute full-time. I especially remember a myriad of lunches with Murray entertainingly and intelligently holding forth on whatever topic came up in conversation!"

Jerry Sabloff, Past President and External Professor, SFI

It's a sad day for all who experienced his incomparably bright genius. Discussing Physics and Complex Systems with Murray at lunch at SFI was always an exhilarating (and a little scary!) experience. May his spirit live on in all of our lives and work!

Luis Bettencourt, External Professor, SFI

> A great loss to humanity!
>
> **Aviv Bergman**
> **External Professor, SFI**

Murray's enduring interest and passion was actually in everything . . . Murray maintained throughout his life and enduring passion for understanding how the messy world of culture, economies, ecologies and human interaction, and especially language, evolved from the beautifully ordered world of the fundamental laws of nature.

Geoffrey West, Shannan Distinguished Professor and Past President, SFI

Murray, knew, maybe all too well, the human side of science. And that's the really difficult stuff. In the years that I knew him at SFI he used that knowledge to guide and support many of us in the younger generation. I know that Murray regretted being too shy to engage with Einstein when they overlapped at the Institute for Advanced Study in Princeton. And I think that maybe that contributed to his attitude towards the kids at SFI. His door was always open . . .

The moments when his eyes lit up when something meaningful emerged — It didn't matter one bit to him that my claims, which I didn't quite dare to say out loud, came from a nobody who just turned 30 or so. He eventually asked me if I wanted to co-author a paper with him. I have no doubt that he did that to help me to keep telling this bit of truth that I had discovered and not be silenced by received wisdom or the fashions of the day, no matter how loud they are or who's behind them. This kind of mental clarity goes far beyond science. It goes to the core and is maintained only by hard work, protected by a constantly challenged, but never defeated sense of humor. Murray pitted this sense of humor against an open, frustrating world. Those of us who are weak like me and often just want to give up, we need Murray if no longer in person, then in memory.

Ole Peters, External Professor, SFI

Murray's precise mind was not just a great asset in the search for truth and fundamental laws of nature. It was also a filter of daily life, sometimes brutal and paralyzing taskmaster, which reigned over Murray like a tyrant. I loved my friend Murray . . . Curiosity was leading him always to ask interesting questions. This observation of Murray led to my writing down a maxim of sorts that has inspired me and guided my life request. The quality of life is determined by the quality of questions one asks. *To date this maxim has indeed been the driver of my life and led me the inner most recesses of my being on my guide to a path with heart.*

Jerry Murdoch, Trustee, SFI

Beyond Borders *(cont. from page 2)*

the founding discussions. These were dominated by Murray — in a very constructive way. One of the things he says is: "You could say that it's a problem of personality types, that there are people who like cold logic, reason, analysis, and careful structuring of problems, especially in their work. There are other people who like syntheses, qualitative considerations, general remarks, natural history, and description. Finally, there are a few people who try to combine both. Some people call these Apollonian, Dionysian, and Odyssean types. If one can find just a few people who can combine these various characteristics, it would make an enormous difference."

Most of you know that Murray was drawn to what one might call the metaphysical detective story — those of Conan Doyle, GK Chesterton, Edgar Allan Poe, and Jorge Luis Borges. And in the way that Borges is the keeper of the gates of the sensibility of our science — I think that the story "Funes the Memorius" is a melancholy reminder of the extraordinary abilities of MGM.

In Funes, Borges writes, "In the seventeenth century Locke postulated and condemned an impossible language in which each individual thing — every stone, every bird, every branch — would have its own name. Funes once contemplated a similar language, but discarded the idea as too general, too ambiguous. The truth was, Funes remembered not only every leaf of every tree in every patch of forest, but every time he had perceived or imagined that leaf . . . . He saw that by the time he died he would still not have finished classifying all the memories of his childhood.

We shall miss Murray, the original Metaphysical Detective covering the precincts of complexity. *Verae vollaut ea nientiandam ides sent volentotat.*

— David Krakauer
President, Santa Fe Institute

In 2009, SFI External Professor **Stephanie Forrest**, director of Arizona State University's Biodesign Center for Biocomputing, Security and Society, co-authored a paper reporting a practical demonstration of using biological processes like evolution to find and repair software bugs. The paper, "Automatically Finding Patches Using Genetic Programming," was recognized as the Ten-Year Most Influential Paper at the 41st International Conference on Software Engineering (ICSE) in Montreal May 25–31, 2019. The award is presented at each ICSE meeting to the authors of the paper "that is judged to have had the most influence on the theory or practice of software engineering during the 10 years since its original publication."

