WINTER 2020-21

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

"A single tree dying is not the aspen dying . . ." (Image: Aspens in winter, courtesy Steve McBride Fine Art)

Toward a new theory of birth, aging, and death

Few things occupy the public imagination like aging and death. But when it comes to organisms and systems beyond ourselves, there is still much we do not understand about either — even something as seemingly obvious as when something can be considered deceased.

"We know what we mean when we say a person is dead. This is because our concept of death is tightly connected to our own experience of life," says Annette Baudisch, a demographer with the University of Southern Denmark. "Once we start discussing other types of individuals, it becomes tempting to mix up different kinds of death." For example, at first glance, it may appear to us that a dead aspen tree is a dead aspen tree. But in reality, it represents the death of just one part of a larger organism that is still very much alive.

"A single tree dying is not the aspen dying because we know that aspens are clones," says SFI President David Krakauer, an evolutionary theorist. "So even in the world of life, what's living and what has died is complicated. Phenotypes might die as genotypes live on"

When it comes to inanimate objects or ideas, the definition of death becomes even murkier. When we say an old constitution no longer used for governing is "dead," is it really dead, or merely dormant? Similarly, is an idea that people no longer discuss really dead, even though someone might resurrect it one day?

These are some of the themes that emerged in a small planning meeting for a new working group, "The Birth and Death of Individuals," which plans to develop a new interdisciplinary theory of birth, aging, and death.

The group seeks to combine ideas from formal demography, scaling, and the theory of individuality. They have laid out four steps in forging the new theory: developing a framework for classifying individuals in time; crafting a typology of how individuals age, including individual societies and institutions; creating models to determine patterns of birth and death for those types; and analyzing how individuals within a population age.

At the group's planning meeting on November 24, Baudisch, Krakauer and a small number of researchers from a variety of fields began to tackle the first step.

"Before we talk about death we need to talk about individuals," says Krakauer. "What is this unit that we describe as aging and dying?"

"The idea was that, once we have a kind of backbone general definition of 'the individual' in place, we can begin to put meat on the definition and distinguish among different types of individuals," adds Baudisch. "Ideally we would identify a deep ordering principle along which we could align individual types."

Doing so would lay the foundation for a general classification of death processes.

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An agenda for disinformation research

The use and spread of disinformation — false or misleading information intended to deceive people — is being amplified and accelerated at an alarming rate on the internet via social media.

Within the U.S., this has quickly eroded trust in institutions that serve as the bedrocks of our society, such as science, the media, and government, to the point that we can't even agree on basic facts.

In a white paper for the Computing Research Association's (CRA) Computing Community Consortium (CCC), a group of researchers including SFI's Joshua Garland and Elizabeth Bradley outline steps to begin dealing with the disinformation problem.

A key goal of disinformation is often to create confusion and dismantle trust in traditionally trustworthy organizations. One obvious example of disinformation today is the way COVID-19 has been called a "hoax," which resulted in many people not viewing it as a real threat to their health or taking necessary precautions to prevent and contain its spread.

"Within the past few months, we've seen other large-scale disinformation about elections and the democratic process in terms of the validity, legality and security of mail-in ballots, fraudulent voting, rigged elections, dead people voting, supercomputers changing votes, etc.," says Garland, an Applied Complexity Fellow at the Santa Fe Institute. "And there are many other examples surrounding migrants, vaccines, and climate change."

Disinformation is an existential threat to democracy and society, points out Bradley, an SFI External Professor and a professor of computer science at the University of Colorado.

"We technologists created many of the tools being used by disinformation creators and circulators — the internet, social media, etc. — and it's incumbent upon us to think about solutions," Bradley says.

One of CRA's goals is to explore how computing research can help address national priorities. "Disinformation and the poisoned information environment we're all swimming in needs to be a national priority," says Nadya Bliss, executive

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Searching for life as we don't know it

Living things leave behind tell-tale signs of their existence: fossilized bones, DNA, the chemical byproducts of metabolism. *Living things on Earth*, that is. There currently exists no predictive theory to completely guide astrobiologists searching for life beyond our planet, where the chemical signatures of life, and the geo- and atmospheric chemistries under which it evolved, might look quite different from Earth.

In early November, NASA's Astrobiology Program launched the new Interdisciplinary Consortia for Astrobiology Research (ICAR), supporting eight teams focusing on specific outstanding questions in astrobiology. SFI External Professor Sara Walker (Arizona State University) is leading one of the teams, an interdisciplinary group of theorists and experimentalists whose expertise in geochemistry, microbiology, exoplanet atmospheres, network theory, and complex systems will help them explore the question: What detectable universal patterns distinguish living chemistries across diverse planetary environments?

Answering this question, Walker says, will help astrobiologists develop a theoretical framework to refine their search for extraterrestrial life, and to be able to recognize life as we don't know it.

"So far, astrobiology has been really focused on the looking for chemistry of life as we know it — amino acids, metabolic byproducts like oxygen or methane," says Walker. "What we're trying to do is say that life is not a property of individual molecules; it's a systems-level property that emerges from the interactions of many molecules and reactions. We want to understand and quantify the patterns in those molecules and reactions, then use those as new predictors of biosignatures."

The team will build on SFI-related research on scaling laws and use techniques from complex systems science — tools that are fairly new in astrobiology. SFI Professor Chris Kempes, who is already leading a NASA Astrobiology Research Coordination Network has worked on identifying scaling laws and regularity in life on Earth, is part of Walker's ICAR team. He hopes to uncover the

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The observable universe. (Illustration: Pablo Carlos Budassi / Wikipedia)

BEYOND BORDERS

EXISTENTIAL GAMES IN QUARANTINE

This year more than a few of us sought solace in the labyrinth of the game board. This is hardly a novel retreat or original compensation for reality. Vladimir Nabokov (who analyzed these ludic variations on Plato's cave) described the habits of the ascetic master Rubinstein, observing Rubenstein "didn't like to see his opponent. But an empty chair across the chessboard also irritated him, so they put a mirror there, and he saw his own reflection." All in all, this sounds like a fair metaphor for contemporary reality.

Writing seven hundred years prior to Nabokov, the Italian author Giovanni Boccaccio in his Decameron (set during the depredations of the Black Death) describes the third day of quarantine wherein all things lost and desired are discussed. Recounting how "some went thither, whilst others, overcome with the beauty of the place, willed not to leave it, but, abiding there, addressed themselves, some to reading romances and some to playing chess or tables, whilst the others slept." This might even surpass — in relevance — Nabokov's reflections on Rubinsteinian reclusiveness.

For over a millennium chess and Go have provided a microcosm for exploring analytical, aesthetic, moral, and practical matters. They have done so in different ways, reflecting in their contrasting elements something resembling a chronology of science. Let's call this a shift from reductionism to emergence, or a focus on parts in chess and patterns in Go. It should be said that chess at the highest levels has always been about patterns. But in Go the beginner has no choice but to think in patterned terms and so the Go novice learns to play the way an ideal chess player matures.

Here are some notable differences. In Go there is only one piece, whereas in chess there are six unique pieces each with a different value. The chess board is a square lattice of eight-by-eight cells. The Go board is 19-by-19 cells. In chess the board starts with all pieces present in a fixed position and gradually empties. In Go the board starts with no pieces and gradually fills. In chess the objective is to capture pieces. In Go the objective is to capture territory. The opening game in chess is highly scripted — somewhat like the end game of Go. Both games have an equal complement of black and white pieces.

