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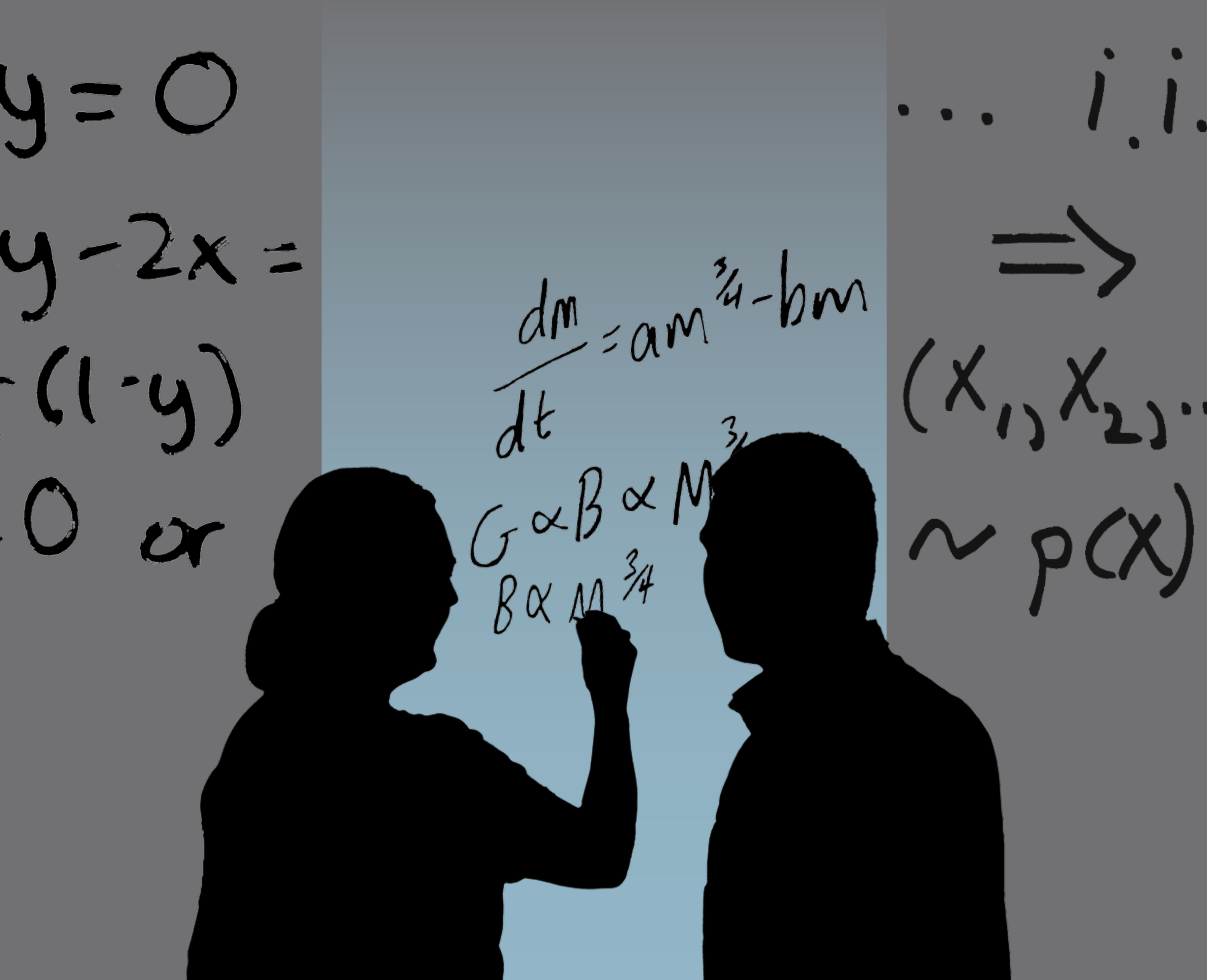
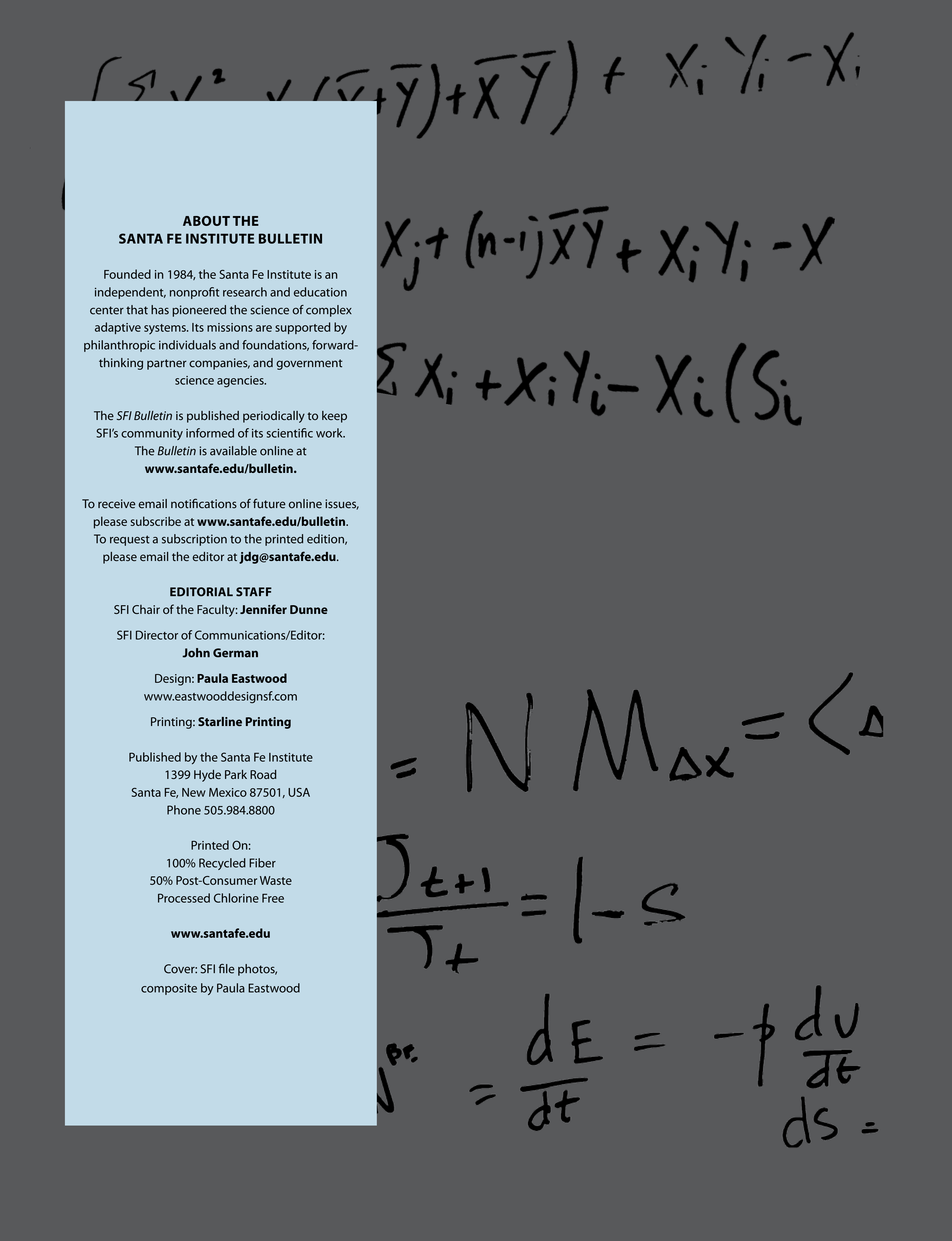
2014, Volume 28, Issue 2

SFI@30

FOUNDATIONS AND FRONTIERS





ABOUT THE SANTA FE INSTITUTE BULLETIN

Founded in 1984, the Santa Fe Institute is an independent, nonprofit research and education center that has pioneered the science of complex adaptive systems. Its missions are supported by philanthropic individuals and foundations, forward-thinking partner companies, and government science agencies.

The *SFI Bulletin* is published periodically to keep SFI's community informed of its scientific work. The *Bulletin* is available online at **www.santafe.edu/bulletin.**

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SFI@30

A VIEW OF SFI'S FOUNDATIONS & FRONTIERS


MINESH BACRANIA PHOTOGRAPHY

On the Institute's 30th anniversary, even as we imagine tomorrow's intellectual frontiers, we take a moment to recount the three decades that saw SFI's birth and its development as the world center for complex systems research. The seven essays in this issue of the *Bulletin* present brief, personal stories about several deeply transdisciplinary topics that our founders and their colleagues grappled with during the Institute's first decade and since.

These (and the many other important SFI scientific themes not covered here) serve to demonstrate SFI's unique role and important contributions to the scientific landscape. With the early programs in complexity economics and adaptive computation, for example, the Institute quickly established itself as *the* incubator for science that challenges conventional wisdom and addresses previously unasked questions – questions that normally fall into the cracks between traditional research disciplines.

SFI also quickly became the "go to" place for bringing novel quantitative approaches to bear on existing questions, as we see in the essays about research on the origins of life, scaling theory, and human history. And, given the backdrop of emergence as a core organizing concept, SFI established itself as a place to pursue the broadest cross-cutting themes by asking what, if anything, all complex systems have in common.

Today, SFI continues to cast a wide net while diving deep. It does this by building on its early foundations of asking big questions, ignoring boundaries, applying computational and analytical approaches, and developing and testing quantitative theory. This is the spirit of inquiry that we, the inheritors of this grand intellectual experiment, are grateful to continue and expand on for the next 30 years and beyond.

Jennifer Dunne
Professor
Vice President for Science
Santa Fe Institute

From Passionate Curiosity
TO EMERGENT SCIENCE

On a Saturday evening in November 1984, as the second of the Institute's two exploratory founding workshops wound to a close, our founders – George Cowan, Murray Gell-Mann, David Pines, and their colleagues – knew at last they had in their net a new and rather charming species of scientific inquiry.

Decades before, mathematician and meteorologist Edward Lorenz had proffered the "butterfly effect" as a metaphor for how seemingly inconsequential changes to the initial conditions of a dynamical system could profoundly influence the later state of that system; theoretically, he speculated, disturbances caused by the flapping of a butterfly's wings in Brazil could set up the conditions for a tornado in Texas (later dramatized as a hurricane).

What utterances might have stirred the minds of the workshop participants and set up the conditions for SFI-style science, we can never know. But we can ask what intervened – what happened between the butterfly and the tornado? For this issue, a tribute to SFI's 30th anniversary, I asked some of SFI's people to trace for us a few of the themes that have endured here across the decades.

These seven essays are by no means a comprehensive look at the history of thought at SFI. (Can you imagine the heft of such a volume?) You'll easily spot as many omissions as essays. Nor are these seven authors representative of the many contributors and lineages of thought within each theme. The authors are individuals, and as such they come with particular perspectives that you might find too narrow, or not narrow enough.

So be it. I am grateful to each of them for sharing the SFI adventure as she or he experienced it. I hope this issue promotes more of the compelling and daring transdisciplinary thought we can and should expect from the Santa Fe Institute.

John German
Director of Communications
Santa Fe Institute

BUTTERFLY: LINCOLN NATIONAL FOREST/USFS; HURRICANE KATRINA: NASA; BACKGROUND RIPPLE: ISTOCKPHOTO.COM

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ECONOMICS

Complexity:

A DIFFERENT WAY TO LOOK AT THE ECONOMY

BY W. BRIAN ARTHUR
External Professor, Santa Fe Institute;
Visiting Researcher, Palo Alto Research Center

Left: W. Brian Arthur. **Above:** 18th century moral philosopher Adam Smith coined the term "invisible hand," later interpreted as a metaphor for an unseen self-regulating force that guides a market towards its natural equilibrium.

Economics is a stately subject, one that has altered little since its modern foundations were laid in Victorian times. Now it is changing radically. Standard economics is suddenly being challenged by a number of new approaches: behavioral economics, neuroeconomics, new institutional economics. One of the new approaches came to life at the Santa Fe Institute: complexity economics.

Complexity economics got its start in 1987 when a now-famous conference of scientists and economists convened by physicist Philip Anderson and economist Kenneth Arrow met to discuss the economy as an evolving complex system. That conference gave birth a year later to the Institute's first research program – the Economy as an Evolving Complex System – and I was asked to lead this. That program in turn has gone on to lay down a new and different way to look at the economy.

To see how complexity economics works, think of the agents in the economy – consumers, firms, banks, investors – as buying and selling, producing, strategizing, and forecasting. From all this behavior markets form, prices form, trading patterns form: aggregate patterns form. Complexity economics asks how individual behaviors in a situation might react to the pattern they together create, and how that pattern would alter itself as a result, causing the agents to react anew.

This is a difficult question, so, traditionally, economics has taken up a simpler one. Conventional economics asks how agents' behaviors (actions, strategies, forecasts) would be upheld by – would be consistent with – the aggregate patterns these cause. It asks, in other words, what patterns would call for no changes in micro-behavior, and would therefore be in stasis or equilibrium.

The standard, equilibrium approach has been highly successful. It sees the economy as perfect, rational, and machine-like, and many economists – I'm certainly one – admire its power and elegance. But these qualities come at a price. By its very definition, equilibrium filters out exploration, creation, transitory phenomena: anything in the economy

LEFT PAGE: IAN TUTTLE, PORCUPINE PHOTOGRAPHY; THIS PAGE: WIKIMEDIA COMMONS


FOTOSEARCH.COM

The economic crisis that began in 2008 caused many economists to look for new ways to understand temporary phenomena such as bubbles and crashes.

that takes adjustment – adaptation, innovation, structural change, history itself. These must be bypassed or dropped from the theory.

By the mid 1980s, many economists were ready for a change.

Just what that change would consist of we were not quite sure when our program began. We knew we wanted to create an economics where agents could react to the outcomes they created, where the economy was always forming and evolving and not necessarily in equilibrium. But we didn't quite know how to achieve that.

In fact, in 1988 the Institute was still very much a startup. The program consisted in its first two years of 20 or so people, several of whom proved central: John Holland, Stuart Kauffman, David Lane, and Richard Palmer. We would meet, in an early version of what became Santa Fe style, in the kitchen of the old convent on Canyon Road in the late mornings and loosely discuss ways forward.