Stephanie Forrest

SFI External Professor **John Geanakoplos** was honored with a Yale College undergraduate teaching prize on May 8. Geanakoplos, the James Tobin Professor of Economics at Yale, received the Lex Hixon '63 Prize, which is awarded for teaching excellence in the social sciences by the Yale College Committee on Teaching and Learning.

John Geanakoplos

SFI External Professor **Jenna Bednar** (University of Michigan) has won the 2019 Martha Derthick Award for her book *The Robust Federation*. The Award is conferred by the American Political Science Association for the best book on federalism and intergovernmental relations published at least 10 years ago that has made a lasting contribution to the study of federalism and intergovernmental relations. According to the University of Michigan, Bednar's book "carved out a new frontier of institutional analysis that contemplates how ensembles of overlapping institutions and safeguards balance exploration and exploitation to produce robustness."

Jenna Bednar

The Eric Hoffer Book award once again recognized SFI Miller Scholar **Laurence Gonzales**, with a 2019 Legacy Nonfiction award for his book *Flight 232: A Story of Disaster and Survival*. In 2018, Gonzales had won the Eric Hoffer Book Award and Montaigne Medal for his bestseller *Deep Survival: Who Lives, Who Dies, and Why.*

Laurence Gonzales

Melanie Mitchell co-chairs SFI Science Board

Computer scientist Melanie Mitchell, creator of SFI's online education platform, was named co-chair of SFI's Science Board at its 2019 spring meeting.

The principal role of the Science Board is to advise the President and the Board of Trustees on matters of scientific strategy for the Institute. Mitchell joins co-chair Daniel Schrag (Harvard University), who has co-chaired the board since 2016 with outgoing co-chair Mercedes Pascual (University of Chicago), an External Professor.

"We are delighted to have Melanie play this important advisory role for SFI — especially given her multifaceted involvement since the early days of the Institute," says VP for Science Jennifer Dunne. "With her long view of SFI science activities and education programs, and her deep expertise in artificial intelligence, she is a valuable addition to the Science Board."

Melanie Mitchell

Since 1992, Mitchell has served SFI as a faculty member, advisor, and interim Vice President for Education. In addition to being a Science Board co-chair, she is also currently an SFI External Professor, and is based at Portland State University, where she researches artificial intelligence, machine learning and evolutionary computation, cognitive science, and complex systems.

Mitchell earned her Ph.D. in computer science from the University of Michigan in 1990, then in 1992, she "jumped at the chance" to work at SFI on the new Adaptive Computation Program. She became the director of the program, which over the course of six years made significant contributions to the rapidly developing field.

She also originated the Santa Fe Institute's Complexity Explorer platform, which offers online courses and other educational resources in the field of complex systems. Her wildly popular "Introduction to Complexity" has introduced more than 38,000 students from around the world to complexity science, and is Complexity Explorer's flagship course.

Mitchell is the author of over 80 scholarly papers in the fields of artificial intelligence, cognitive science, and complex systems, and is the author or editor of six books including *Complexity: A Guided Tour* (Oxford, 2009), which won the 2010 Phi Beta Kappa Science Book Award. Her newest book is *Artificial Intelligence: A Guide for Thinking Humans*, which will be published by Farrar, Straus and Giroux in October 2019.

During her tenure as Science Board co-chair, Mitchell will also return to SFI for an extended residency, from Jan. to Dec. in 2020.

Acknowledging royal women's political power

The narratives we tell about the past often feature a cast of familiar main characters: kings and rulers, warriors and diplomats — men who made laws and fought wars, who held power over others in their own lands and beyond. When women enter our stories, we rarely afford them much agency. But across the globe in a variety of societies, royal women found ways to advance the issues they cared about and advocate for the people important to them.

Profile of queen Ankhnespepy II of Egypt from her funerary temple." (Photo: Juan R. Lazaro/Wikimedia)

In a recent paper published in the *Journal of Archaeological Research*, SFI External Professor Emerita Paula Sabloff analyzes the archaeological and written records of eight pre-modern states separated by both time and space, detailing ways that queen rulers and main wives took political action. Her comparative analysis reveals similar patterns in the societies despite the fact that they were isolated from one another.