Through the game of chess we invented a fairly strong model of physical reality. Starting in a state of near-perfect order, all the pieces in play, moving through annihilating interactions, reducing the board to a sparse set of pieces with nowhere left to move. With Go we invented a model for adaptive evolution, emphasizing how patterns emerge from simple beginnings, how the constraints of pattern impose limitations on strategy, and the way growing territories form shapes of near endless complexity.

The early history of science is often told as if it were a chess-like epistemological dissection — taking plants, animals, and atoms apart so as to reveal their constituent parts. And then determining which of these parts is essential or dominates in accounting for a property of interest. The recent history of science, and complexity science in particular, is far more interested in how we put these

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SFI IN THE MEDIA

Melanie Mitchell, SFI Davis Professor of Complexity, and External Professor **Daniel Dennett** contributed to a special *New York Times* review of "The Lasting Lessons of John Conway's Game of Life." An iconic example of emergence, the game produces diverse patterns from a few simple rules.

In "Playing Go with Darwin," a *Nautilus* op-ed, SFI President **David Krakauer** used Go as a metaphor for evolution — a "game played across deep time."

The Washington Post, *The Atlantic*, and other outlets have credited SFI's **Harold Morowitz** and his co-author Carl Sagan for first expounding on "Life in the clouds of Venus?" in a 1967 paper. The work is gaining new attention after a recent, independent discovery of phosphine gas on Venus, which could indicate the presence of life (*see p.3*).

Quanta magazine included SFI research on individuality in their year-end biology review (see below).

In an op-ed for *The Conversation*, syndicated by *Yahoo* news and other outlets, SFI Professor **Mirta Galesic** and Wandi Bruine de Bruin of USC Dornsife described how to make election polls more accurate by using questions that ask participants to speculate how others will vote.

External Professor **Henrik Olsson**, who is a collaborator on the polling project, was quoted in a *Los Angeles Times* feature about the efficacy of polling questions.

External Professor **Lauren Ancel Meyers** and her team were recognized n a *New Yorker* feature titled "The Plague Year" for their early discovery of pre-symptomatic coronavirus transmission.

Distinguished Shannan Professor **Geoffrey West** appeared on the French podcast *The Urban* to discuss cities as the heart of the climate issue.

External Professor **Ole Peters**' ergodicity approach to economics, which began with conversations at SFI during his postdoctoral fellowship, was featured in *Bloomberg* in an article titled "Everything We've Learned About Modern Economic Theory Is Wrong."

The *Financial Times* quoted External Professor **Doyne Farmer** in an article about a rising call amongst economists to measure a country's economic health using contracts rather than GDP.

A biology breakthrough

Quanta magazine named SFI's information theory of individuality in their annual review of biology breakthroughs. It was one of six selections for 2020.

"This will always be remembered as the year the COVID-19 pandemic exploded," wrote the magazine's deputy editor, John Rennie. "Grim as events have been, however, remarkable science has soldiered on."

The SFI study, published March 24 in the journal *Theory in Biosciences*, uses information theory to answer one of biology's biggest questions: what is an individual?

The study was subsequently featured in a *Quanta* article by staff writer Jordana Cepelewicz, and named in the magazine's year-end review under "Biological Individuality and Symbiosis."

Instead of focusing on anatomical traits, like cell walls, study authors SFI President and William H. Miller Professor of Complex Systems David Krakauer, Nils Bertschinger (Frankfurt Institute for Advanced Studies), Eckehard Olbrich (Max Planck Institute for Mathematics in the Sciences), SFI Professor Jessica Flack, and SFI Professor Nihat Ay

Coral polyps on Molasses Reef. Florida Keys National Marine Sanctuary (Photo: Brent Deuel/NOAA Photo Library)

(also of the Max Planck Institute for Mathematics in the Sciences) look to structured information flows between a system and its environment. "Individuals," they argue, "are best thought of in terms of dynamical processes and not as stationary objects."

Rather than a noun, they describe the individual as "a kind of verb."

Jennifer Dunne reflects on a year without 'superpowers'

In the Fortress of Solitude there's a chamber that glows red like the Kryptonian sun. There, the 1980 Superman lost his super-speed, super-strength, and ability fly — all the powers that defined him as a DC superhero.

The Santa Fe Institute has always been defined by its ability to bring diverse, leading thinkers into the same room to tackle important research questions. So for SFI, 2020 has been something like stepping into that red chamber in the Fortress of Solitude. Jennifer Dunne, SFI's Vice President for Science, jokes that the pandemic, with its necessary restrictions on in-person gatherings, "took away our superpower."

We recently spoke with Dunne about which aspects of SFI science can and cannot be replicated in a virtual environment, and what this means going into 2021.

Q: You've convened workshops and working groups to explore the role of creativity in the scientific process. How do in-person vs. online gatherings play into that process?

Dunne: SFI is very much about the creativity phase of science — the generation of new ideas and new collaborations. Given all the different ways of interacting deeply with people in person on and off campus, that's much harder to do virtually. On Zoom, due to latency and other issues, you can't have opportunistic and easy-flowing conversations. The big drawback of online interactions is that you miss that serendipity of bumping into new as well as familiar people in the hallway or over lunch, tea, or coffee breaks. You miss going out to dinner and going on walks.

But I think people are starting to realize the upsides of the online format. In terms of meetings, you can meet for a couple hours a day, several days in a row, and cater to

Jennifer Dunne hikes the Anne Nitze trail on SFI's Cowan Campus. (Photo: Gabriella Marks)

participants in different time zones — holding half the session on Australia time, and then trade recordings with the half-session conducted on European or U.S. time, for example. Online meetings are also inexpensive and frictionless in a lot of ways, which makes them much easier to organize. Our colloquium staff, our flash workshop organizers, and our Applied Complexity team have also found it easier to engage high-profile speakers and attendees on short notice for online meetings and talks. So there's definitely an upside to online.

Q: Could you tell us more about some of the science meetings that did and did not convene in 2020?

Dunne: There are several working groups and workshops that were approved to be held in 2020 that never occurred because of COVID-19. But some organizers went ahead and held virtual versions that I think were very successful. David Wolpert* loved his three-day virtual workshop on stochastic thermodynamics co-hosted with the Complexity Science Hub Vienna — he's said that he finds virtual groups a better format for getting junior scientists to speak.

David Krakauer's* Aging, Adaptation, and Arrow of Time group held a virtual meeting on a multiscale theory of life and death, and they found it helpful to split the group into multiple meetings to prevent zoom fatigue.

Then there were also the very successful, short-format flash workshops on the pandemic, which Cris Moore*, and Michael Lachmann*, and David Krakauer* organized earlier this year. Because of the lower time commitment, they were able to bring in people who would ordinarily be very hard to schedule.

Other organizers of previously approved meetings are waiting until conditions allow them to hold their meetings in person, as originally planned. Another possibility some are considering is holding an initial online version of the meeting and following it up with a regular meeting at SFI in the "after times."

Q: How do you envision the future of SFI science meetings? Will there still be a place for virtual gatherings after everything "gets back to normal"?