These "emerged" slowly – sometimes painfully – mainly by talking over why economics did things the way it did and how alternatives might work. Our group was motley, even eccentric. Halfway through the first year the journalist James Gleick asked me how I would describe my group. I was hard put to reply. He pressed the question. Finally I said, "You remember the bar in Star Wars, at the end of the galaxy with all the weird creatures, Chewbacca and the others? That's our group."

We did have some tools. We had new stochastic dynamic methods, and nonlinear dynamics, and novel ideas from cognitive science. And of course we had computers. But it took us a couple of years before we realized we were developing an economics based not just on different methods, but on different assumptions.

Instead of seeing agents in the economy as facing perfect, well-defined problems, we allowed that they might not know what situation they were in and would have to make sense of it. Instead of assuming agents were perfectly rational, we allowed there were limits to how smart they were. Instead of assuming the economy displayed diminishing returns (negative feedbacks), we allowed that it might also contain increasing returns (positive feedbacks). Instead of assuming the economy was a mechanistic system operating at equilibrium, we saw it as an ecology – of actions, strategies, and beliefs competing for survival – perpetually changing as new behaviors were discovered.

Other economists – in fact some of the greats like Joseph Schumpeter – had looked at some of these different assumptions before, but usually at one assumption at a time. We wanted to use all these assumptions together in a consistent way. And other complexity groups in Brussels, France, Ann Arbor, and MIT were certainly experimenting with problems in economics. But we had the advantage of an interdisciplinary critical mass for a program that ran across all of economics.

We had the advantage of an **interdisciplinary critical mass** for a program that ran across all of economics. The result was an approach that saw economic issues as playing out in a system that was **realistic, organic, and always evolving.**

The result was an approach that saw economic issues as playing out in a system that was realistic, organic, and always evolving.

Sometimes we could reduce the problems we were studying to a simple set of equations. But just as often our more challenging assumptions forced us to study them by computation. We found ourselves creating "artificial worlds" – miniature economies within the computer – where the many players would be represented by little computer programs that could explore, respond to the situation they together created, and get smarter over time.

Our artificial-worlds-in-the-computer approach, along with the work of others both inside and outside economics, in the early 1990s became agent-based modeling, now a much-used method in all the social sciences.

One early computer study we did was a model of the stock market. In a stock market, investors create forecasts from the available information, make bids and offers based on these, and the stock's price adjusts accordingly. Conventional theory assumes homogeneous investors who all use identical forecasts (so-called "rational expectations" ones) that are consistent with – on average validated by – the prices these forecasts bring about. This gives an elegant theory, but it begs the question of where the identical forecasts come from. And it rules out transitory phenomena seen in real markets, such as bubbles and crashes and periods of quiescence followed by volatility.

We decided to have "artificial investors" in our computer create their own individual forecasts. They would start with random ones, learn which worked, form new ones from these, and drop poorly performing ones. Forecasts would thus "compete" in a mutually-created ecology of forecasts. The question was how would such a market work? Would it duplicate the standard theory? Would it show anything different?

When we ran our computerized market, we did see outcomes similar to those produced by the standard theory. But we saw other phenomena, ones that appeared in real markets. Some randomly-created forecasts might predict upward price movement if previous prices were trending up; other types of forecasts might foretell a price fall if the current price became too high. So if a chance upward movement appeared, the first type would cause investors to buy in, causing a price rise and becoming self-affirming. But once the price got too high, the second sort of forecast would kick in and cause a reversal. The result was bubbles and crashes appearing randomly and lasting temporarily.

Similarly, periods of quiescence and volatility spontaneously emerged. Our investors were continually exploring for better forecasts. Most of the time this created small perturbations.

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A crowd gathers outside the New York Stock Exchange during the stock market crash of 1929. Complexity economics seeks to understand market perturbations as emergent phenomena arising from the actions and reactions of many agents.

But occasionally some would find forecasts that would change their behavior enough to perturb the overall price pattern, causing other investors to change their forecasts to re-adapt. Cascades of mutual adjustment would then ripple through the system. The result was periods of tranquility followed randomly by periods of spontaneously generated perturbation – quiescence and volatility.

The program, as it developed, studied many other questions: the workings of double-auction markets; the dynamics of high-tech markets; endogenously-created networks of interaction; inductive reasoning in the economy. In an SFI program parallel to ours, Josh Epstein and Rob Axtell created an artificial society called "Sugarscape" in which cooperation, norms, and other social phenomena spontaneously emerged. And in 1995 John Miller and Scott Page started an annual workshop in computational social sciences at SFI where postdocs and graduate students could get practical training in the new methods.

The approach finally received a label in 1999, when an editor at *Science* asked me on the phone to give it a name. I suggested "complexity economics," and that name stuck.

Things have widened a great deal since then. Doyne Farmer has taken up studies of how technologies improve over time. And he, Axtell, and others have been using large datasets, along with agent-based modeling methods, to understand the recent housing-market crisis. Other groups in the U.S. and Europe have been using complexity methods to look at economic development, public policy, international trade, and economic geography.

None of this means the new, non-equilibrium approach has been easily accepted into economics. The field's mainstream has been interested but wary of it. This changed in 2009 after the financial meltdown when, as the *Economist* magazine observed dryly, the financial system wasn't the only thing that collapsed; standard economics had collapsed with it. Something different was needed, and the complexity approach suddenly looked much more relevant.

Where does complexity economics find itself now? Certainly, many commentators see it as steadily moving toward the center of economics. And there's a recognition that it is more than a new set of methods or theories: it is a different way to see the economy. It views the economy not as machine-like, perfectly rational, and essentially static, but as organic, always exploring, and always evolving – always constructing itself.

Some people claim that this


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In complexity economics, an economy is treated as an ecology of actions, strategies, and beliefs competing for survival – and perpetually changing as new behaviors are discovered.

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All the buying, selling, producing, strategizing, forecasting, and reacting by individual agents in an economy produces sometimes unexpected aggregate patterns.

economics is a special case of equilibrium economics, but actually the reverse is true. Equilibrium economics is a special case of nonequilibrium and hence of complexity economics.

Complexity economics is economics done in a more general way.

In 1996 an historian of economic thought, David Colander, captured the two different outlooks in economics in an allegory. Economists, he says, a century ago stood at the base of two mountains whose peaks were hidden in the clouds. They wanted to climb the higher peak and had to choose one of the two. They chose the mountain that was well defined and had mathematical order, only to see when they had worked their way up and finally got above the clouds that the other mountain, the one of process and organicism, was far higher. Many other economists besides our Santa Fe group have started to climb that other mountain in the last few years. There is much to discover. ◀

W. Brian Arthur is an External Professor at the Santa Fe Institute and a Visiting Researcher at PARC in California. He has served on the Institute's Science Board and Board of Trustees. Formerly at Stanford, he is the recipient of the inaugural Lagrange Prize in Complexity Science and the Schumpeter Prize in Economics. His book, Complexity and the Economy *(Oxford University Press) appeared in 2014.*

IAN TUTTLE, PORCUPINE PHOTOGRAPHY

THIRTY YEARS OF RESEARCH ON THE ORIGIN OF LIFE

BY HAROLD MOROWITZ

Science Board Chair Emeritus, Santa Fe Institute;
Clarence J. Robinson Professor of Biology and Natural Philosophy, Krasnow Institute, George Mason University

Right: Harold Morowitz. **Above:** Gathered around SFI's first workstations during the 1987 "Matrix of Biological Knowledge" workshop in Santa Fe are (clockwise from back left) Jotun Hein, Chris Overton, Kimberle Koile, and an unknown participant.

Biogenesis – the generation of a life form from nonliving material – was among the first topics of interest at SFI. Manfred Eigen and Peter Schuster were early consultants. Their 1978 paper on "The Emergence of Hypercycles," which postulated the self-reinforcing linkage of reaction cycles as an explanation for the self-organization of prebiotic systems, was the kind of big-question research envisioned for Santa Fe, and the paper was widely acclaimed for its potential to advance the study of life's origin.

Over SFI's 30-year history, these two leading scientists have served on the Institute's Science Board, as journal editors, and as external faculty and visitors, and they continue to serve today.

By 1987, the explosion of computer studies in biology led to the call for a summer workshop on what we called the "Matrix of Biological Knowledge." Having obtained modest support from the National Institutes of Health (NIH), the Department of Energy (DOE), and the Sloan Foundation, the workshop's organizing committee – made up of representatives chosen by the funding organizations – was looking for an institution that could supply housing and flexible work space, and that would not eat up our limited funds in overhead.

George Bell of Los Alamos National Lab (LANL), who was a consultant to the group, told the planning committee about the newly born Santa Fe Institute, the Institute's cooperative arrangement for meeting space with St. John's College, and his perception of a willingness on SFI's part to negotiate overhead with programs that fit their vision.

A few weeks later, George Cowan and I were in the Mother Superior's office in the newly rented Cristo Rey Convent, the Institute's then-headquarters. We negotiated with remarkable speed. After all, we needed each other, and Cowan introduced Ginger Richardson, who was to handle our arrangements with St. John's.

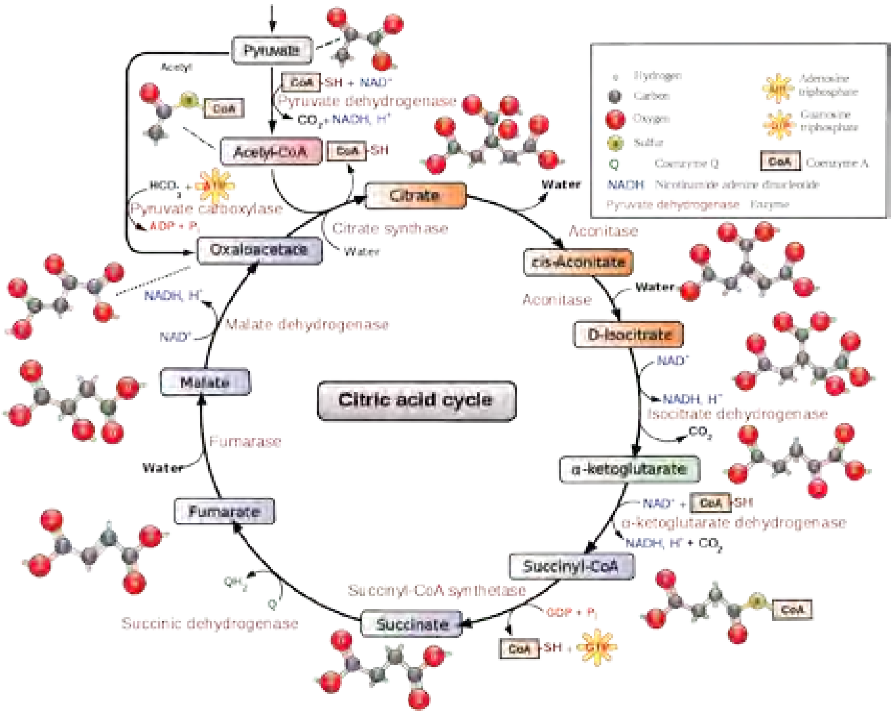
The summer program was to be run by biophysicist Temple Smith, then of Harvard; James Willett, then of NIH; and myself, then of Yale. We recruited a faculty to be in attendance from one day to one month. Advertisements in the journals *Nature* and *Science* brought us 29 participants, largely graduate students, postdocs, junior faculty members, and industrial representatives.

A few computers on loan from IBM put us in business. Within a week of starting, the

RIGHT: NERISSA ESCANLAR; ABOVE: SFI ARCHIVE

Reading **George Cowan's memoir** 20 years later I saw his hidden hand at work. He wrote: "I felt that the Morowitz/Kauffman interests represented the potentially most important theme at SFI and gave them my full support." **I suspect Kauffman and I still have a bit of arguing to do.** — Harold Morowitz biologists and chemists were at the keyboards and the computer scientists were poring over Lehninger or Stryer, leading scholars whose textbooks shed light on our emerging understanding of bioenergetics and metabolic chemistry. (For those interested, a 200-page report of the summer's activity is still available.)

Under Cowan's unseen hand, we were visited by Garrey Carruthers, then-Governor of New Mexico; Charles DeLisi of DOE; and Pete Domenici, then-U.S. Senator from New Mexico. Thus, the broader world was informed of what we were up to. My invitations brought William Gay of NIH, James Rodman of the National Science Foundation (NSF), and Harold Schoolman of the National Library of Medicine, who helped introduce us to the scientific community. The list of faculty and attendees of this workshop are now among the leaders in biological computer informatics and large-scale databases, names like Bruce Schatz, Peter Karp, Jotun Hein, Anthony Nicholis, and Chris Beecher.



The citric acid cycle is a series of chemical reactions used by aerobic living organisms to generate energy. The cycle provides precursors for the biosynthesis of compounds.

Thoughts about life's origin were among the many perspectives being discussed at St. John's that summer. Around that time, MacArthur Fellow Stuart Kauffman was putting his thoughts to biogenesis at the SFI convent, and Chris Langton at LANL was developing the construct of Artificial Life (A-life). Langton's vision led to major conferences and publications that established the field and its relation to life's origin. He joined the institute in 1991. Kauffman was establishing a viewpoint that autocatalytic loops could self-select from very complex chemical arrays and lead to highly ordered biochemistry. New disciplines were being established.

When I got involved with SFI after the 1987 workshop, the discovery of reductive autotrophs – bacteria growing in the absence of oxygen and synthesizing all organics from one-carbon compounds (i.e., carbon dioxide, carbon monoxide, methane, methanol) – was leading me to the notion of biochemical complexity emerging from the simplicity of the periodic table of elements. Reading George Cowan's memoir 20 years later I saw his hidden hand at work. He wrote: "I felt that the Morowitz/Kauffman interests represented the potentially most important theme at SFI and gave them my full support." I suspect Kauffman and I still have a bit of arguing to do on these approaches.

Walter Fontana arrived at SFI in 1991, beginning a very different and more mathematically formal approach to life's origin. He began a collaboration with Leo Buss of Yale that has been well described by science author and journalist George Johnson in his book *Fire in the Mind*: "In the early 1990s Fontana, the Santa Fe Institute

NOAA

Researchers searching for the origin of life have discovered some of the deepest-branching organisms on the tree of life in extreme environments found near hydrothermal vents and chimneys on the ocean floor.

chemist, and his colleague, the Yale biologist Leo Buss, began collaborating on a theory of how life arose and then arrayed itself in a grand architecture of tiers piled on tiers." They were among the original developers of algorithmic chemistry, an important theoretical approach. With his SFI association continuing in one capacity or another, Fontana has developed sophisticated formal approaches to chemistry and how chemical complexity emerges.