Sabloff's analysis includes three types of regions: independent states or city-states (including the Mari Kingdom of Old Babylonia, 2000-1600 BC, and Protohistoric Hawaii, AD 1570-1788); empires (Old Kingdom Egypt, 2686-2181 BC, Late Shang China, 1250-1046 BC, the Aztec Empire, AD 1440-1520, and the Inca Empire, AD 1460-1532); and states in regions that contained both states and empires (Late Classic Maya, AD 600-800, and Post-classic Zapotec, AD 1050-1500).

As Sabloff described in another recent paper, women were often used as bargaining chips, used to form strategic alliances between states through marriage. "Here are examples of, even when women were pawns in marriage, they still ended up with a lot of power," she says. She found remarkable similarities in the types of power that royal women used.

"Queen rulers held nearly the same political power as kings," she explains. "Main wives were active players in determining succession, governing the polity, building inter- and intra-polity alliances, and expanding or defending territory." These women also exerted influence by obligating courtiers and tradesmen through patron-client relationships, interceded on behalf of their relatives, and sometimes spied on or conspired against their royal husbands. "Political agency wasn't just about waging war," says Sabloff. "It was about being able to influence policy, to influence who is on the throne. There were levels of agency, but hers was right behind his."

Language *(cont. from page 1)*

body," says Gabrielle Beans, former Complexity Explorer Program Manager. Volunteers can choose which videos they work on, and the Education team has up-to-date accessibility data on every video.

So far, 467 people have contributed subtitles to Complexity Explorer. In 2019, two subtitlers, Diego Diaz Cordova and Hazm Talab, broke the 600-minute mark for the first time.

For Diaz Cordova, who is based in Buenos Aires, subtitling is a way to give others access to the courses he's enjoyed. "I thought it was a great idea to start to translate to Spanish, not only because it is a way to reach Spanish language communities, but a way to retake the course for my own and get a more comprehensive view about complexity and chaos," he wrote in an email. "Subtitling was a great opportunity to refresh the learned lessons."

Talab, who subtitles in Arabic, recalls being inspired to get involved by the course on Dynamical Systems and Chaos — taught, as it happens, by Feldman. "I was studying mathematics and was interested in the computational approaches for solving mathematical problems, and I found Complexity Explorer presenting amazing courses that deal with the subjects both theoretically and computationally," he wrote from his home base in Istanbul, Turkey. A huge draw, he adds, is the knowledge that he is contributing to a free, accessible knowledge base.

To know that someone who may be thousands of miles away is paying such close attention to the words you've spoken is, for Feldman, a humbling thought. It's difficult, he says, "to capture the magnitude of what some of these folks have done."

Most thrilling, perhaps, is the way in which the global subtitling project is self-referential: its network-based structure and emphasis on collective knowledge reflect the very content that Complexity Explorer teaches.

Algorithms *(cont. from page 1)*

the next generation of algorithms," says Katzgraber. "We will not just focus on quantum hardware, but any type of hardware. We do not expect that a quantum device will be able to solve all problems; the key is to determine what problems will work really well, and what will not work at all."

Katzgraber hopes the meeting will spur new algorithms, collaborations, and perhaps a new collection of white papers or a special issue of a journal.

Mendelian *(cont. from page 2)*

response reflects current enthusiasm in the field more generally. At the moment, the field is bursting with new questions and diverse approaches. There are both micro (cognitive) and macro (social) approaches to cultural evolution, and a wide variety of methods for studying it that range from large-scale network experiments to social decision-making models to computational textual analysis.

According to Thompson, both the plethora of new cultural datasets and the ongoing refinement of computational methods have fueled current research. He explains that if we take two people who are biologically identical from two different time periods — people who may have had very different technological experiences — we find that their cognitive capabilities can be significantly different. "Yet we cannot explain this difference biologically or in terms of individual learning, and this suggests some other category of explanation." Is this an evolutionary process?

This year, the working group will focus specifically on mechanisms of cultural inheritance. By homing in on the mechanisms that drive cultural stability and change, Boyd, Ferdinand, and Thompson hope to gain more clarity about the cognitive processes that generate the fabric of cumulative culture — and open the way for a new causal framework.

Industry *(cont. from page 2)*

professor at Cambridge University.

As a direct result of Smith's work at SFI, he and colleagues Ron Fouchier and Alan Lapedes developed a method to understand the evolution of viruses they called antigenic cartography, and their work was published in *Science* (2004).