Dunne: I think this is a time of experimenting. When the kryptonite goes away and we get back to in-person activities, we'll be trying to figure out how to retain some of the best features of the online experience and how to bring people in from afar who have a hard time committing to travel to SFI. Before the pandemic, we'd already started Zooming people in on a big TV screen for the smaller working groups in particular, but what we do for bigger workshops is less clear. So

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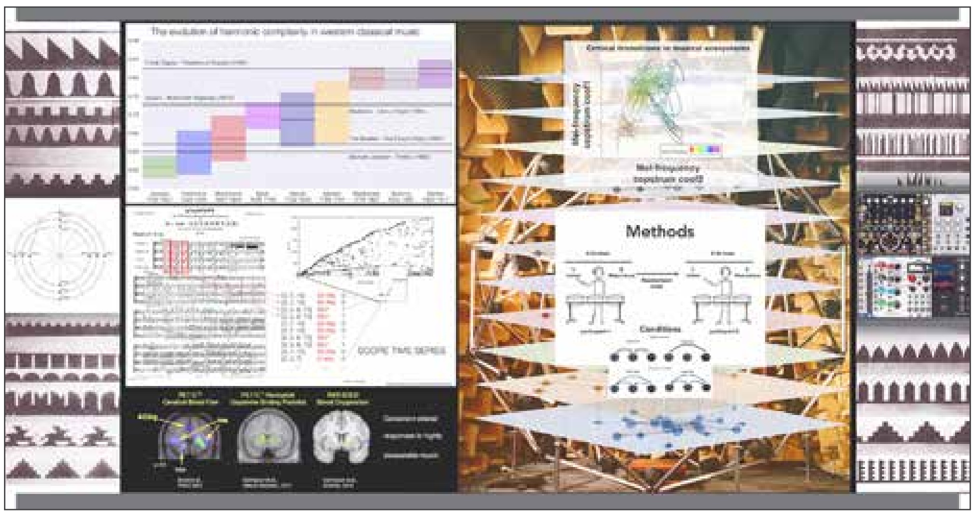


A collage of slides presented at the "Complexity and the Structure of Music" working group (Image: Michael Garfield)

An 'integrated mess of music lovers in science'

Music holds a unique power over our species. Except in rare cases of what is called "musical anhedonia," where a person's brain scans show their auditory cortex isn't linked to their reward circuitry, listening to music is like gambling or making love. So it is hard to imagine a more alluring topic for an SFI working group than "Complexity and the Structure of Music: Universal Features and Evolutionary Perspectives Across Cultures."

Co-sponsored by SFI and the Institute for Advanced Studies of Aix-Marseille University, France (IMéRA), this forum brought together network and complexity scientists, musicologists, music theorists, composers, performers, and neuroscientists to trade licks about the intersections of music and complexity from as many angles as possible.

"The abstraction of musical structures as geometrical spaces naturally invites the analysis of music as a complex system," wrote the working group co-organizers in their meeting description. Co-organizer Miguel Fuentes is a complexity scientist and SFI External Professor, and co-organizer Marco Buongiorno Nardelli (University of North Texas, IMéRA) is a composer, flutist, and computational materials physicist.

Meeting over three days, the international group rotated many conceptual objects of musical structure through myriad key and tempo changes, hosting panels and running an event-long side discussion in the Zoom chat. According to one participant, they were well aware of the meeting itself as an improvisational ensemble with players learning each other's languages.

Ideas flowed at high speed as speakers shared their work: using network-based approaches to study composition and the evolution of form over music history, identifying "rules" of music as emergent properties, asking how the neuroscience of pleasure might encode in us a math and music that reflects our cultural constraints, and investigating how spaces shape the experience and production of music.

"Music is 35,000 years old at least, and we can use these amazing math and network tools to understand how humans think of music," says SFI Complexity Fellow Stefani Crabtree, an archaeologist and musician who participated in the group. "How great is it to work with an interdisciplinary team?"

What is and is not universal stayed a central question through the talks. People teased at the prospects of translating complex datasets to music, or sifting through music-listening data to identify scale-free patterns in human attention, or using a network model for harmony to write generative algorithms for music both like and unlike anything we've ever heard.

On the last day the working group posed questions like, "How soon can we do this again?" and "What kind of fruit can an integrated mess of music lovers in the sciences make?"

Stay tuned!

Cancer evolution, from cells to species and back

Around 150 years ago, only 1 percent of men and women developed some form of cancer in their lifetime. As humans began to live longer in the twentieth and twenty-first centuries, cancer rates increased. Today, the disease afflicts a staggering 40 percent of people in the Western world and is the second leading cause of death globally.

Michael Hochberg

In his 2020 Darwin Lecture, "Cancer Evolution: From Cells to Species and Back," SFI External Professor Michael Hochberg, who is Distinguished Research Director with the Centre National de la Recherche Scientifique at the University of Montpellier, France, drew on insights from network science and his own expertise in disease modeling to provide an overview of how evolution has shaped cancer into the deadly killer it is today.

He illustrated how natural selection and environmental factors have led to a host of highly individualized cancers and cancers types that are difficult to treat.

"When we replay the tape of cancer evolution in humans it does not appear to be identical between cancer types or even within cancer types," says Hochberg. "This high degree of variability creates major challenges for targeted treatments designed to deal with specific tumor types."

Hochberg went on to elucidate how the contributions of selection and environment have influenced cancer patterns in well-studied mammals, such as humans, as well as other interesting organism like the naked mole rat, which is not affected by cancer.

Finally, Hochberg discussed the role natural selection may play in the development and re-occurrence of chemotherapy-resistant tumors as well as new approaches he and other scientists at SFI and elsewhere are developing to treat them.

"One of the issues with conventional cancer treatments is that they have tended to select for chemo-resistant subpopulations which can lead to the recurrence of more difficult-to-treat tumors down the road," he said. "What our new research is showing is that by managing these chemo-resistant subpopulations rather than trying to eradicate them, we can use what amounts to Darwinian processes to lengthen the life of those afflicted by late stage and difficult to treat cancers."

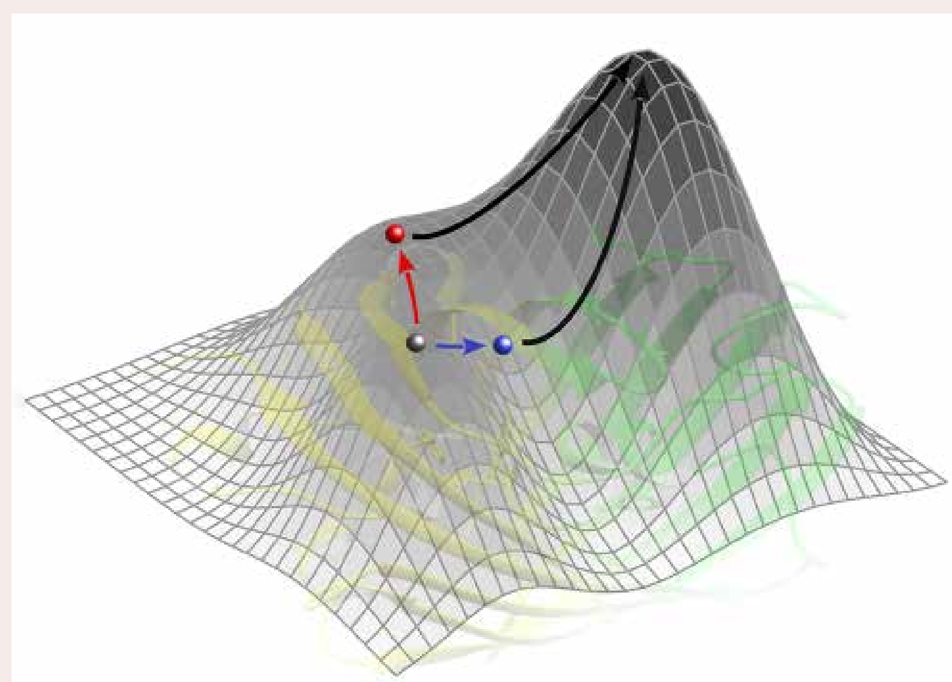
Hochberg's Darwin Lecture was presented by the Linnean Society of London and in association with the Royal Society of Medicine.