Andreas Wagner attended the 1993 SFI summer school and thus began another long-term association as a scientist interested in fundamental questions relating to originating and maintaining planetary life. He was one of the first to stress the importance of metabolism and the metabolic chart. This interest in metabolism is reflected in the work of other SFI researchers since.

Steen Rasmussen was at LANL (beginning in 1988), and he has maintained a constant interaction with scientists at SFI with shared interests in A-life, the origin of life, and synthetic biology. Many of the fundamental studies he has contributed to have been of interest to the origin of life community. He has focused on the physics of complexity and the difference between living and nonliving materials.

In 2000 Eric Smith joined SFI, first as a postdoc, then as faculty, and in 2011 as external faculty. Since the origin of life has been one of his central areas of scholarly research, his work has provided a nucleus for Shelley Copley (University of Colorado), Rogier Braakman, and myself to maintain an ongoing research collaboration on biogenesis during these years.

Discussing our work with the late Carl Woese of the University of Illinois in the early 2000s led to a key moment in origin of life research at SFI when we sought and were awarded a major multi-institution NSF grant titled "From Geochemistry to the Genetic Code." The five-year grant (2005–2010), which was stretched to eight, was centered at the Institute. The principle investigators were Eric Smith (SFI), myself (SFI and George Mason University), Shelley Copley, Nigel Goldenfeld and Carl Woese (University of Illinois), and George Cody (Carnegie Institute of Washington's Geophysics Laboratory). One of the ongoing activities was a one-week conference each summer that provided an opportunity for researchers from diverse disciplines to discuss interdisciplinary problems. The breadth of interest at SFI provided a milieu for this approach.

From 2011 to 2013 while he was at SFI, Rogier Braakman worked on intermediary metabolism, carbon incorporation, and phylogeny. This continued the studies of the NSF program at SFI. He made outstanding progress in the emergence and early evolution of biological carbon fixation.

The NSF grant called for two important outreach activities: a summer school for high school science teachers on the origin of life, one in Santa Fe and another in Fairfax, Virginia; and establishment of a cooperative project with the office of the Secretary of Cultural Affairs of the State of New Mexico (represented by Mimi Roberts) and New Mexico Highlands University to develop a museum

WIKIMEDIA COMMONS/PAUL HARRISON

Stromatolites, pillars formed by the sedimentary deposit of microorganisms, are evidence of the first single-celled microbial life thought to have arisen some 3.5 billion years ago. Here, modern stromatolites in Shark Bay, Australia.

presentation on the origin of life. That exhibit, completed in 2012, is now on permanent display at the Museum of Natural History in Albuquerque and offers an accessible summary of the current understanding of the chemical origin of life.

Where are we today? The thrust of the SFI approach has brought us to the point where we understand that life is a planetary phenomenon, and we comfortably accept life as the fourth geosphere along with the lithosphere, the atmosphere, and the hydrosphere. We are comfortable about minerals evolving along with the biota. Core metabolism is on the order of 3.8 billion years old and intermediary metabolism has been relatively unchanged over that period. Life's emergence consists of layers separated by phase changes (floors and ceilings), leading to separable entities and eventually to individuality, making Darwinian evolution possible.

We have an impressive and growing understanding of the chemistry and geochemistry that take us from the periodic table of the elements to the monomer level. Polymers present a level of complexity with a far greater range of chemical sophistication. An active site may be influenced by four or five side chains, allowing a combinatoric explosion of possibilities tamed by the underlying small-molecule ecological constraints.

This is an aspect of the emergence of cells and the protein nucleic acid coding for which we still lack a satisfactory theoretical approach. There are three higher forms of organization: the emergence of ribosomal translation of peptides and with it a genetic code, the integration of redox and phosphate energy systems, and the compartmentalization observed in cells.

In other words, we are able to describe levels of complexity known to exist in present-day organisms, but we lack a satisfactory understanding of how they became that way. This constitutes a challenge to today's scientists interested in the origin and complexity of life.

The answers to these still-big questions loom over the Sangre de Cristo Mountains and in the minds of the scientists here and around the world. Extracting them should provide the Institute and other scientists plenty to do in this area for the next 30 years. ◀

Harold Morowitz is the Clarence J. Robinson Professor of Biology and Natural Philosophy, Krasnow Institute, George Mason University, and Science Board Chair Emeritus of the Santa Fe Institute. His career research focus has been the application of thermodynamics to living systems and the origin of life on earth. He has made foundational contributions in the fields of biophysics, biochemistry, and molecular biology. He was the founding editor of the journal Complexity.

NERISSA ESCANLAR

THE MURRAY GELL-MANN FUND

Murray Gell-Mann was awarded the 1969 Nobel Prize in physics for his groundbreaking work on elementary particle physics. At the Santa Fe Institute, he has been a central figure in developing the emerging field of complex systems science.

Please help us create a scientific legacy here at SFI by making a gift to honor Murray Gell-Mann's lifetime of scientific achievement.

Make your gift today to support the Murray Gell-Mann Fund.

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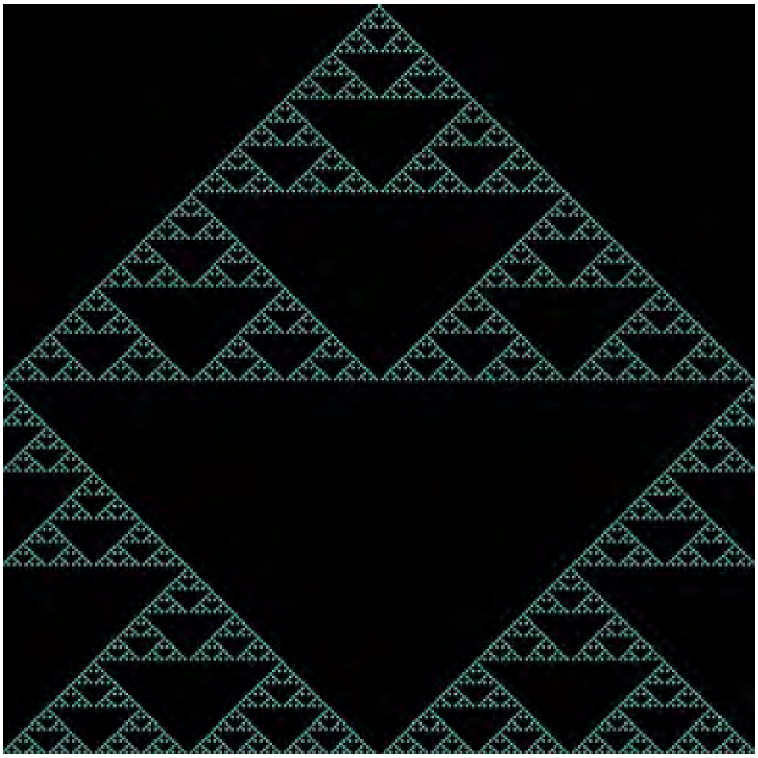
INFORMATION, ADAPTATION, AND EVOLUTION **IN SILICO**

BY MELANIE MITCHELL
Professor, Computer Science,
Portland State University;
External Professor, Santa Fe Institute



Left: Melanie Mitchell. **Above:** SFI researchers explored the use of genetic algorithms to automatically evolve computational structures, including cellular automata – a collection of "colored" cells on a grid that iterates through a number of time steps according to simple rules and often resulting in surprising patterns.

LEFT PAGE: MINESH BACRANIA PHOTOGRAPHY;
THIS PAGE: CREATED BY MELANIE MITCHELL USING NETLOGO

In 1984 the nascent Santa Fe Institute sponsored two workshops on "Emerging Syntheses in Science," at which the Institute's founders brainstormed their plans for the future. At the time I was a beginning graduate student in computer science and had never heard of SFI, but reading the workshop proceedings a few years later, I was very excited by the Institute's goal to "pursue research on a large number of highly complex and interactive systems which can be properly studied only in an interdisciplinary environment."

The founders planned to define particular themes or programs that would benefit from the kind of intensive cross-disciplinary interaction offered by the new institute. SFI's first official program, formed in 1987, was Economics. Before long, several influential players in the field took note of SFI's novel interdisciplinary approach to economics, and the program grew quickly, in fact threatening to take over the fledgling organization.

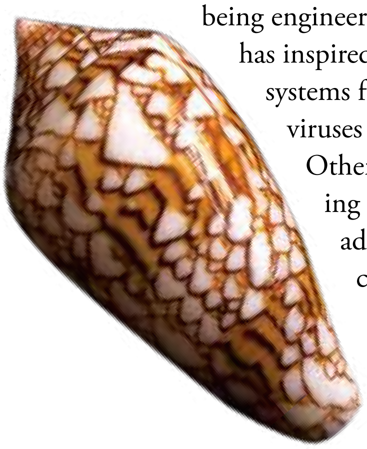
Founder and first SFI President George Cowan wanted to make sure economics did not come to dominate. Cowan wrote: "We had to start somewhere, but we also had to make sure from the beginning that economics didn't become the one interest of the institute…I pushed hard to support at least one other program that would be equal in size to the economics program. We needed to broaden our academic agenda, and spread our bets." Cowan's push was to start a program in "adaptive computation."

What is adaptive computation?

Adaptive computation is a broad area that covers three major threads of computing in the context of complex adaptive systems:

Agent-based simulation: In science, computers have traditionally been used to perform "numerical simulation" – using mathematical equations to simulate behavior in physical systems, such as turbulence in fluids and missile trajectories in space. But in most systems of interest to SFI – economics and other social systems being prime examples – it's hard, if not impossible, to find a set of equations that describes these multi-agent, open-ended, evolving systems. Instead, the study of complex systems has pioneered computational agent-based simulation, in which the behaviors of individual system components ("agents") and their interactions are explicitly simulated, rather than simulating the behavior of equations describing the system as a whole. Agent-based simulation has become a mainstay of research in complex systems ranging from gene networks to financial markets.

Nature-inspired computation: Computers themselves can be made more adaptive and lifelike by adopting ideas from natural adaptive systems. This idea goes back to the beginnings of the computer age, when trailblazers such as Alan Turing and John von Neumann were thinking hard about the connections between programmable computers and living systems. Since that time, theories about the brain have inspired computational neural networks that learn on their own; the theory of Darwinian evolution has inspired genetic algorithms in which programs evolve via computational "natural selection" rather than being engineered by humans; and immunology has inspired software-based artificial immune systems for computers to fight computer viruses and other so-called malware. Other inspirations for new computing methods have come from natural adaptive systems as diverse as ant colonies, slime molds, economic markets, and social networks.



Patterns created via adaptive computational models often resemble those found in nature.

LEFT: NICK ZANTOP, CREATIVE COMMONS/SHAREALIKE 3.0

Computation as a framework for understanding nature: The idea of computation goes beyond what we traditionally call "computers." As former SFI scientist Chris Langton eloquently put it: "The proper domain of computer science is information processing writ large across all of nature." A key property of complex adaptive systems is their ability to process information – to compute – in order to adapt and thrive in an environment. Thus, the concepts and theories of computer science can themselves be adapted to provide a scientific language for understanding information processing in the natural world.

SFI's Adaptive Computation Program

SFI's Adaptive Computation (AC) program originated from the work of John Holland at the University of Michigan in the 1960s and 70s. Holland developed cross-disciplinary theories of adaptation, as well as computer models of evolution and learning. Genetic algorithms (methods for "evolving" programs and other computer structures) were Holland's invention, as were classifier systems (evolving rule-based learning systems) and the "Echo" model (an agent-based model of an evolving ecosystem).

Holland was originally recruited to be SFI's first resident faculty member and to lead the AC program. However, after much thought, he decided to stay at Michigan, albeit with frequent visits to SFI (which continued for 30 years). John Miller, who was Holland's collaborator and SFI's first postdoc, took over direction of the program and organized its 1992 founding workshop, which brought together many of the leading thinkers in areas related to adaptive computation. Miller, however, was soon leaving for a faculty position at Carnegie Mellon University, so another director had to be found.

I had come to the University of Michigan in 1984 to work on artificial intelligence (AI) with Douglas Hofstadter. During my first year there I took John Holland's course, "Adaptation in Natural and Artificial Systems." I was enchanted by the beautiful theory developed by Holland and

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amazed by the abilities of genetic algorithms to evolve sophisticated programs and designs. My focus was still on my AI work with Hofstadter, but I made time to work with Holland and his students (particularly Stephanie Forrest) on genetic algorithms. Holland became my co-advisor. After graduating with a Ph.D. in 1990, I was offered a postdoctoral fellowship in the Michigan Society of Fellows, to work primarily with Holland on genetic algorithms.

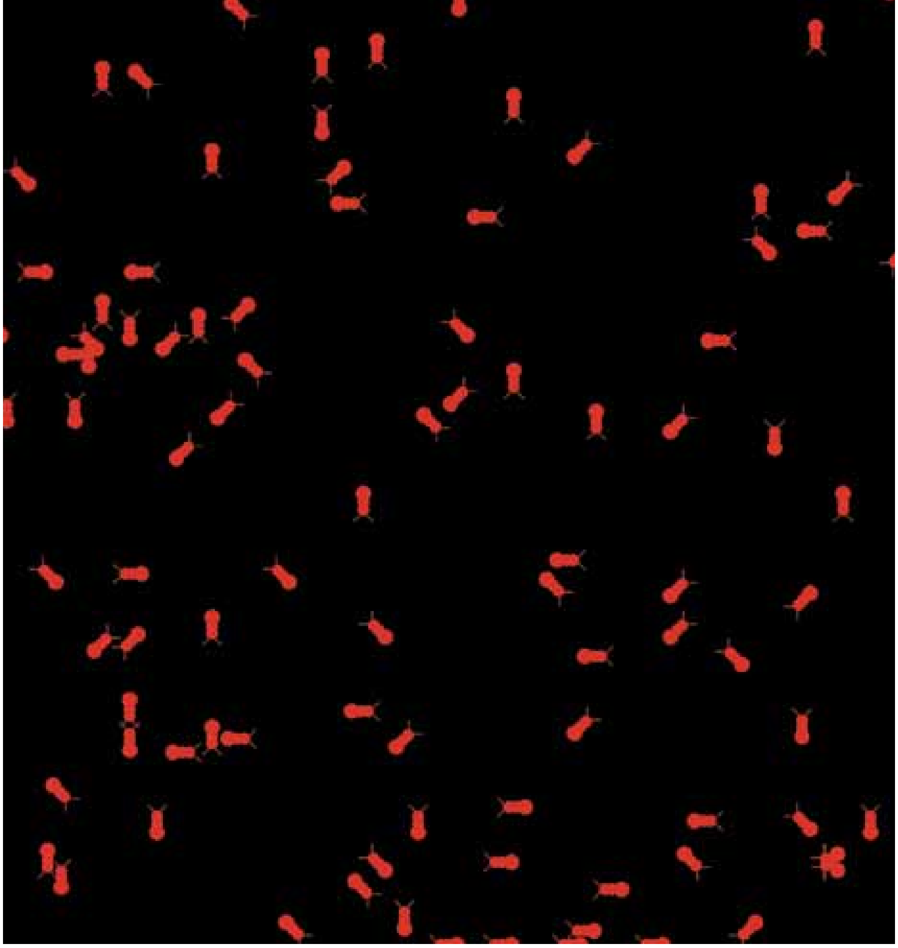
In early 1992, Holland asked me if I might want to come to SFI for the next academic year to direct the AC program. I jumped at the chance. For a young postdoc, it was the opportunity of a lifetime, and I somehow managed to stretch a single year as a visitor into six years as a resident professor at SFI. Over the six years of its existence, the AC program's resident and visiting researchers made significant impacts in all three of the threads described above.