"We looked at the evolution of a virus in a new way, in particular, how it escapes our immune response," Smith explains. "Diseases like HIV, malaria, and influenza persist and are very difficult to create vaccines for because viruses can change their surface proteins, making them much more difficult to understand."

Soon after the paper was published, Smith and team were invited to apply their work to the approximately 20,000 influenza strains analyzed each year by public health laboratories for the World Health Organization. Their objective? Learn how the virus was evolving to identify which strains of flu should go in the vaccine — a process he has been integrally involved in since that first invitation.

"We felt that it was our responsibility to do this work because people's lives are on the line," Smith says. "But we also recognized that by applying our work, there was a real opportunity. The possibility to see the complete global evolution of the virus, in real time, is an evolutionary biologist's dream."

Empowered by this global data and $24 million in funding from NIH and BARDA, Smith and his colleagues are now working to understand this evolution well enough to predict it and apply it to the flu vaccine.

"Derek's success with his flu vaccine work is a perfect example of the insights that can be found in the liminal space between the traditional domains of academia, industry, and public health," says Will Tracy, SFI's VP for Applied Complexity.

SNAPSHOTS FROM THE 2019 INTERPLANETARY FESTIVAL *(clockwise and spiraling inward from top left): Planetary scientist Nina Lanza,* Moonsuit *author Nicholas de Monchaux, Itchy-O, That 1 Guy, festival attendees on the lawn, IP Festival Director Caitlin McShea, panel on Diverse Intelligence, MAKE Santa Fe's booth in the Expo tent, starsuit hula-hooper, panel on Creative Black Futures—and, overlooking it all, DKLA Design's 35-foot polar bear (Photos by Kimberly Corante)*

Parallax
Summer 2019
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'Stardust' in the rearview

InterPlanetary Festival 2019

Thousands of Earth and space enthusiasts attended SFI's second InterPlanetary Festival in the Santa Fe Railyard Park. Fueled and inspired by the research at the Santa Fe Institute, the mid-June festival offered an exploration of complexity science and human ingenuity in the setting of a summer festival full of music, film, art, food, drinks, and more.

"Stardust" was the code name for the second annual festival, which expanded upon the inaugural "Genesis" theme of 2018 with a more playful investigation of the InterPlanetary Project's central question — What would it take to become an InterPlanetary civilization?

In addition to live music, podcasts, immersive art, games, and an innovation expo, festival-goers enjoyed panel discussions with leading thinkers on topics central to the future of our species—space exploration, extremophile cities, game design, world building, diverse intelligences, creative black futures, and the origins of life.

Video recordings of all panel discussions are available through the Santa Fe Institute's YouTube channel: youtube.com/user/santafeinst. Additional information about the annual festival, including information about the upcoming 2020 festival (code name: Voyager), can be found on the InterPlanetary Festival website: www.interplanetaryfest.org

Research Briefs, continued from page 5

that instead some form of selection governs word choice. In particular, our choice of dominant words is guided by positive frequency-dependent selection, a bias that makes us disproportionately likely to use the words that most others use.

DISCRETE POWER-LAWS AND SELF-SIMILARITY

Continuous power-law distributions are commonly used in studying complex systems, and are associated with scale-free behavior and self-similarity. However, many self-similar processes occur only at discrete steps that do not follow a continuous scale-free distribution. In a publication in *Physical Review Letters* on April 19, External Professor Van Savage (UCLA) and collaborator Mitchell Newberry introduce a discrete power-law distribution, and derive the maximum-likelihood estimate for its exponent. They then apply this to empirical data to show that modeling discrete self-similar processes with a continuous power-law distribution can lead to errors, and that a discrete distribution is essential for properly describing many biological and physical systems.

A NEW NORMAL: STUDY EXPLAINS UNIVERSAL PATTERN IN FOSSIL RECORD

The fossil record of marine invertebrates since the Cambrian period reveals that extreme events of diversification and extinction have happened more often than a typical, Gaussian, distribution would predict. Previously, in 2009, SFI External Professor Miguel Fuentes used superstatistics to describe a similar fat-tailed distribution in the stock market. In a June 26 paper published in *Science Advances*, Fuentes, Omidyar Fellow Andy Rominger, and External Professor Pablo Marquet show that using Fuentes' approach — in this case, looking at fluctuations within groups of animals that share a common lineage rather than fluctuations across all types of organisms — could also accurately describe the unusual patterns in the fossil record.