New books by SFI authors

The Chemistry of Fire (University of Arkansas, 2020) is a collection of 14 new essays by former SFI Miller Scholar Laurence Gonzales, a multiple-award-winning journalist and author of numerous books that meld deep reporting with captivating storytelling. In his most recent book, Gonzales offers a variety of stories that chronicle travels to and exploration of far-away and dangerous places, from a trip to the International Space Station, the discovery of the wreck of the Titanic, to the top of New Hampshire's Mount Washington, a place with "the worst weather in America." Kirkus Reviews notes that the essays, set in both exotic places and those closer to home, "explore what it means to be human," and that as Gonzales keenly observes the people around him, he "shows himself to be a caring, questioning man with a dry wit and big heart."

Complexity Economics: Proceedings of the Santa Fe Institute's 2019 Fall Symposium (SFI Press, 2020), includes panel and talk transcripts from SFI's 2019 Applied Complexity Network Symposium, with new introductions and reflections. When SFI scientists first started working on economics more than thirty years ago, many of their insights, approaches, and tools were considered beyond heterodox. While these approaches are now increasingly considered mainstream, SFI continues to expand the boundary of our economic understanding by pioneering fields as diverse as collective intelligence and organizational scaling. Edited by SFI External Professors W. Brian Arthur, Eric D. Beinhocker, and Allison Stanger, who is also an SFI Science Board member, this book represents both scholarly and practitioner perspectives, and explores the history and frontiers of complexity economics in a broad-ranging, accessible manner.

RESEARCH NEWS BRIEFS



Representation of the evolutionary fitness landscape (Zheng et al. SCIENCE 2020 (10.1126/science. abb5962))

NATURAL SELECTION PLAYS MAJOR ROLE IN AN ORGANISM'S CAPACITY TO EVOLVE

We know that natural selection shapes how animals and plants evolve and adapt. But does natural selection also influence an organism's very capacity to evolve? And if so, to what degree? A new study, published December 4 in *Science*, hints at some surprising answers to that question. A team of researchers led by External Professor Andreas Wagner (University of Zurich) subjected populations of a yellow fluorescent protein from a marine invertebrate to weak and strong selection pressures to find out which one enhances evolvability more effectively. The evolutionary end-goal was to get the protein populations to evolve from yellow fluorescence to green. The group under strong selection pressure won, because those populations underwent mutations that made them more robust — and therefore better able to evolve. "To our knowledge, this is the first experimental proof that selection can drive the ability to adapt in a Darwinian sense and increase evolvability," says Wagner. He is hopeful that the study will help settle the long-standing controversy over whether an organism's evolvability itself can evolve.

Read the paper at doi.org/10.1126/science.abb5962

THERMODYNAMICS OF OFF-EQUILIBRIUM SYSTEMS

Arguably, almost all truly intriguing systems — stars, planetary systems, digital circuits — are far from equilibrium. But, until now, systems far from thermal equilibrium couldn't be analyzed with conventional thermodynamics and statistical physics. In a paper published in the journal *Physical Review Letters*, SFI Professor David Wolpert presents a new hybrid formalism, weaving in nonequilibrium statistical physics and Bayesian networks to overcome all of the limitations of the earlier-developed, traditional fields. As an example of the power of this new formalism, Wolpert derived results showing the relationship between three quantities of interest in studying nanoscale systems like biological cells: the statistical precision of any arbitrarily defined current within the subsystem (such as the probabilities that the currents differ from their average values), the heat generated by running the overall Bayes net composed of those subsystems, and the graphical structure of that Bayes net.

Read the paper at doi.org/10.1103/PhysRevLett.125.200602

DIVERSITY BEGETS DIVERSITY

Most forms of life — species of mammals, birds, plants, reptiles, amphibians, etc. — are most diverse at the equator and least diverse at the poles. This distribution is called the latitudinal gradient of biodiversity.

Former SFI Postdoctoral Fellow Marcus Hamilton (University of Texas at San Antonio), Professor Chris Kempes, and their co-author were intrigued by the fact that human cultural diversity shows exactly the same distribution with latitude: human cultures are more diverse near the equator and least at the poles. To understand why, the group conducted a biogeographic and macroecological study of the distribution of mammal species diversity and human ethnolinguistic diversity around the world.

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SFI IDEAS: Pandemic paths and the road ahead

One of the clearest messages to emerge from the science around the coronavirus pandemic is that science alone cannot contain a crisis. With this in mind, our faculty have been contributing to the public dialogue around the pandemic, sharing insights from complex systems through SFI's own "Transmission" series and through op-eds in national news outlets. Here, we point to six prescient writings that made sense of the pandemic year and offer new insights for navigating the road ahead.

THE COMPLEXITY CRISIS

Nautilus

The COVID-19 pandemic can be understood as the first complexity crisis in history, according to SFI Distinguished Shannan Professor Geoffrey West and SFI President David Krakauer. By capturing the kinds of tradeoffs that lie at the heart of such crises, complexity science can help us manage the pandemic's long-term ramifications.

Complexity crises have two main features, Krakauer and West argue. First, they involve the "failure of multiple coupled systems — our physical bodies, cities, societies, economies, and ecosystems." Second, they call for solutions that involve unavoidable tradeoffs that amplify initial system failures.

The COVID-19 pandemic has forced us to negotiate a tradeoff between social conventions of the past and new conventions that help us manage contagion. We choose between a handshake and elbow bump, for example. In general, it is much easier for human communities to retain old conventions than to adopt new ones. Complexity scientists call the way that we lock-in old habits "path dependence." In the pandemic, path dependence suggests that trading old habits for new ones is not a straightforward switch. Not only must we adopt new habits, we must also expend energy in breaking old ones. By illuminating the path dependence that characterizes the tradeoff between past and future conventions, complexity science can help us better manage contagion.

In their op-ed for *Nautilus* (also published in SFI's "Transmission" series), Krakauer and West show that when we gain a clearer picture of the ways that different tradeoffs make us vulnerable, we can become better at shoring up our interrelated life systems.

Read more at nautil.us/issue/87/risk/the-damage-were-not-attending-to

MISINFORMATION IS IMPORTANT PUBLIC HEALTH DATA

STAT

The spread of the novel coronavirus has been a lesson for epidemiologists in the interplay between contagion of disease and contagion of misinformation. Until recently, however, many epidemiological models have failed to account for the ways that misinformation shapes the spread of disease.