Here I summarize some prominent examples of results from this program:

Computer models of adaptive systems: SFI's AC program promoted sustained collaborations between computer scientists and evolutionary biologists in building models of biological evolution at different scales. In addition, scientists in the program built extensively on Holland's work on genetic algorithms and classifier systems; his thoughts about energy flow in ecologies were formalized in the "Echo" model (developed by Holland, Terry Jones, and Stephanie Forrest).

Stephanie Forrest and Alan Perelson pioneered work on agent-based modeling of the adaptive immune system. AC program researchers also collaborated with economists, creating agent-based models of economic markets in which the agents (like real-world decision makers in an economy) had limited rationality and knowledge, but were able to adapt and learn. This notion of adaptive economic agents has become a central aspect of what is now called complexity economics.

Finally, the AC program included several visitors who worked on agent-based models of human and animal learning and on the



CREATED BY MELANIE MITCHELL USING NETLOGO

Modeling the dynamics of "swarm intelligence" using principles from insect colonies was among the early research of SFI's Adaptive Computation program.

interaction between learning and evolution. These modeling efforts were variously based on genetic algorithms, classifier systems, neural networks, and dynamical systems.

Nature-inspired computation: A few examples of the program's wide-ranging research included development of computational "immune systems" that used immunological principles to recognize computer viruses and network attacks and set up a defense; the use of genetic algorithms to automatically evolve computational structures such as computer programs, neural networks, and cellular automata; the implementation of "swarm intelligence" using principles from insect colonies; and the simulation of host-parasite co-evolution in order to improve the performance of learning programs ("hosts") on the data they learn from ("parasites").

I'll expand a bit on one of these examples. SFI's Jim Crutchfield and I led the "Evolving Cellular Automata" group. Our research focused on using genetic algorithms to evolve cellular automata to perform "emergent computation." Invented in the 1940s by computing pioneers John von Neumann and Stanislaw Ulam, a cellular automaton is a grid of simple (simulated) "cells." In our formulation, each cell can be in one of two "states" – black or white – and is connected to a small number of neighboring cells. At each time step, each cell updates its state (either staying the same color or changing color) depending on the states of its neighbors.

In a given cellular automaton, each cell obeys the same "rule" in updating its state, but different cellular automata can have different rules. Our group's work was on using genetic algorithms to evolve cellular automata rules that would enable a cellular automaton to act as a specialized sort of computer. We showed that this was not only possible, but that the genetic algorithm was able, in many cases, to discover more sophisticated "solutions" than had been created by humans working on the same problem.

Computation as a framework for understanding nature: The SFI AC program included several computer scientists (including myself) who were intensely interested in what their field could offer to the study of natural systems beyond the development of modeling algorithms and tools. A major focus was to understand how the complex dynamics we observe in many natural systems give rise to information processing.

As one example, we found that cellular automata produced by our genetic algorithm exhibited dynamical patterns that roughly resembled physical particles moving through a medium, colliding, and producing new particles. We were able to show that these cellular-automata-based "particles" were the locus of information storage: their movements through the grid affected information transfer, and their collisions were the sites of information processing.

In this way, we were able to make sense of the emergent computational properties of a cellular automaton in terms of its underlying dynamics. This is a novel approach to understanding computation that has had impacts ranging from new ideas for the design of nanoscale computers to the understanding of how plants process information to regulate the balance between their water intake and carbon dioxide output.

Impact of SFI's AC program

The examples of research I've described above, and many others, put SFI on the map as a key, well-respected player in adaptive computation. In addition to the many publications written and invited lectures given by program members, there was one particularly impressive honor.

In 1997, five years after the AC program's founding, *Business Week* polled a large group of researchers for the answer to this question: "If you were 35 and had just won the first Nobel Prize for Information Technology, triggering invitations to the lab of your choice, which one would you pick?" Once the votes were counted, *Business Week* published the top-ten list, which included Stanford, Berkeley, MIT, Bell Labs, Microsoft, and similar institutions. Of these, tiny SFI was tied for 5th. And when the question was restricted to labs focusing on biologically inspired computation, SFI moved up to first place.

SFI's small size and limited resources means that for it to prosper intellectually, it must keep bringing in new ideas and "new blood." Thus, the Institute has no tenure and no permanent faculty positions. It also has no permanent programs. In 1999, with my SFI faculty term coming to an end, I left the Institute for an academic job in Oregon. The Adaptive Computation program also came to an end (as did the Economics program). More generally, the whole idea of official, broad "programs" at the Institute was restructured into the notion of ever-changing interdisciplinary research themes.

However, the spirit of adaptive computation remains strong at SFI, and many people incorporate AC into their research, on topics ranging from agent-based models of ancient state formation to genetic algorithms for automatically finding software bugs. Furthermore, the ideas of adaptive computation have spread far and wide into universities' computer science curricula, and into many other departments.

Indeed, our program's results impressed not only computer scientists, but people in many areas of science. Perhaps my favorite example of this was the well-known (and famously skeptical) evolutionary theorist Richard Lewontin, who, after hearing about SFI's Adaptive Computation research, announced, "I don't believe in adaptation. But I sure as heck believe in computation!"

Whether it is through adaptation or computation, or both, I'm proud to have been part of the birth and development of this foundational program for understanding complex adaptive systems. ◀

Melanie Mitchell is a Professor of Computer Science at Portland State University and an External Professor and member of the Science Board at the Santa Fe Institute. She has held faculty positions at the University of Michigan, Los Alamos National Laboratory, and the Oregon Graduate Institute School of Science and Engineering. She is author or editor of five books and more than 70 scholarly papers in artificial intelligence, cognitive science, and complex systems. Her most recent book, Complexity: A Guided Tour *(Oxford University Press, 2009) won the 2010 Phi Beta Kappa Science Book Award and was among Amazon.com's ten best science books of 2009.*

MINESH BACRANIA PHOTOGRAPHY

A Unifying Theme

FOR 21st CENTURY SCIENCE

BY DAVID PINES
Co-Founder in Residence, Santa Fe Institute

Right: David Pines. **Above:** From complex interactions of matter and energy arise the emergent properties of our universe, including the formation of stars such as this cosmic nebula with a neutron star.

RIGHT: MINESH BACRANIA PHOTOGRAPHY; ABOVE: DREAMSTIME.COM

When electrons or atoms or individuals or societies interact with one another or their environment, the collective behavior of the whole is different from that of its parts. We call this resulting behavior emergent. Emergence thus refers to collective phenomena or behaviors in complex adaptive systems that are not present in their individual parts.

Examples of emergent behavior are everywhere around us, from birds flocking, fireflies synchronizing, ants colonizing, fish schooling, individuals self-organizing into neighborhoods in cities – all with no leaders or central control – to the Big Bang, the formation of galaxies and stars and planets, the evolution of life on earth from its origins until now, the folding of proteins, the assembly of cells, the crystallization of atoms in a liquid, the superconductivity of electrons in some metals, the changing global climate, or the development of consciousness in an infant.

Indeed, we live in an emergent universe in which it is difficult, if not impossible, to identify any existing interesting scientific problem or study any social or economic behavior that is not emergent.

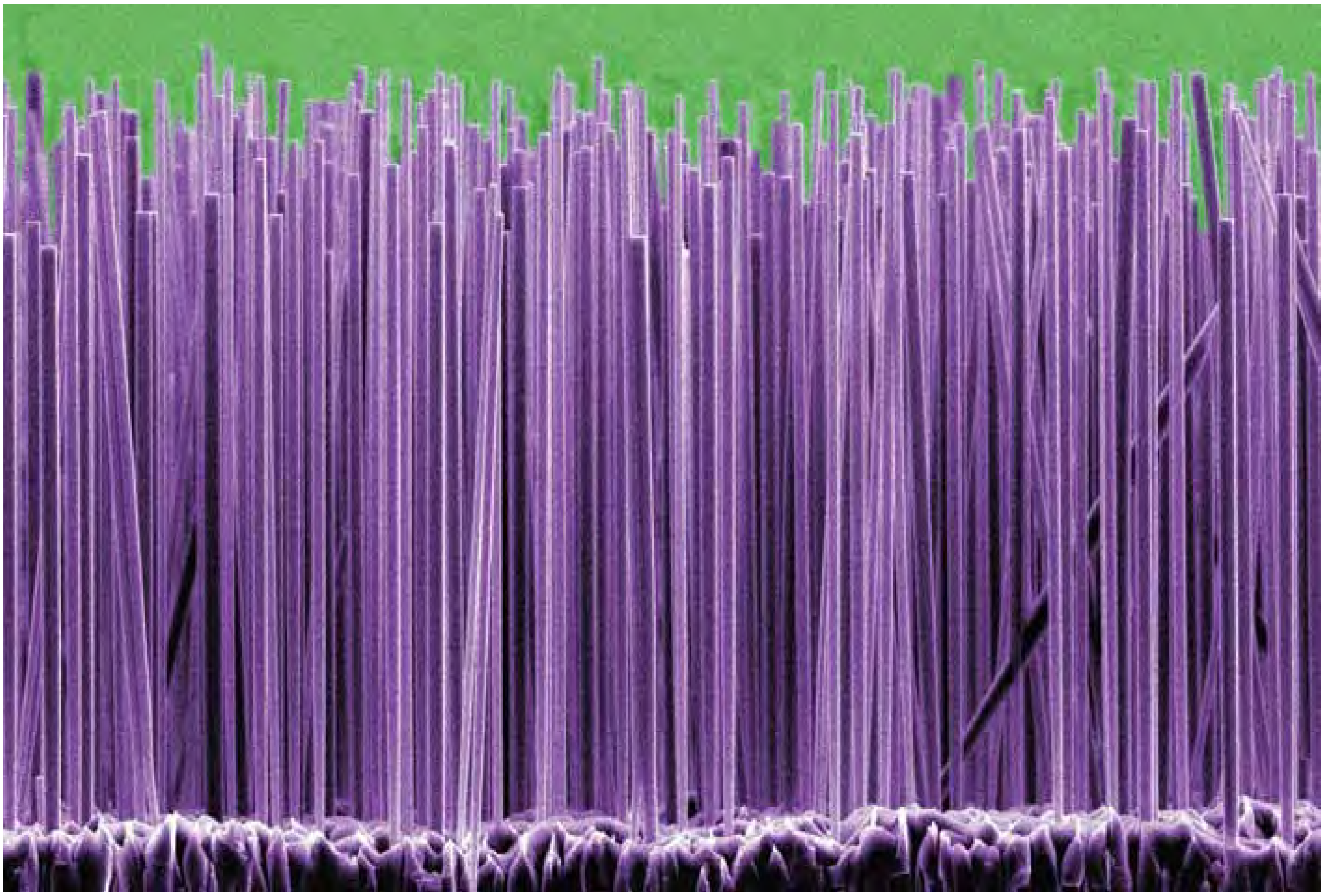
From emergence to complexity to emergence

The Santa Fe Institute began exploring emergent behavior in science and society at its 1984 founding workshops, "Emerging Syntheses in Science," during which every speaker dealt with an aspect of emergent behavior as well as the search for the organizing principles that bring about that behavior[1]. However, in the early days of SFI, SFI's scientists often focused on defining and understanding the ways these systems were complex, rather than focusing on the organizing principles responsible for the emergent behavior these systems exhibited. Indeed, some members of the Institute's growing scientific community dreamed of creating a unified science of complexity through which complexity itself could be defined and quantified – and thus classify complex systems in some kind of grand hierarchical schema.

In 1993 SFI held a major workshop to define complex adaptive systems and assess the status of its initial quest for a science of complexity. As the title of the resulting proceedings – "Complexity: Metaphors, Models, and Reality" – suggests, in the course of that workshop the dream of a unified theory of complexity was abandoned[2]. As it turns out, we might have heeded our friend, the great mathematician Stanislaw Ulam, who, prior to his death in 1984 just as the Institute was forming, had dismissed the predecessor of complexity science, nonlinear science, as "the study of non-elephants" – by which he meant that nonlinear is not a useful descriptor because everything is nonlinear (a.k.a. complex). By the end of the workshop the participants agreed that while complexity is difficult to define, and that there can be no unified science of complexity, it is highly useful to devise models of a wide variety of systems and ask to what extent the ideas behind a model that describes complex behavior in one system might be applicable to understanding another system.

In arriving at this realization, we were endorsing the pursuit of emergence as a unifying theme for science at SFI – but without using the language of emergence. To paraphrase the character M. Jourdain in Molière's *Le Bourgeois Gentilhomme* (1670) – who remarks, "Good heavens! For more than forty years I have been speaking prose without knowing it" – we were studying emergent behavior in complex adaptive systems without being explicit about doing so.

But our lexicon began to change within a few years. In what was perhaps the first general-


U.S. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Nanowires like these grown by depositing atoms layer by layer on a silicon crystal are among new manmade materials with emergent properties.

audience book to focus on emergent behavior, *Emergence: From Chaos to Order* (Helix Books, 1998), John Holland, one of SFI's early intellectual leaders, wrote about systems (e.g. games, simple molecules, etc.) in which the organizing principles responsible for emergent behavior are a set of comparatively simple rules. His book was soon followed by *The Emergence of Everything: How the World Became Complex* (Oxford University Press, 2002), in which another early SFI intellectual leader, Harold Morowitz, addressed emergent behavior from the perspective of a theoretical biologist. He considered systems for which the rules are not yet known, and wrote about emergence in nature, from the Big Bang to the emergence of humans on earth and the development of agriculture.

Still another SFI perspective on emergence, that of the theoretical physicist, can be found in two articles addressed to a general scientific audience. In a remarkably prescient article, "More Is Different"[3], written more than a decade before SFI's founding, Philip Anderson (who spoke at our 1984 founding workshops and later co-chaired, with fellow Nobel laureate Ken Arrow, the Institute's initial foray into economics) questioned the way fundamental research was characterized by many leading scientists. He also discussed the role of hierarchies and symmetry in complex systems from what we would today describe as an emergent perspective. A companion piece, "The Theory of Everything"[4], was written 28 years later by Stanford physicist R.B. Laughlin and myself. Both perspectives emphasized the limitations of a reductionist approach to complex systems in which one seeks to explain them by studying their components in ever-finer detail[5].

Although **we know the simple equations** that govern our immediate world, we find that these formulas are almost useless in telling us about the emergent behavior we encounter, whether we are working on a problem at the frontiers of science or **seeking to understand and change** familial or societal behavior.

Laughlin and I pointed out that the dream of some 20th century reductionists – discovering a "Theory of Everything" whose equations would enable one to derive all properties of matter – is hollow, and that such ambitions should be replaced by a focus on emergent behavior. Richard Feynman famously said "Life is nothing but the wiggling and jiggling of atoms." We argued that this perspective does not tell us how atoms gave rise to LUCA, the last universal ancestor that is the progenitor of living matter, to say nothing of the subsequent 3.5 billion years of evolution.

Although we know the simple equations that govern our immediate world, we find that these formulas are almost useless in telling us about the emergent behavior we encounter, whether we are working on a problem at the frontiers of science or seeking to understand and change familial or societal behavior. In concluding our article, we wrote:

> *"The central task of theoretical physics in our time is no longer to write down the ultimate equations, but rather to catalogue and understand emergent behavior in its many guises, including potentially life itself. We call this physics of the next [21st] century the study of complex adaptive matter. For better or worse, we are now witnessing a transition from the science of the past, so intimately linked to reductionism, to the study of complex adaptive matter, firmly based in experiment, with its hope for providing a jumping-off point for new discoveries, new concepts, and new wisdom."*

Emergence as a unifying paradigm

What replaces the reductionist path to understanding emergent behavior in the physical, biological, and social sciences? The short answer is a new starting point: recognizing that understanding emergent behavior requires a focus on the emergent collective properties that characterize the system as a whole and a search for their origin. It means identifying emergent collective patterns and regularities through experiment or observation, and then devising models that embody candidate collective organizing concepts and principles that might explain them. These patterns, principles, and models are the *gateways to emergent behavior* observed in the system under study. Only through studying these gateways can we hope to grasp emergent behaviors on a grand, unifying scale.

For the physicist or chemist studying emergent electronic behavior in quantum matter or turbulence in fluids, the gateways might include growing and studying new materials and developing new probes to measure fluctuations that might disclose universal scaling behavior or new coherent and possibly competing ordered states. The candidate organizing concepts that accompany these gateways often include introducing effective fields to describe emergent interactions, and can include the possibility of protected behavior that is independent of detail and governed by higher organizing principles.

For the biologist, biological physicist, or ecologist studying living systems, the collective components begin with proteins, neurons, or species and go on to cells, brains, and ecological dysfunction. The candidate organizing concepts include self-organization, energy landscapes, chemical motors that supply energy, and above all, evolution and replication – as biological systems are often far from equilibrium. Their study is made even more difficult because evolution has fine tuned earlier organizing principles. Thus, what we can observe is often the remnants of many interacting evolutionary processes.

The scientist studying human and animal behavior or social and economic systems searches for patterns in human development, societal behavior, and in economic and urban data. Candidate organizing concepts include self-organization into groups/communities/societies and the role played by environment – be it climate change, new technology, or societal regulations – in bringing about emergent behavior. The tools for that study often include an approach pioneered at SFI, agent-based and group-based modeling.

The scientific strategies employed by the physicist, biologist, ecologist, cognitive scientist, and archaeologist are thus quite similar:

- Use experiment or observation to identify emergent patterns of behavior in the system as a whole.
- Decide what might be the most important connections or interactions between objects, individuals, or groups.
- Construct and solve a simple model that incorporates these connections into organizing concepts that might explain the observed emergent behavior. (In so doing, it is often helpful to consider organizing concepts used in models that have previously been shown to explain emergent behavior in other systems or fields.)
- Compare your results and predictions with experiment or observation.

Recent progress on emergence at SFI

Recent books and articles by SFI authors, a new SFI online course, and workshops held at SFI are adding significantly to our understanding of emergent behavior. *Complexity: A Guided Tour* (Oxford University Press, 2009) is a Phi Beta Kappa prize-winning book in which computer scientist Melanie Mitchell introduces the nonscientist to the field and the methods now known as complexity science, with its many examples of emergent behavior. Her massive open online course (MOOC) addressed to the nonscientist, "Introduction to Complexity" (complexityexplorer.org), explains many of the building blocks used

The **scientific strategies** employed by the physicist, biologist, ecologist, cognitive scientist, and archaeologist are thus **quite similar.**

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The Tiananmen Square protests in Beijing in 1989 arose from deep-seated and widespread grievances about inflation, limited career prospects, and corruption of Communist party elites. At the height of the protests, about a million people assembled in the Square.

to understand emergent behavior.

In *Spin Glasses and Complexity* (Princeton University Press, 2013), SFI Science Board Co-Chair Dan Stein and his co-author Charles Newman of UC Irvine provide a lucid introduction to an important gateway to emergent behavior in science and society, the spin glass: a system of randomly distributed magnetically interacting particles. As Stein's PhD thesis advisor Phil Anderson noted in his talk introducing the topic at SFI's 1984 founding workshops, fields in which spin glass concepts serve as important building blocks include statistical mechanics, computer science, evolutionary biology, neuroscience, possibly protein structure, and the immune system. A recent book review in *Physics Today*[6] extends that list to communications, economics, and engineering. Frustration is a key concept in spin glasses, and a recent review by Peter Wolynes and his collaborators, *Frustration in Biomolecules*, provides an extensive review of the concept and its many applications[7].

Two SFI workshops have dealt explicitly with general approaches to understanding emergent behavior. "Models of Emergent Behavior in Complex Adaptive Systems" (December 2007), organized by Simon Levin, the University of Michigan's Carl Simon, and me, brought back to SFI two of its early leaders, Phil Anderson and John Hopfield, and introduced its future President, Jerry Sabloff, to the Institute. The meeting was

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Flocking, the collective motion of many birds in flight, is an emergent behavior arising from individuals following simple rules without central coordination or leadership.

co-sponsored by ICAM (the Institute for Complex Adaptive Matter), a distributed institution with its home on the web. ICAM's scientific strategy for studying emergent behavior in quantum, soft, and living matter was informed by SFI and the article by Laughlin and myself cited above. ICAM last year joined SFI in co-sponsoring a followup workshop, "Gateways to Emergent Behavior in Science and Society" (September 2013), that was organized by four members of SFI's Science Board: John Holland, Simon Levin, Don Saari, and me[8].

In the course of these workshops, many big questions about emergence were proposed for the scientific community. One of the most important questions concerned a science-based "emergent" approach to solving societal problems. The grand challenge is to develop an emergence-based framework for approaching major societal issues – a protocol/strategy that can inform policies and help design and assess the experiments that are being proposed to solve the major problems that we face as a society. This is urgently needed so that science can more effectively inform policy making as we face unprecedented societal and environmental challenges.

Emergence, SFI, and the unity of science

In the first half of the 20th century, there were sustained efforts to find a wider unity in science, and to connect science and the humanities. To honor the 1957 retirement from Harvard of Philipp Frank, the noted scientist and philosopher and a leader in those efforts, Gerald Holton (Frank's former doctoral student and Harvard colleague) organized a conference, "Science and the Modern Worldview – Toward a Common Understanding of the Sciences and Humanities." In a 2004 memoir[9], Holton describes the conference, and then writes:

"In a speech at that meeting, contrary to most others, Robert Oppenheimer had, perhaps presciently or prematurely, predicted that for the time being the energy to reach that old aim of unification had run out: 'It may be a question [whether there] is one way of bringing a wider unity in our time. That unity, I think, can only be based on a rather different kind of structure than the one most of us have in mind when we talk of the unity of culture… The unity we can seek lies really in two things. One is that the knowledge that comes to us in such a terrifyingly, inhumanly rapid rate has some order in it… The second is simply this: We can have each other to dinner. We ourselves, and with each other by our converse, can create, not an architecture of global scope, but an

MINESH BACRANIA PHOTOGRAPHY

immense, intricate network of intimacy, illumination, and understanding.'"

More than half a century later, we are now able to respond to Oppenheimer (who was my own teacher and mentor) by noting that while there are many forms of order in scientific knowledge, scientists of the 21st century do share a unifying paradigm and a shared goal: understanding emergent behavior in its many different guises. Our shared emergent perspective and the way we acquire and use that knowledge binds us together and offers a way to bridge the gap between the scientist and the humanist. Those of us at SFI, an emergent institution that arguably is one of Oppenheimer's legacies, can continue to strive to make it a place in which his "dinner conversations" become collaborations that lead to his proposed unifying network of "intimacy, illumination, and understanding." ◀

David Pines is Distinguished Research Professor of Physics at UC Davis; Research Professor of Physics at UIUC; and a Co-Founder-In-Residence, past Chair of the Board of Trustees, and Co-Chair Emeritus of the Science Board of the Santa Fe Institute. A member of the American Philosophical Society and the National Academy of Sciences, he has made seminal contributions to the scientific understanding of quantum matter and to international scientific collaboration.

Emergence for Everyone

AS WE EDUCATE OURSELVES, OUR COLLEAGUES, AND THE PUBLIC AT LARGE ABOUT EMERGENCE, I would like to suggest two challenges for SFI that relate to its potential role as a world leader in science education.

First, given the importance of emergence as a unifying paradigm for science, can the SFI community help spread the word about emergence to learners of all ages? Could we, for example, create an online course that introduces middle and high school students to science through the study of emergent behavior – and helps them develop an emergent perspective on the world around them? Could we increase the focus on emergent behavior in our existing educational programs, beginning with our middle school programs, and infuse this kind of thinking into our signature summer schools?

Second, can we create an effective "Gateways Registry" —an accessible, jargon-free catalogue of existing organizing concepts and principles that have been successfully incorporated into models that explain emergent behavior. We would then add new ones as they are discovered.

In my view, it is the Institute's responsibility to capture and catalogue what we have learned about gateways to emergence for the benefit of future generations of scientists. —*David Pines*

Notes:

1. D. Pines (ed.). 1988. *Emerging Syntheses in Science.* Addison-Wesley.
2. G. Cowan, D. Pines, & D. Meltzer (eds.). 1994. *Complexity: Metaphors, Models, and Reality.* Westview Press.
3. P.W. Anderson. 1972. *More is Different.* Science 177: 393.
4. R.B. Laughlin & D. Pines. 2000. *The Theory of Everything.* PNAS 97: 28.
5. According to Wikipedia, reductionism can either mean (a) an approach to understand the nature of complex things by reducing them to the interactions of their parts, or to simpler or more fundamental things, or (b) a philosophical position that a complex system is nothing but the sum of its parts, and that an account of it can be reduced to accounts of individual constituents.
6. S. Boettcher (review). 2014. *Spin Glasses and Complexity.* Physics Today 67(1): 48.
7. D.U. Fereiro, E.A. Komives, & P.G. Wolynes. 2013. *Frustration in Biomolecules.* arxiv.org 1312.0867.
8. *Gateways to Emergent Behavior in Science and Society.* 2013. Participant posters and slides from the ICAM/SFI Workshop: http://tuvalu.santafe.edu/events/workshops/index.php/Gateways_to_Emergent_Behavior_in_Science_and_Society
9. G. Holton. 2004. *Philip Frank at Harvard* (lectures at Philip Frank conferences in Prague and Vienna).

REVEALING PATTERNS IN THE ARC OF **HUMAN HISTORY**

BY HENRY WRIGHT

Albert C. Spaulding Distinguished University Professor of Anthropology, University of Michigan; External Professor and member of the Science Board and Science Steering Committee, Santa Fe Institute

When SFI's founders took up the challenge of developing a predictive science of complex systems in 1984, some of them already had in mind the utility of such an approach to solutions for long-term human problems. Murray Gell-Mann had a lifelong interest in archaeology and matters of deep history. Robert McCormick Adams was a key contributor to the study of the evolution of civilizations in both Mesopotamia and Mesoamerica. Could not the deep-time perspective and the solidly material record afforded by archaeology provide the data to test the implications of complexity theory for understanding the emergence of new forms of human organization?

Surprisingly, the first major SFI initiatives did not involve the study of the first states and empires, what anthropologists, archaeologists, and historians have termed "complex societies." Instead, perhaps because of the chronological precision and the year-to-year record of rainfall (crucial for village farmers in a semi-arid environment) provided by tree-ring studies, or perhaps because of the insight provided by the living descendants of the earlier Pueblo peoples, or perhaps because SFI is located in the North American Southwest, our first major archaeological study was of emerging forms of organization in our own backyard.

Early simulations of societal change

As has so often been the case with SFI research, Institute scholars tried several different initial approaches, not in competition but in a mutually informed exploration of different assumptions, different scales of analysis, and different computer platforms for expressing social emergence in the Southwest. Here are some examples.

George Gumerman was head of SARG – the Southwestern Archaeological Research Group. SARG was concerned with building a comprehensive database of environmental, demographic, and social information for the entire region's prehistory. As this work proceeded, the group's members saw a need for some way to integrate the many different interacting variables thought to be important in the cultural ecology of the prehistoric agriculturalists of the Southwest.