In their op-ed for *STAT*, former SFI postdoctoral fellow Laurent Hébert-Dufresne (University of Vermont) and Vicky Chuqiao Yang, current Complexity Postdoctoral Fellow and Peters Hurst Scholar, argue that if scientists hope to develop better epidemiological models, they must grasp the complex interplay between social behavior and disease.

To illustrate their point, Hébert-Dufresne and Yang turn to data from the 2019 measles epidemic that spread across the Philippines, wherein 40,000 people were infected and 500 died. As the authors explain, "the onset of the epidemic was largely driven by the spread of anti-vaccination sentiment, itself fueled by a dengue vaccine that failed to account for the interplay of dengue strains." In short, the measles contagion took a path that was shaped significantly by social behavior and public misinformation.

For Hébert-Dufresne and Yang, "social communication and behaviors during an outbreak are just as important to public health as tests and diagnoses." Scientists must seek data on these facets of epidemics if they are to model the complex path that epidemics take on the ground.

Read more at statnews.com/2020/04/07/misinformation-outbreak-is-important-public-health-data/

FEAR AND THE NEXT EPIDEMIC

Politico

For scientists who study the social dynamics that drive the COVID-19 pandemic, contagion is not a singular thing. As SFI External Professor Joshua Epstein of New York University states in an op-ed for *Politico*, the contagion of fear is as significant to the current pandemic as the novel coronavirus itself.

He observes that fear can both help and hinder public health responses to pandemics. In the 1918 influenza pandemic, for example, fear was helpful for reinforcing social distancing measures. When these measures were effective, and fear abated, it was most likely the decline in fear that caused the second spike.

On the other hand, scientists recognize that fear of both economic crisis and vaccination can worsen the prospects for recovery. Fear of economic collapse drives risky economic reopening; fear of vaccination can threaten our prospects for long-term public immunity.

For Epstein, to formulate the strongest possible public health response to the current pandemic, political leaders must manage fear contagion on three fronts: disease spread, economic recovery, and vaccination.

Read more at politico.com/news/magazine/2020/03/31/coronavirus-americafear-contagion-can-we-handle-it-157711

BATTLE FOR THE COVID-19 NARRATIVE

Financial Times

COVID-19 is fundamentally changing the way we talk about the economy, write SFI External Professor Wendy Carlin of University College London and SFI Professor Sam Bowles in an op-ed for the *Financial Times*. This shift presents opportunities to develop language that fosters more humane economic policy. At other times in history, the authors point out, political leaders have redirected economic policy by reframing how we speak about economic life. Franklin D. Roosevelt, for example, shifted attention from "heedless self-interest" to "freedom from want."

At the moment, Carlin and Bowles write, "the battle to control the narrative is already underway." Thought leaders have choices to make about what facets of human experience they will emphasize in the economic vernacular of the near future. For Carlin and Bowles, the new narrative would do well to embrace three truths: first, that to be effective, governments depend upon citizenries that "trust public health and [are] committed to rule of law." Second, that political communities can and do act in strikingly civic-minded ways. And third, in contrast, segments of political communities can act in strikingly xenophobic ways. If we express these three truths in our economic narratives, Carlin and Bowles contend, we will be better equipped to respond to the kinds of crises that we can anticipate in our post-pandemic and climate futures.

Read more at www.ft.com/content/cb827cea-849d-11ea-b6e9-a94cffd1d9bf

MODEL FOR A JUST VACCINATION PROGRAM

Nautilus

The COVID-19 pandemic has brought to light complex forms of racial injustice that are deeply entrenched in the American public health system.

In their op-ed for *Nautilus*, SFI External Professor Melanie Moses (University of New Mexico) and her UNM colleague Kathy L. Powers, both members of the Interdisciplinary Working Group for Algorithmic Justice, argue that the strategies scientists typically take to work with large-scale data often fail to address the grossly disproportionate effects of the pandemic on populations that face the highest risk. Moses and Powers argue that if scientists are to help public health policymakers meet their stated goal of protecting the most vulnerable, they must refine their methods to focus on the complex systems that govern communities that are most at risk.

For Moses and Powers, the arrival of COVID-19 vaccines presents an opportunity to undertake this kind of analysis — and in so doing, address longstanding inequities. If we take a closer look at how vulnerable populations are likely to access and respond to vaccines, we can begin strategically to restructure systemic injustice in ways that will help high-risk communities become more resilient in the future.

Read more at nautil.us/issue/93/forerunners/a-model-for-a-just-covid_19-vaccination-program

UNCERTAIN TIMES

Aeon

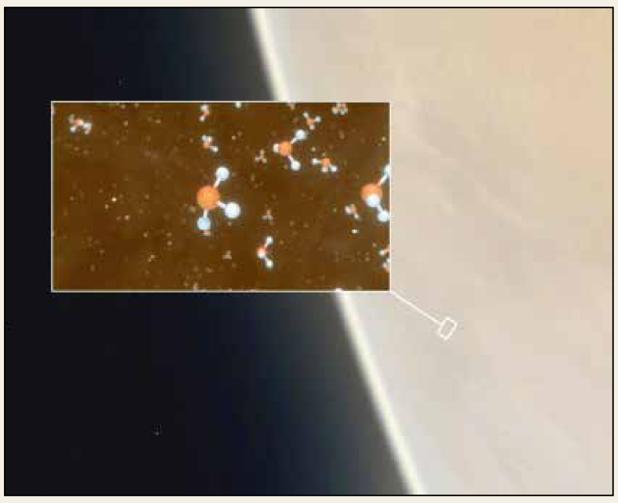
For SFI Professor Jessica Flack and SFI Davis Professor Melanie Mitchell, the COVID-19 pandemic prompts us to revisit the ways that complex systems retain stability in the biological world. By learning from biological systems, we can begin to shore up the vulnerability inherent in the complex systems that undergird human life.

As they explain in their recent essay for *Aeon*, complex systems are characterized by instability, uncertainty, randomness, and information flux. As we see in the pandemic, complex systems are coupled systems. A decision in one part of the system, say, social distancing policies, reverberates in another part, say, stock market fluctuation, which reverberates in another part, say, governmental stimulus, and so on. Anyone looking at either the unfurling pandemic or the list of terms that characterize complex systems might wonder if we could detect clear patterns of stability in either place.

Yet as Flack and Mitchell illustrate, many complex biological systems help us see that nature regularly responds to destabilization with strategies that help life systems remain robust and adaptable. Schools of fish, when met with the threat of a shark, experience what scientists call a tipping point. The threat prompts the fish not into chaotic panic, as one might expect. Rather, it compels them to shift from shoaling, a weakly aligned formation, to school formation, which is highly aligned and allows the group more easily to evade the predator.

Understanding how biological systems respond to uncertainty and destabilization can help us discover strategies to engineer stability in our human complex systems — for the pandemic and beyond.

Read more at aeon.co/essays/complex-systems-science-allows-us-to-see-new-paths-forward



Above, left: SFI External Professor Harold Morowitz. Right: Artist's impression of Venus, with an inset showing a representation of the phosphine molecules detected in the high cloud decks. (Image: JESO / M. Kornmesser / L. Calçada & NASA / JPL / Caltech)

First to forecast life above Venus

September 2020 brought a landmark discovery for astrobiology — the detection of a chemical compound in the clouds of Venus that is often associated with the presence of life. Though no SFI researchers were on the team that published the recent discovery of phosphine, one SFI scientist first forecast the possibility of Venusian life more than 50 years earlier.