Gumerman and his team of human biologists, hydrologists, paleo-climatologists, and others joined with Joshua Epstein and colleagues from the Brookings Institution (around 1993) to create an agent-based model using a modeling platform called "Sugarscape." In this model, called "Ancient Anasazi," electronic people were born, grew up, married, raised children, migrated, and died on a landscape mimicking the resources of an actual valley in northeastern Arizona called Longhouse Valley. This valley was represented as 100-meter squares, each with soil features and centuries of year-by-year rainfall change inferred from the ancient tree-ring record.

On another front, Tim Kohler – a veteran of research on the ecology and social organization of both woodland societies in the North American Southeast and ancestral Pueblo communities in southwest Colorado – had taken a post at Washington State University and attended an SFI workshop in 1992. There he met SFI's Chris Langton, who was in the process of developing "Swarm," a

Left: Henry Wright. **Above:** Some of SFI's earliest archaeological projects sought to build databases incorporating environmental, demographic, resource, and social information. Between AD 900 and 1150, Chaco Canyon in today's northwestern New Mexico was a major center of Pueblo culture.

LEFT: INSIGHTFOTO
THIS PAGE: SCOTT HAEFNER PHOTOGRAPHY

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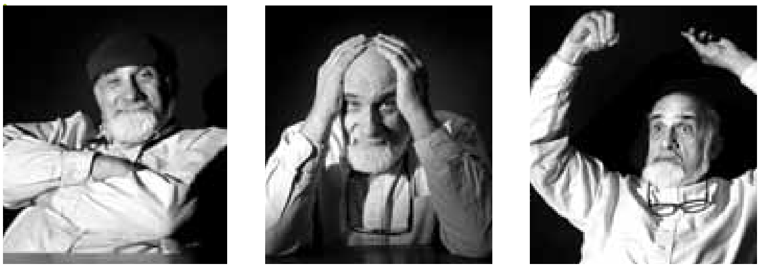
Year-to-year records of rainfall provided by tree-ring studies informed some of the Institute's early archeological studies of ancient societies in the present-day Southwestern United States.

prototype agent-based modeling platform.

One of Kohler's Ph.D. students, archaeologist Carla Van West, had recently completed a reconstruction of maize productivity for southwest Colorado with a spatial resolution of 200 meters and a temporal resolution of one year. This team of three modeled household location and community development through an application built on Swarm, which they called "Village." In this model, virtual households contained people who were born, grew up, married, raised children, migrated, and died on a landscape representing the resources including water, game, fuels, and maize – all changing from year to year.

Interestingly, the two independent simulation projects – although they used different platforms and models, spatial configurations, and production assessments – produced regional population rises and falls that tracked well with the archaeological record established through archaeological surveys in the two areas. The details of which settlements grew to be important centers and how and when population declined, however, were not elucidated by the first simulations.

Both teams have since added additional kinds of interactions. These include forms of economic production other than agriculture, exchange, mechanisms for the development of social alliances, leadership, and conflict – all of which help to generate simulations more useful in both understanding specific trajectories of human systems and in testing hypotheses about human systems in general.



INSIGHTFOTO

Patterns in deep human history

In recent years at SFI, the special contribution of archaeologists and historians has been the study of the trajectories of human organization over long periods of time.

New methods for precisely dating cultural phenomena, for example, emphasize the often-rapid pace of organizational transformations and the primacy of some variables over others. My own work on 18th century state formation in central Madagascar shows that the region was transformed from small, warring polities to a consolidated regional state in less than 15 years. Precise estimates of the population using a model developed by the late anthropologist Robert Dewar show that the population increase was too fast to have been a result of local reproduction as some scholars have argued. It is more likely that families, and perhaps whole communities, moved in to join the new and increasingly successful form of hierarchical polity. Thus, in this case (and no doubt in others), population growth is not an external driver of political change, but a variable within the socio-political system.

The comparison of different cases of societal transformation reveals often-unexpected regularities. A number of recent initiatives supported by the John Templeton Foundation seek to approach the coding of comparable cases. In particular, a research project led by SFI President Jerry Sabloff is undertaking a comparative study of the rise of the first archaic states across the globe.

Within this overall project, one study, headed by SFI Professor Paula Sabloff, is coding a range of state and nonstate societies known from the archaeological and documentary records.

Map of the pre-Hispanic Basin of Mexico, site of modern-day Mexico City, showing various sizes of human settlements (blue dots) and early lake boundary (light blue area).

Coding has revealed data mismatches due to the varying archaeological and historical traditions in various parts of the world. But these are being overcome, and the SFI research is revealing interesting patterns in the slow pace of village development after the shift to agriculture, versus the rapid pace of the emergence of state polities and urban economies.

In another perspective, a team led by Scott Ortman and Luis Bettencourt has started to apply theory introduced by Bettencourt in a 2013 article in *Science* – one viewing modern cities as social and spatial networks – to ancient settlements, specifically the pre-Hispanic Basin of Mexico. In a recent article in *PLOS ONE*, Ortman and Bettencourt found that these settlements exhibit scaling properties consistent with modern cities, but with different baseline parameters reflecting simpler transportation technology and agricultural productivity.

Together with Arizona State University faculty members Jose Lobo and Michael Smith, they also are beginning to code data to characterize the most ancient cities in places such as Mesopotamia, China, Mesoamerica, and the central Andes to see if the scalar relations observed in modern urban centers by SFI's cities and urbanization research team, led by Bettencourt and Geoffrey West, also apply throughout human history – and how they might need modification or reconceptualization.

These latest projects underscore an acceleration of research at SFI on long-term regularities and on the unexpected emergence of similar organizational phenomena in unrelated parts of the world. In my view, the future holds great promise, not only for theory building, but also for the creation of genuinely practical strategies for dealing with communication crises, political instability, and urban inequality in our world today. ◀

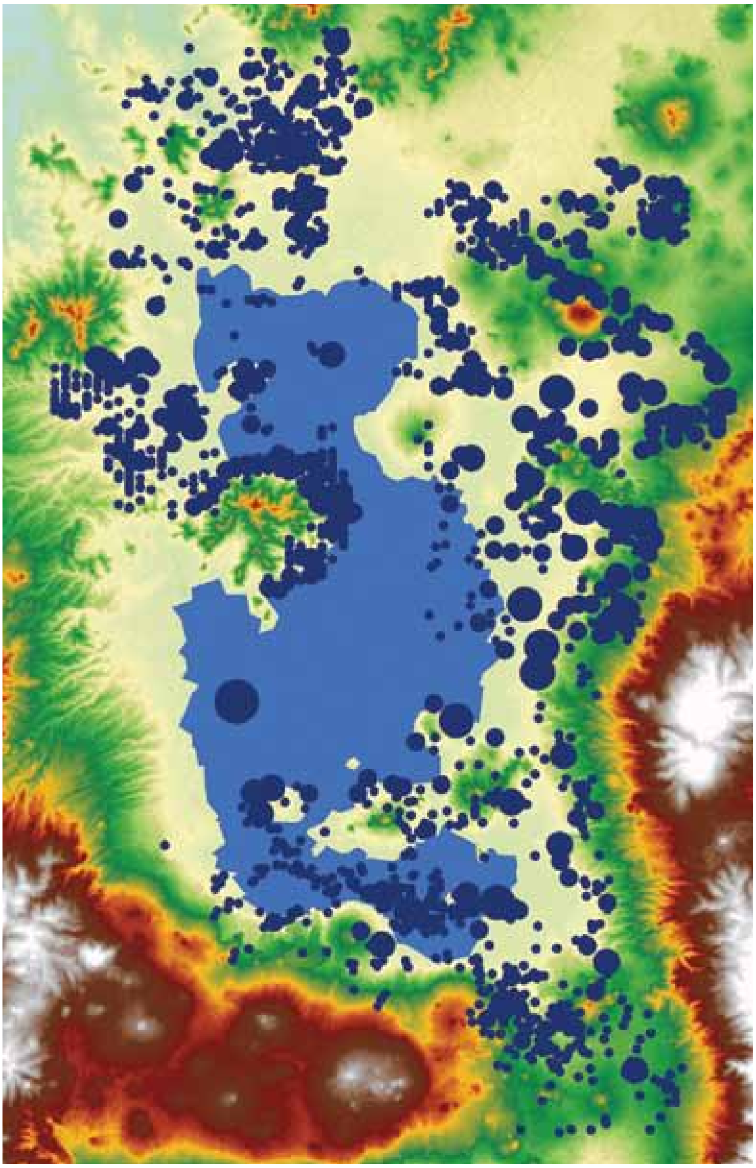


IMAGE BY DREW CABANNIS USING ARCGIS, LAKE BOUNDARY AND SETTLEMENT DATA FROM J.R. PARSONS ET AL.

Henry T. Wright is the Albert C. Spaulding Distinguished University Professor of Anthropology, University of Michigan, Department of Anthropology and Museum of Anthropology. Early in his career he became fascinated with competing explanations of the evolution of complex human social formations. His subsequent research took him to Iraq, Iran, Turkey, Egypt, Madagascar, Syria, and China, where he focused on the development of models for understanding societal and ecological change, including state formation. He is a MacArthur Fellow and a fellow of the National Academy of Sciences and is an External Professor and member of the Science Board and Science Steering Committee of the Santa Fe Institute.

SCALING

THE Surprising Mathematics
OF LIFE AND CIVILIZATION

BY GEOFFREY WEST
Distinguished Professor and Past President, Santa Fe Institute

NASA

Left: Geoffrey West. **Above:** Recent research at SFI considers the city not only as people and infrastructure, but as a network of interactions in space and time. In this nighttime satellite image, populated areas branch out to form the New York City metropolitan area.

In late 1995 Mike Simmons, then-SFI vice president, introduced me to Jim Brown. At that time I was overseeing the high energy physics program at Los Alamos National Laboratory while Brown, who had recently moved to the University of New Mexico's biology department, was developing an ecology program at SFI. Serendipitously we had both been thinking about a longstanding problem in biology, namely the origin of so-called "quarter-power allometric scaling laws." I will elaborate on what this means later but, roughly speaking, it refers to the surprising observation that across the entire spectrum of life, almost all physiological variables and life-history events scale with size in a remarkably simple, systematic, and predictable fashion.

Sandwiched between quarks, Higgs, strings, and dark matter, I had been struggling with developing a physics-inspired network theory for the origin of these scaling laws, while Brown and his then-student, Brian Enquist (now at the University of Arizona), had been speculating that nutrient transportation through the bloodstream was a key ingredient.

Simmon's intuition that we might have something to say to one another changed our lives and

LEFT PAGE: MINESH BACRANIA PHOTOGRAPHY

> What happens to cities or companies **if their sizes are doubled?** What happens to buildings, airplanes, economies, or animals **if they are halved?** ... Does an animal that is half the mass of another animal require half as much food?

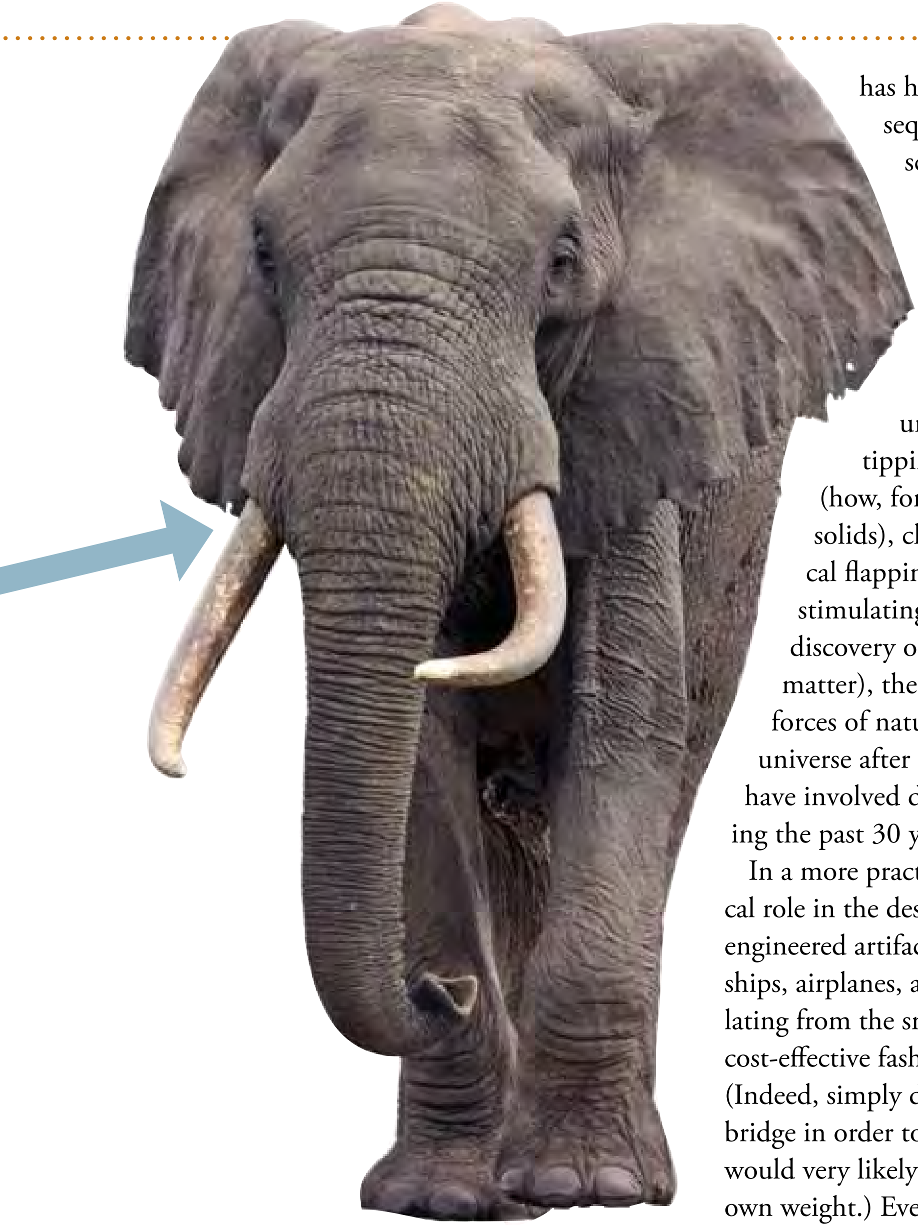
The best-known scaling relationship from biology is for metabolic rate; doubling the size of an organism only requires an increase in metabolic energy (food intake) of about 75%, rather than 100%, as might naively be expected.

MOUSE: WIKIPEDIA.COM; BABY: DREAMSTIME.COM

marked the beginning of what became known as the "scaling program" at SFI. The implications of scaling phenomena later expanded beyond biology, ecology, and biomedicine to embrace human socioeconomic systems such as cities and companies – even extending to the challenge of global sustainability. Thus began a beautiful relationship with Brown, Enquist, and SFI and, by extension, with the ensuing cadre of wonderful postdocs, students, and faculty who have since worked on the Institute's scaling and cities programs.

Our sustained collaboration has been enormously productive, extraordinarily exciting, and tremendously fun. Beginning in 1996, initially with Brown, Enquist, and me, and later with the expanded group, we met every Friday at SFI from 9 a.m. to around 3 p.m. This continued almost uninterrupted until just the last couple of years. At the outset this was a huge commitment as both Brown and I ran large research groups elsewhere.

Once the ice was broken and some of the cultural barriers were crossed, we created a refreshingly open atmosphere where all questions and comments, no matter how elementary, speculative, or seemingly stupid, were encouraged, welcomed, and treated with mutual respect. There were lots of arguments, speculations, and explanations; struggles with big questions and small details; lots of blind alleys; and an occasional aha! moment – all against a backdrop of a whiteboard (and sometimes Institute windows) covered with equations, graphs, and illustrations. Brown and Enquist patiently acted as biology tutors, exposing me to the world of natural selection, evolution, adaptation, fitness, physiology, and anatomy, all of which were embarrassingly foreign to me. For my part, I tried to reduce complicated mathematical equations and technical physics arguments to relatively



simple, intuitive calculations and explanations. In other words, we were engaged in a typical transdisciplinary Santa Fe Institute experience!

So what is "scaling"? In its most elemental form, it simply refers to how systems respond when their sizes change. What happens to cities or companies if their sizes are doubled? What happens to buildings, airplanes, economies, or animals if they are halved? Do cities that are twice as large have approximately twice as many roads and produce double the number of patents? Should the profits of a company twice the size of another company double? Does an animal that is half the mass of another animal require half as much food?

Asking such seemingly innocuous questions has had remarkably profound consequences across the spectrum of science, engineering, and technology and has impacted almost every aspect of our lives, even including how we perceive our place in the universe.

Over the past 50 years, scaling arguments have led to a deeper understanding of the dynamics of tipping points and phase transitions (how, for example, liquids freeze into solids), chaotic phenomena (the mythical flapping of a butterfly's wings in Brazil stimulating a hurricane in Florida), the discovery of quarks (the building blocks of matter), the unification of the fundamental forces of nature, and the evolution of the universe after the Big Bang. Three Nobel prizes have involved discoveries related to scaling during the past 30 years.

In a more practical context, scaling plays a critical role in the design of increasingly large human engineered artifacts, such as buildings, bridges, ships, airplanes, and computers, where extrapolating from the small to the large in an efficient, cost-effective fashion is a continuing challenge. (Indeed, simply doubling all dimensions of a bridge in order to traverse a river twice as wide would very likely lead to it collapsing under its own weight.) Even more challenging, and of perhaps greater urgency, is to understand how to scale organizational structures of increasingly large and complex cities, corporations, and governments, where underlying principles are typically not well understood because these – like living systems – are continuously evolving and adapting.

Our research was originally stimulated by the observation that, despite the extraordinary complexity and diversity of life, many of its most fundamental metrics scale in a remarkably simple and systematic fashion across an immense range, from cells to ecosystems. The best known of these is for metabolic rate (the rate at which energy is needed to sustain an organism), which scales as a so-called power law with an exponent of ¾ over an astonishing 27 orders of magnitude.

THIS PAGE: ISTOCKPHOTO.COM

In English, this means that doubling the size of an organism from, say, 10g to 20g, or from 100kg to 200kg, only requires an increase in metabolic energy (food intake) of about 75%, rather than 100%, as might naively be expected. Remarkably, this systematic economy of scale permeates biology. Similar systematic scaling laws hold for almost any measureable physiological trait or life-history event: life spans, growth rates, DNA nucleotide substitution rates, genome lengths, tree heights, and the mass of cerebral grey matter. Of equal importance, the corresponding exponents express a universality, invariably approximating simple multiples of ¼. (This is the origin of the phrase "quarter-power allometric scaling" introduced at the beginning of this article; the term "allometry" was coined in 1936 by Julian Huxley and Georges Tessier to designate scaling in biology, though the ¾ power law for metabolic rate was proposed earlier by Max Kleiber in 1932.)

The predominance of quarter-power scaling across all life forms is particularly surprising because each organism, each sub-system, each cell type, and each genome has evolved in its own particular, ever-changing environmental niche with its own unique circumstances and history. Thus, one would not have expected any systematic behavior to have emerged. Instead, we might expect a huge variance reflecting the historical contingency and randomness implicit in natural selection. The presence of regularity strongly suggests that generic underlying dynamical mechanisms have constrained evolutionary processes, thereby opening a possible window into determining quantifiable emergent laws that capture the essential features and coarse-grained behavior of living systems. Although the problem had attracted the attention of many biologists, including Huxley, Haldane, and D'Arcy Thompson, no general theory had yet been developed when we began to address these questions in 1995.

We conjectured that the key lies in the generic mathematical properties of networks. Highly

Scaling from small to large in an efficient, cost-effective manner plays a critical role in the design of increasingly large human engineering projects, such as the effort now underway to replace the 16,000-ft. cantilevered Tappan Zee Bridge that spans New York's Hudson River (artist's rendition of future bridge design).

COURTESY OF NEW YORK STATE THRUWAY AUTHORITY complex self-sustaining systems – whether they are cells, organisms, ecosystems, cities, or corporations – require close integration of many constituent units that require an efficient supply of nutrients and the disposal of waste products. We suggested that this servicing – via, for instance, circulatory systems in organisms, or perhaps transport systems in cities – is accomplished through optimized, space-filling, fractal-like branching networks whose dynamical and geometric constraints are independent of specific evolved organismic design.

Eventually these ideas led to a general quantitative, predictive mathematical framework for deriving quarter-power scaling and for understanding many essential features of diverse biological systems and functions, including vasculature, forest communities, tumors, aging and death, sleep, cell size, and evolutionary rates. Because these branching networks determine rates at which energy and resources are delivered to functional terminal units, such as cells, they set the pace of physiological processes and life history events, such as life spans, turnover times, and growth rates. The theory predicted, in agreement with observation, that, from cells and whales to community structures, the pace of life systematically and predictably slows down with increasing size, and that this is accompanied by increasing economies of scale. Much of this body of work became known as the metabolic theory of ecology.

The theory's success naturally led to a possible extension to other networked systems, such as cities and companies, which superficially have much in common with organisms and ecosystems. This new exploration began with informal discussions at SFI around 2002 between David Lane (who had previously run the Institute's economics program), Sander van der Leeuw (an anthropologist then on sabbatical at SFI, now at Arizona State University), and myself. We soon became joint principal investigators – with Denise Pumain (an urban geographer at the Sorbonne) – of a broad European Union-funded program we called ISCOM (the Information Society as a Complex System). A major component of this effort was to ask whether cities also manifest scaling and, if so, to develop a quantitative and principled theory for understanding the structure and dynamics of urban systems. To address these challenges, a new multidisciplinary SFI-style collaboration was assembled.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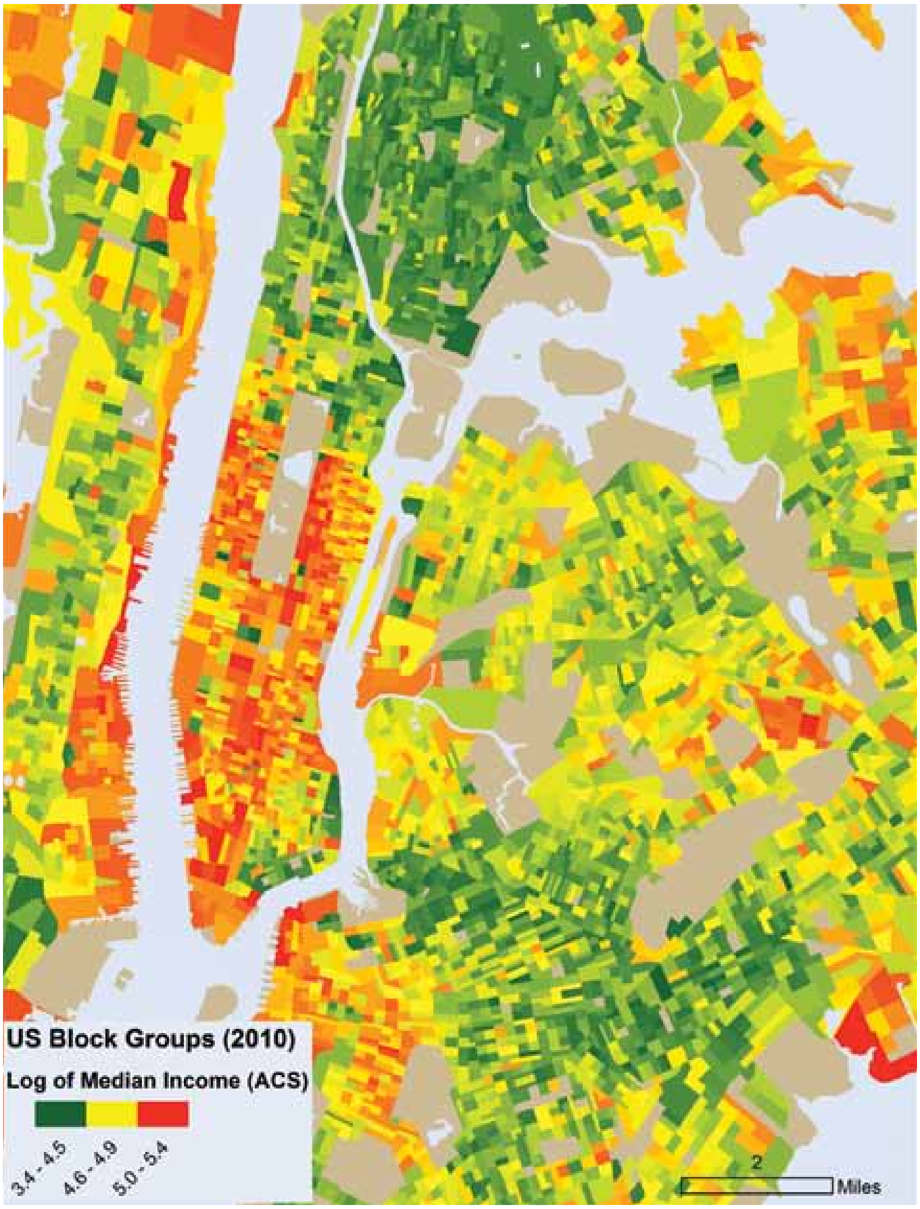
The world is urbanizing at an unprecedented rate, requiring new and growing cities, especially in India, China, and parts of the developing world.

With Dirk Helbing (a physicist, now at ETH Zurich) and his student Christian Kuhnert, and later with Luis Bettencourt (a Los Alamos physicist now an SFI Professor), Jose Lobo (an economist, now at ASU), and Debbie Strumsky (UNC-Charlotte), we discovered that cities, like organisms, do indeed exhibit "universal" power law scaling, but with some crucial differences from biological systems.

Infrastructural measures, such as numbers of gas stations and lengths of roads and electrical cables, all scale sublinearly with city population size, manifesting economies of scale with a common exponent around 0.85 (rather than the 0.75 observed in biology). More significantly, however, was the emergence of a new phenomenon not observed in biology, namely, superlinear scaling: socioeconomic quantities involving human interaction, such as wages, patents, AIDS cases, and violent crime all scale with a common exponent around 1.15. Thus, on a per capita basis, human interaction metrics (which encompass innovation and wealth creation) systematically increase with city size while, to the same degree, infrastructural metrics manifest increasing savings. Put slightly differently: with every doubling of city size, whether from 20,000 to 40,000 people or 2M to 4M people, socioeconomic quantities – the good, the bad, and the ugly – increase by approximately 15% per person with a concomitant 15% savings on all city infrastructure-related costs.

No wonder cities have continued to grow. When we move to a city within an urban system that is twice as large, we become, on average, 15% more wealthy, more productive, more creative… and we do this using a fraction of the infrastructure. The discovery of economies of scale and the resulting fruits of innovation and wealth creation brought a fundamentally new dynamic beyond classic biology to the planet. This surprising universality is observed in urban systems in the United States, China, Japan, Europe, and Latin America and transcends history, geography, and culture. What a remarkable outcome manifested in the emergent behavior resulting from human interaction and social networking!



CLIO ANDRIS

SFI reseachers have examined the underlying structures of networks and how they influence city dynamics. Here, a data map of Manhattan and surrounding areas shows average household wealth by borough. Shades of red are the highest-income areas. Shades of green are the lowest-income neighborhoods.

As in biology, these regularities have led to the beginning of a quantitative theory of cities based on the underlying dynamics and organization of social networks integrated with the physical networks of urban infrastructure. Fundamentally, cities are facilitators of social interaction. Our collaboration has been exploring the multiple implications and extensions inspired by this conceptual framework. In addition to developing the basic theory, we are exploring, among many other topics, the questions of open-ended growth and the increasing pace of life, the diversity of businesses and employment, the consequences and benefits of the rapid migration into cities we are witnessing today, and the statistics of how cities deviate from scaling regularities and what that implies

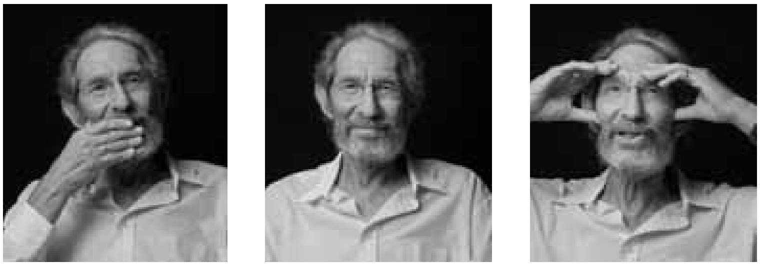
ISTOCKPHOTO.COM

Rapid urbanization means cities often grow faster than infrastructures. When they do, informal settlements, such as this slum in Sierra Leone, often arise. Recent SFI research seeks to understand the dynamics of rapid city growth, both to help slum dwellers articulate their needs and help decision makers better manage growth.

for particular cities. Our theoretical predictions have been confirmed for urban social interactions across time and space, from the fascinating study led by Luis Bettencourt and Scott Ortman on pre-Columbian Mexican settlement data, to a recent analysis of 21st century cell phone data we conducted in collaboration with colleagues at MIT. In related research led by Bettencourt, the work is being extended to a better understanding of slums, informal communities, and neighborhoods – all of which play an important role in the development of megacities.