With co-author Carl Sagan, the late SFI Science Board member and External Professor Harold Morowitz made a plausible case for a habitable niche in Venus's atmosphere, in a speculative article published in the journal *Nature* in 1967.

"While the surface conditions of Venus make the hypothesis of life there implausible, the clouds of Venus are a different story altogether," wrote Morowitz and Sagan. They moved on to describe how microbial life forms could survive by floating above the scorching surface of the planet, taking advantage of water, sunlight, and carbon dioxide which are prerequisites for photosynthesis.

The 2020 discovery brought a new wave attention to Morowitz and Sagan's article, with citations popping up in prominent science news outlets and in mainstream media outlets. *(See SFI in the Media, p.2)*

Morowitz, who passed away in 2016, was instrumental in establishing SFI as a leading research center for questions relating to biophysics and life's origins. He convened the Institute's inaugural workshop on the origins of life in 1987, which grew into a multi-institution, National Science Foundation-funded investigation that produced two leading, but incomplete, scientific explanations.

BEYOND BORDERS *(cont. from page 2)*

pieces back together to produce life — a Go-like epistemological biosynthesis.

In our ludic pursuits, whether these be chess, Go, or myriad alternative board and computer games, we have been exploring these two approaches to physical reality. Nabokov's Rubinstein and Boccaccio's exiles did not willingly forfeit society in times of duress — they created simulacra. And however diminished their shadow realms, they nevertheless challenge us to think through the elements and emergent patterns of existence. It seems extraordinary to me that with chess and Go we recapitulated — or perhaps more accurately *precapitulated* — some of the styles of thought that have come to dominate our understanding of physical reality. It is as if the entertainments sought in our confinement are the unwitting homework required to better cope with the world upon our release.

— David Krakauer
President, Santa Fe Institute

SFI External Professor **André de Roos**, a Professor of Theoretical Ecology at the University of Amsterdam, was named the King Carl XVI Gustaf Professor in Environmental Science for 2021-22. The appointment from the Royal Swedish Academy of Sciences will bring de Roos to Sweden for a one-year residency at the interdisciplinary IceLab at Umeå University.

André de Roos

SFI Professors **Chris Kempes** and **Michael Lachmann** were both among the 50 awardees of this year's John Templeton Foundation Ideas Challenge. Kempes' entry, awarded in the Macro-evolution track, relates to his work identifying universal biological laws. Lachmann's winning idea was awarded in the Open track, a topical area that recognized diverse ideas around goal-directed outcomes in nature.

Michael Lachmann, Chris Kempes

Sean Carroll

SFI External Professor **Sean Carroll** of Caltech has been elected a member of the American Association for the Advancement of Science (AAAS) for his "distinguished contributions to cosmology, gravity, and dark matter research," as well as for his "exceptional contributions in communicating and promoting science to the public."

Sid Redner

SFI Professor **Sidney Redner** will receive the 2021 Leo P. Kadanoff Prize. The annual prize from the American Physical Society is one of its highest honors in theoretical physics.

SFI External Professor **Tanmoy Bhattacharya** of Los Alamos National Laboratory has been named a 2020 Laboratory Fellow. He is one of seven LANL scientists and engineers to receive this recognition for their scientific leadership.

Tanmoy Bhattacharya

InterPlanetary transmits new signal

SFI's InterPlanetary Project has found a new way to celebrate the mutual influence of sci-fi and science.

In a podcast interview series that launched November 18, host Caitlin McShea, SFI's InterPlanetary Festival Director, asks artists, authors, athletes, and scientists to imagine one alien technology that could change the trajectory of human advancement.

Called "Alien Crash Site," the series is based on the novel *Roadside Picnic*, by brothers Boris and Arkady Strugatsky, which imagines that an alien civilization visited our planet and left behind mysterious technologies at the landing site.

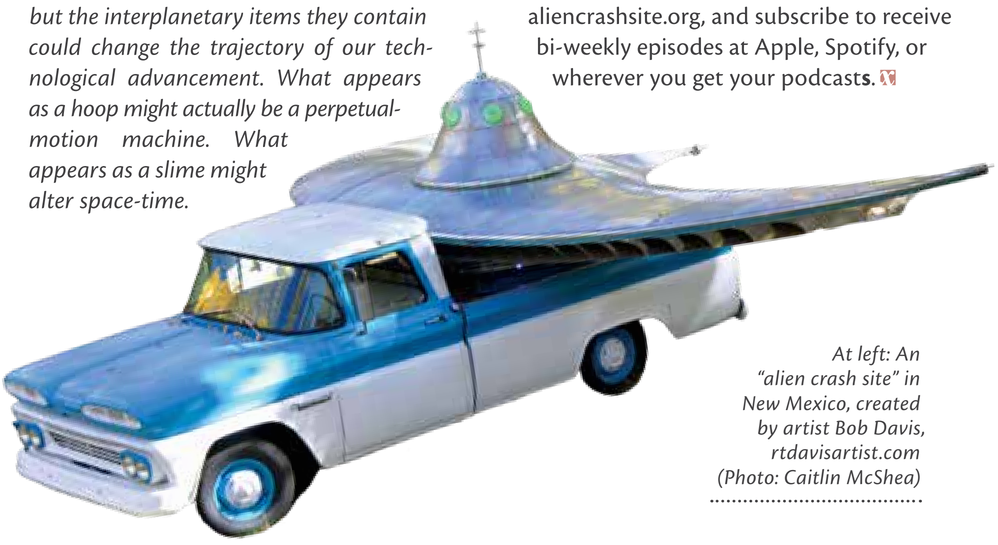
The story on the website reads:

> *Thirteen years ago, an alien civilization visited our planet, and left behind myriad, mysterious materials in their crash sites. These areas, Zones, behave very strangely, but the interplanetary items they contain could change the trajectory of our technological advancement. What appears as a hoop might actually be a perpetual-motion machine. What appears as a slime might alter space-time.*
>
> *Spend too much time in the Zone and your genes might mutate, your bones might dissolve, your body might be ground into meat. If you're lucky enough to make it out alive, you'll likely be imprisoned. But a successful trip in and out of the Zone could alter human history.*
>
> *Do you dare? And for what?*

As to why SFI, a scientific research institute, is discussing science fiction, SFI President David Krakauer, who conceived the podcast's theme, says, "It's because we believe that imagination should be unchained, and that, often, ideas of scientific value are derived outside of the rigorous scientific domain . . . the imagination and method together have superpowers."

Alien Crash Site is SFI's second active podcast, joining its official podcast, Complexity.

Catch the first four conversations at aliencrashsite.org, and subscribe to receive bi-weekly episodes at Apple, Spotify, or wherever you get your podcasts.



At left: An "alien crash site" in New Mexico, created by artist Bob Davis, rtdavisartist.com (Photo: Caitlin McShea)

A UCR meeting in 2020

SFI's first-ever virtual complexity undergrad program a success

It takes patience and plenty of good-will to transform a dynamic and intensive in-person summer program into a virtual experience that offers genuine and impactful connections. With the support of SFI Professor and Program Director Chris Kempes and Education Program Manager Carla Shedivy, ten students around the U.S. and 11 SFI researcher-mentors proved up to the task. This summer, in response to the ongoing coronavirus pandemic, SFI Education held its first-ever virtual Undergraduate Complexity Research (UCR) program.

"After some unpleasant experiences with online classes in the months leading up to the SFI UCR program, my hopes were not very high for a virtual research experience," says program participant Julia Beckwith. "I expected to be cordial with my peers, perhaps make some professional connections, and spend most of my time on Zoom daydreaming about the mountains in Santa Fe. I ended up making new friends, having great conversations with SFI professors and staff, and looking forward to our cohort's daily Zoom call."

> "Ultimately I learned that it really is possible to have your life changed over Zoom."
>
> BRONWYNN WOODSWORTH, UNDERGRADUATE COMPLEXITY RESEARCHER

Each summer, UCRs receive dedicated and expert mentorship on individual research projects, opportunities to meet SFI faculty, tutorials on how to conduct good research, and support and learning from one another. These experiences establish professional relationships that last far beyond the duration of the program. The virtual community created this year preserved theses important parts of the UCR experience.

"What sets the SFI undergraduate research program apart is that students become equal members of the SFI research community," says Kempes. "Rather than simply assisting with someone else's work, we ask them to take full ownership of their project. They decide what they want to study and how to go about it with guidance from an SFI mentor. We were eager to preserve this approach in the online program."

Through the program, UCR participants build confidence and competence conducting research, gaining salient experience to inform their subsequent careers. During the final week, UCRs present their efforts and findings to the broader SFI community.

"My UCR experience gave me the confidence to believe that I could obtain a PhD and become a researcher if I wanted to," said UCR Bronwynn Woodsworth. "Designing my own project from scratch and gathering enough data for a final presentation was an incredible feeling."

But the UCR program isn't all work; The immersive mix of scientific collaboration and socializing gives the program a special kind of magic. To re-create the interactivity of in-person programming, SFI postdocs hosted two virtual game nights with the UCRs. Movie nights and other self-organized social activities rounded out opportunities to connect for fun as well as study.

In 2020, the UCRs' virtual constraints offered its own magic. "The summer was challenging but also exhilarating in ways that I never expected; I loved jumping on Zoom to play online drawing games and talk about stand-up comedy and research dilemmas with my fellow UCRs before returning to edit an excessively long Python script," says Woodsworth. "Ultimately I learned that it really is possible to have your life changed over Zoom."

AGING & DEATH *(cont. from page 1)*

At the group's next meeting, the team plans to further refine the concept of the aging individual and identify and recruit researchers from additional disciplines who have studied different types of death. In the meantime, Baudisch plans to begin work on a periodic table of sorts that lays out the organizing principles of life and death.

DISINFORMATION *(cont. from page 1)*

director of the Global Security Initiative at Arizona State University.

To address disinformation, the researchers emphasize that both supply and demand must be addressed. "On the supply side, we need to develop better methods for detecting and isolating, or at least mitigating, disinformation before it spreads," explains Bliss. "On the demand side, we need improved efforts to educate the citizenry so people are less susceptible to believing and spreading disinformation."

Purveyors of disinformation are excellent at manipulating human emotions — they create content that is meant to seem believable while triggering an emotional response. As an individual, the best thing you can do to stop the spread of disinformation is to be sure you aren't part of the problem. If you're online and see a post that outrages you, Bliss cautions to take a moment to think before sharing it.

The researchers say the challenge of combating disinformation requires a comprehensive response that goes far beyond computing research, and includes education, psychology, journalism, and other disciplines.

"There's a tremendous need to understand how data-empowered algorithms are impacting our reality and the offline world," says co-author Chris Wiggins, an associate professor of applied mathematics at Columbia University's School of Engineering and Applied Science and the Chief Data Scientist at *The New York Times*. "Just like for any other complex system, addressing this will require interacting with the system — here the information ecosystem — in a way that respects ethical concerns for rights, harms, and justice."

"Our white paper outlines a clear agenda for research on the topic that could help inform a national response driven by the public and private sectors together," says Bliss.

SUPERPOWERS *(cont. from page 2)*

we need to up our game in terms of our technology for melding virtual and in-person experiences at multiple scales.

There will be a significant backlog of in-person workshops and working groups, so we'll also need to take of advantage of that online flexibility while also looking toward a future when we can get back to what we do best, which is bringing people together in person for intensive brainstorming and research, as well as food, margaritas, and time spent outdoors.

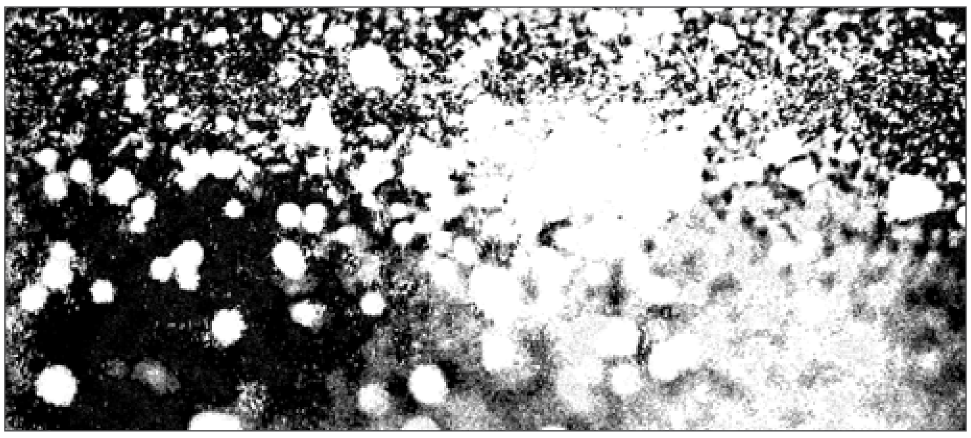
**Wolpert, Moore, and Lachmann are all SFI Professors. Krakauer is SFI President and William H. Miller Professor of Complex Systems.*

LIFE *(cont. from page 1)*

mechanisms that lead to scaling relationships as well as other biochemical and physiological properties of life. "Finding those mechanisms will be really essential for understanding whether certain properties or behaviors are really universal or not," he says.

As the team studies universal patterns on Earth, they plan to consider its biosphere as a multilayered network, where the atmospheric, geochemical, and biochemical networks interact as a coupled system. "The importance of this approach is highlighted by the recent phosphine-on-Venus debate," says Kempes. "Phosphine was detected on Venus, and the question becomes: Is it a biosignature — for Venus? In general? — and is it likely to be a false positive or a false negative? To get at those questions, you need to understand the planet's coupled networks and how different they might be with or without life in the loop."

Walker adds, "If we are to ever unambiguously detect alien life, or even know how to properly look for it, we need quantitative frameworks. We need proper theory that allows us to know what life is. The tools to do that naturally come from complex systems research."



The images used in the SFI Press volume Worlds Hidden in Plain Sight (2018) *were created using sand from SFI's Cowan Campus. (Photo: SFI Press sfipress.org)*

SFI Press explores the art of science publishing

We judge books by their covers, but also by their spines. These slim billboards teem with titles, authors, and taglines to attract the roving reader's eye. All the more jarring, then, for that eye to fall upon a spine that from a distance has no words at all. In their place flare symbols that might belong equally to a civilization chalking runes long before paper was pulped or an extraterrestrial symbology discovered eons after humans leap into the cosmos.

Open the book, however, and we find that its origins are as contemporary as it gets: this is a brand-new volume from the Santa Fe Institute, home of complexity science.

Academic publishing rarely attracts praise for aesthetics, affordability, or alacrity, but all three have defined the SFI Press since its founding in 2017. Supported by Bill Miller and the Miller Omega Program, it aims to bring new research from submission to publication within a year, at trade-book prices and in unique, collectible style.

As for the mysterious symbols on the spine? These are the SFI Glyphs.

"At SFI we are great admirers of the work of Turing and fellow codebreakers at Bletchley, as well as the doodle art of Henri Michaux, and the book notation systems of Walter Benjamin," says SFI President David Krakauer, who also serves as the Press's publisher and editor-in-chief and originated the series' distinctive look. "In what shall remain a secret conversation [between SFI Press Manager Laura Egley Taylor and artist Brian Crandall Williams] combined with a series of stochastic permutations with SFI staff, these influences and algorithms coalesced into the Glyphs."

On the shelf, Krakauer adds, those glyph-stamped spines give the impression of "an ancient artifact or ciphertext" while honoring the restrained tradition of Fitzcarraldo or Gallimard. So too does the cross-hatching of past and future circumscribe the books' original artwork, from sand grains kaleidoscoped via macro-lens to the ambitious "photo-weavings" accompanying *InterPlanetary Transmissons: Stardust*, the proceedings of the second InterPlanetary Festival.

"The idea that you can choose to create beautiful scientific texts can surprise some people," says Egley Taylor. But then again, this is SFI: a place where a single conversation might range from Turing's codebreaking to the iridescent sheen of a parakeet feather and back, and a designer is perfectly at home among physicists, computer scientists, and even a novelist or two. "There was no other way to do this."

WINTER 2020-21
Parallax
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RESEARCH BRIEFS *(continued from page 5)*

Their study, published in *Scientific Reports*, uses a novel sampling method to explore biodiversity. It finds parts of the planet that are diverse biologically and culturally are even more diverse than you'd expect.

Read the paper at doi.org/10.1038/s41598-020-76658-2

THE RHYTHM OF CHANGE

Cultural practices evolve over time, influenced by widely studied psychological factors among individuals and, likely, by environmental factors like availability of materials or physical space. However, the effects of environmental influences have not been investigated experimentally, says SFI Complexity Postdoctoral Fellow Helena Miton. In a paper published in *Proceedings of the Royal Society B*, Miton and her collaborators described the results of their experiments using three identical drums, four spatial configurations, and over 100 participants to investigate the influence of material constraints on the development of culture. Participants were divided into groups of six people. The first person listened to a simple sequence of beats played on three drums, and then attempted to replicate the rhythm. The second person listened to the first person's attempt and tried to replicate it, and so on. Miton and her collaborators studied how the rhythms changed through the transmission. They hypothesized, correctly, that over time the rhythms would diverge significantly from the original seed rhythm, and in a specific way for each configuration.

Read the paper at doi.org/10.1098/rspb.2020.2001

A NETWORK MODEL FOR IMPLICIT MEASURES OF ATTITUDES

Our attitudes are composed of an interacting constellation of feelings, beliefs, and behaviors, and these elements can be in conflict with each other. For instance, a person might believe in principles like justice and equality while simultaneously harboring negative feelings toward a minority group. Building on a network theory of human attitudes, SFI Postdoctoral Fellow Jonas Dalege and co-author Han L. J. van der Maas (University of Amsterdam) have shown why implicit measures are better suited to assess such conflicting attitude elements. Their findings are published in a new paper in the journal *Social Cognition*. Our beliefs often outweigh feelings when we ponder them, but we tend to act on our feelings and implicit biases when making quick decisions. Implicit measures, which assess attitudes in a noisier state, give a fuller, more accurate, picture of someone's attitudes, says Dalege.

Read the paper at doi.org/10.1521/soco.2020.38.supp.s26

ENTROPY PRODUCTION GETS A SYSTEM UPDATE

The Second Law of Thermodynamics tells us that the average entropy of a closed system in contact with a heat bath — roughly speaking, its "disorder" — always increases over time. Puddles never refreeze back into the compact shape of an ice cube and eggs never unbreak themselves. But the Second Law doesn't say anything about what happens if the closed system is instead composed of interacting subsystems — the complex, self-contained subsytems that compose most of the universe. New research by SFI Professor David Wolpert published in the *New Journal of Physics* considers how a set of interacting subsystems affects the second law for that system. If you consider a thing as many interacting subsystems, Wolpert says you arrive at a "stronger version of the second law," which has a nonzero lower bound for entropy production that results from the way the subsystems are connected.

Read the paper at doi.org/10.1088/1367-2630/abc5c6

IMPLICIT BIAS 'PERVASIVE' WITHIN NEUROSCIENCE

In a *Nature Reviews Neuroscience* viewpoint piece published in September 2020, SFI External Professor Danielle S. Bassett (University of Pennsylvania) helped mark the 20th anniversary of the journal by sharing thoughts about remarkable neuroscience developments during the past two decades.

Basset and her coauthors point out that implicit bias within the field of neuroscience is perhaps more pervasive now — despite more diversity in terms of sex, gender, sexual orientation, race, ethnicity, and disability. Implicit bias is reflected in peer review, paper acceptance rates, grant funding, and a growing (rather than diminishing) undercitation of women in reference lists of neuroscience journal articles within the past 20 years. "Each of us as citizens of science can choose to own and mold our culture to realize a more equitable future," she says.

Read the paper at doi.org/10.1038/s41583-020-0363-6

PREVENTING ECOSYSTEM TIPPING POINTS

To help prevent ecosystems on Earth from reaching their tipping points, SFI External Professor Ricard Solé (Universitat Pompeu Fabra) and colleagues are turning to synthetic biology — with a twist on the old concept of terraforming or "Earth forming" on Mars to be used to save our own planet.

In a *Royal Society Open Science* paper published in August 2020, they explore the concept of ecosystem terraformation, in which a synthetic organism is used to counterbalance some nonlinear effects causing the tipping points. "Many ecosystems may experience catastrophic decays within this century," says Solé. "We need to explore new avenues to prevent it, and develop new interdisciplinary approaches and engineering strategies. We've been modifying the Earth by exploiting resources to build our civilization, but now our actions must help save the biosphere and ourselves."

Read the paper at doi.org/10.3390/life10020014

METABOLIC SCALING THEORY FOR ROBOT SWARMS

A group of researchers recently designed a scalable architecture for a large swarm of robots to collect resources from an expansive area, such as the surface of Mars, and bring them back to a base station. In a paper published by IEEE in 2020, SFI External Professor Melanie Moses (University of New Mexico) and her students describe putting metabolic scaling theory to the test with swarms.

In 2D, they found that a hierarchical branching network that mimics a cardiovascular network increases per-robot efficiency to -1/3 power of the swarm size, consistent with the theory. They also used the theory to predict the size of robot depots — essentially dump trucks — required on each branch of the network to overcome scaling constraints and produce scale-invariant foraging. "We show in simulations of thousands of robots, and a proof of concept with a real robot depot, that scaling theory provides a blueprint for an engineered network with near-perfect scaling," says Moses. "Every robot is equally efficient no matter the size of the swarm."

Read the paper at doi.org/10.1109/ICRA40945.2020.9196762