Perhaps of even greater relevance is that the long-term sustainability of the planet is inextricably linked to the fate of our cities. We are urbanizing at an exponential rate, with more than half of the world's population now living in urban centers. The biggest global challenges we are facing from climate change, the environment, availability of energy and resources, social unrest, and financial markets are generated in cities, but cities are also the hubs of innovation, wealth creation, and power. Put slightly differently, cities may well be the problem, but they are also the solution. This strongly suggests that there is a great urgency to develop a more quantitative, predictive, computational framework that can complement the traditional, more qualitative, narrative approaches to understanding cities – a framework that can help inform today's and tomorrow's practitioners and policy makers. ◀

Geoffrey West is Distinguished Professor and former President of the Santa Fe Institute and a Senior Fellow at Los Alamos National Laboratory. He holds a B.A. from Cambridge and a Ph.D. from Stanford where he was on the faculty. His interests have been in fundamental questions from elementary particles to scaling laws in biology and social systems, and on developing a science of cities, companies, and global sustainability. His research includes metabolism, growth, aging, sleep, cancer, ecosystems, and the accelerating pace of life. He has received many awards and was on Time*'s 2006 list of "100 Most Influential People in the World." His work was cited by the* Harvard Business Review *as a breakthrough idea of 2007.*



MINESH BACRANIA PHOTOGRAPHY

BUILDING A LEARNING CONTINUUM FROM SCRATCH

BY GINGER RICHARDSON, McKinnon Family Vice President for Education and Outreach, Santa Fe Institute

Right: Ginger Richardson. **Above:** Summer C.A.M.P. (Computation and Modeling Program) is a two-week residential science program for high school students that combines field research, lectures and seminars, and data analysis.

This is the story of educational outreach at the Santa Fe Institute: how we began with a grand vision, thudded back to earth, and then – through doggedness, windfall opportunities, an unanticipated digital revolution, and sheer luck – coaxed a program to emerge that is surprisingly resonant of the original idea.

The conversations among SFI's founders in the early 1980s envisioned SFI on a Rockefeller University model – a research institute offering accredited graduate education. "Teaching would be accomplished mostly in seminars and short series of lectures, but, above all, by means of apprenticeship and research," wrote Murray Gell-Mann in "Emerging Syntheses in Science," the volume memorializing the Institute's founding workshops.

At the time, Gell-Mann estimated that "three units" (a unit being $100 million) would be sufficient as an endowment to get the Institute off the ground. Unfortunately, such monies were not forthcoming. The research program would begin, but a student campus would have to wait. Further, the administrative hurdles of the accreditation process loomed larger than anticipated. Without specific funds for outreach or prospects for a campus, with no apparent legitimacy, and without obvious access to students (only a few of the Institute's founders were at universities), SFI's original Big Plan for education soon needed a reset.

Despite these logistical obstacles, George Cowan and his founding colleagues had some strong intangibles in their favor. Most important, they had a clear mission; scholarship would focus on the transdisciplinary study of complexity, a concept that provided a broad canopy for exploring various systems.

Second, they knew they wanted to initially target graduate students and postdocs – for both selfish and altruistic reasons. Scientists at this early-career stage could be trained relatively quickly as practitioners of complexity science – and become future ambassadors for the new approach.

Third, although the founders were not teaching experts, they agreed on several pedagogical

RIGHT: MINESH BACRANIA PHOTOGRAPHY; ABOVE: SFI ARCHIVES

SFI ARCHIVES

SFI's Research Experiences for Undergraduates program, supported by the National Science Foundation, offers a summer-long immersion in complex systems science. Participants work closely with Institute faculty on individual and small-group projects.

principles: students would work in multigenerational, collaborative groups; theories and toolkits would be drawn from a range of disciplines; and active learning would be the model – students would learn science by doing science. These elements have been intrinsic to SFI-style education ever since.

Finally, the founders had remarkable social resources at their disposal, including robust intellectual networks, strong institutional and personal convening power, and no lack of self-confidence.

When in 1987 Harold Morowitz called with an educational proposition, the Institute – despite its fledgling state – seized the opportunity. Morowitz, at Yale at the time, had the prescient idea of building a biology-wide information system with the ultimate end of pushing theoretical biology forward. He proposed convening biology, computer science, and information system grad students at a "Matrix of Biological Knowledge" summer school to begin this work.

Morowitz wrote a National Institutes of Health proposal that included support for student participants and – because we had no equipment – also funded a dozen workstations. We put an ad in *Nature*. Morowitz and his co-organizers, James Willet of NIH and Temple Smith of Harvard, tapped into their networks to recruit students. Classroom and dorm space were rented from nearby St. John's College (a relationship we continue to this day for SFI summer schools).

In hindsight, "Matrix of Biological Knowledge" turned out to be a seminal event in the emerging field of bioinformatics; many of the participants are now among the leaders in biological computer informatics and large-scale databases. Multidisciplinary, collaborative, and research-based, its organization and format was a proof-of-concept for future SFI schools. Most important, we pulled it off.

While Matrix was taking place, Institute founders were spearheading the first-ever Complex Systems Summer School (CSSS). Started in

1988, the annual, month-long residential event continues today and is the central node of SFI's educational programs. Every June, CSSS provides an intensive introduction to complex behavior in mathematical, physical, living, and social systems to some 65 graduate students and postdoctoral fellows. The school drives new complexity science content, pedagogy, and novel educational formats.

More important, CSSS is a community-building event. The summer school alumni roster reads like a Who's Who in complexity science. Lecture invitations strengthen existing faculty relationships and draw new collaborators. SFI undergraduate interns get their first immersion in the field, and postdoctoral fellows gain teaching experience there. Many of our postdocs come to us through the portal of CSSS.

> Often we were approached by **young scholars eager to be involved with SFI's new science,** and we realized we needed to figure out a way to accommodate them. And we did so, often informally.

John Miller attended the first summer school in 1988. He also was the Institute's first postdoctoral fellow. His ensuing career accomplishments and long-term SFI connections make him an SFI education program poster child. Now a Professor of Economics and Social Science at Carnegie Mellon, he has spent several extended residencies here. For the past 20 years he has, with Scott Page, co-directed our Graduate Workshop. The central scientific theme of this program, computational social science, has become a subfield for which Miller is certainly among the world's pioneers.

His success, along with the examples of many other SFI postdocs, belies the founders' early worries that a segue into complexity science could be a career killer. In fact, the Institute's postdocs consistently move into leadership positions in academia, research, and industry.

This trend was bolstered in 2008 with creation of the Omidyar Fellows program that formally seeks to develop what we call the "new leadership for new science." Omidyar Postdoctoral Fellows spend up to three years at SFI where they pursue their own research in complexity science – and take part in a training program structured to develop leadership skills for their residencies and beyond. Although the program's creation was accompanied by the familiar worries about career trajectories that include complexity (what university department would want a young faculty member who had so boldly stepped out of the primary scholarly stream?), those fears again proved to be unfounded. Our Omidyar Fellows have landed on their feet, and many of them already lead major programs in academia and industry. The program's current faculty director is John Miller.

Miller came to SFI though our social network. Our first undergraduate fellow, Julie Rehmeyer, just knocked on the door. "When I was sixteen years old in 1988, I wandered down the hill from St. John's College to a convent on Canyon Road," she writes. "I'd heard that the Santa Fe Institute was housed in it, and although I didn't quite know what people did there, I'd heard that it involved interesting math and science and I wanted to be part of it. I asked Mike Simmons, the vice president, if I might become an undergraduate intern. 'What a great idea,' he said. 'We'll start an undergraduate internship program!'"

That Eureka moment didn't immediately play out, but Rehmeyer gets it essentially right: often we were approached by young scholars eager to be involved with SFI's new science, and we realized we needed to figure out a way to accommodate them. And we did so, often informally.

In 1992 we successfully applied for National Science Foundation (NSF) funding and ever since have supported summer undergraduate research – usually with about a dozen students in residence. Students work with an SFI mentor on a mutually determined research project that often results in publication. For her part, Rehmeyer pursued several such research projects at SFI, went on to study applied mathematics, and became a well-known science writer; in January 2014 she returned as an SFI Journalism Fellow.

Thus, by 1988 – within two years of opening our doors – we had established what would become the backbone of SFI's educational outreach. Over the next decade we would tweak the schools and residential programs to include international events, student workshops on special topics, and fellowship opportunities for graduate students and high school participants. Tuition-free, education funding was sourced from external grants and unrestricted SFI monies. Promotion and recruitment got more sophisticated, and word of mouth worked in our favor.

Meanwhile new digital technologies were emerging that would impact us. At MIT's Media Lab, Mitch Resnick's group built StarLogo, a programmable modeling environment for exploring the workings of decentralized complex systems. StarLogo's programming language is accessible to middle and elementary schoolers without advanced mathematical or programming skills. Suddenly a door to reaching younger students opened. Here were the 21st century citizens whom the founders dreamed of reaching with the complexity paradigm.

Suddenly **a door to reaching younger students** opened. Here were the 21st century citizens whom the founders dreamed of reaching with the **complexity paradigm.**

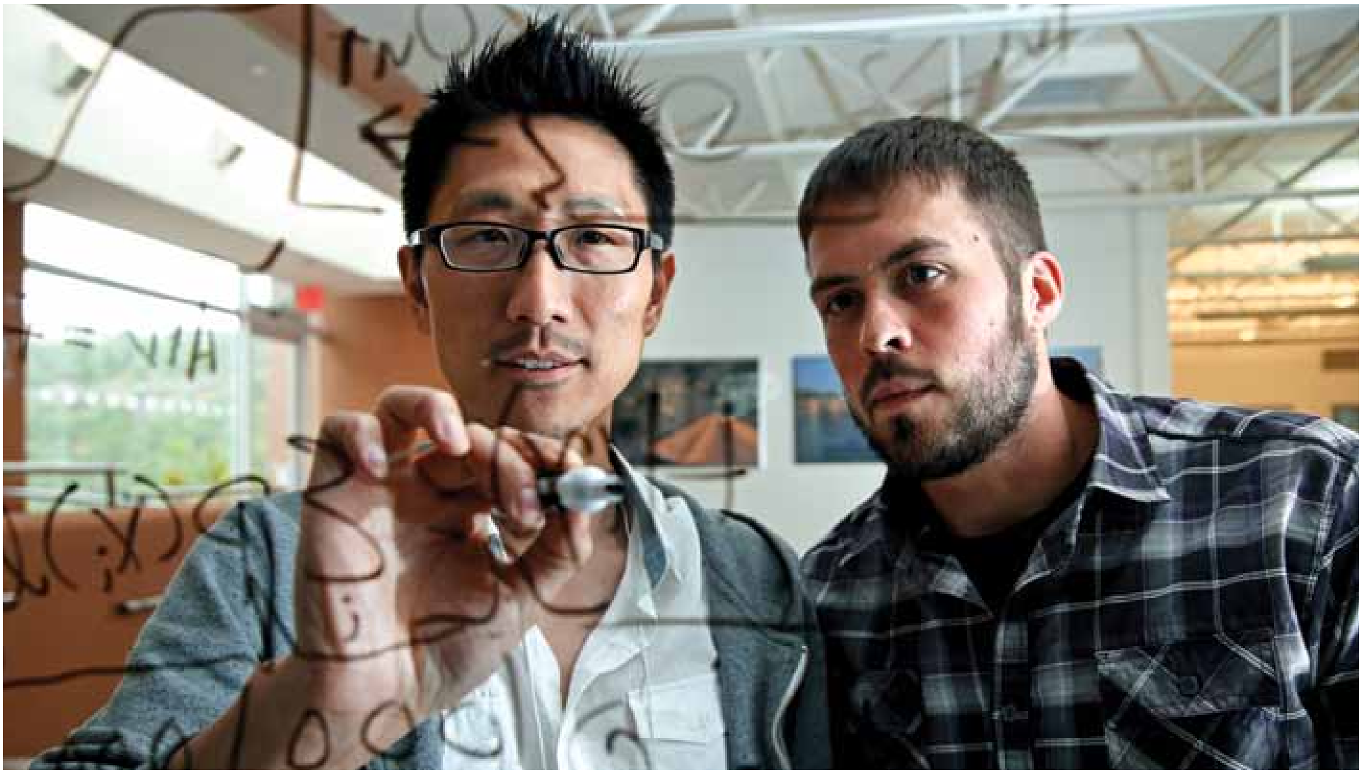
COMPLEXITY
EXPLORER
SANTA FE INSTITUTE

Here, too, was an unexpected opportunity to add a youth component to the SFI program. In 1999 one of Resnick's students, Eric Klopfer, visited SFI as an NSF Postdoctoral Fellow researching teacher professional development using computer simulations. Klopfer and Irene Lee – a member of the SFI spinoff Swarm Development Group, game developer, and science education specialist – launched a series of "Adventures in Modeling" workshops to explore how to best bring new complex systems content and teaching practices to middle and secondary schools. Funded by the NSF, these workshops explored different formats over the next decade and ultimately launched Project GUTS: Growing Up Thinking Scientifically. This afterschool program introduces middle school students to computer modeling and complex systems using the students' schools and neighborhoods as the context for science inquiry. There are now 30 GUTS clubs in New Mexico, and the nonprofit code.org is in the process of taking the program to schools nationwide.

In 2012, the Institute expanded on the GUTS initiative to create the SFI Learning Laboratory, with Lee as its director. The Lab researches best practices in teaching complexity science, evaluates current education efforts, and creates new models for complex systems education. It is complemented by the Complexity Explorer (complexityexplorer.org), an SFI-curated website that provides online courses and other educational materials related to complex systems science.

The Explorer completes a continuum, of sorts: today, a complex systems learner can step through Institute-sponsored activities ranging from middle school to adult career development, or they can enter them at any point in their education journey. Every year hundreds of participants do so.

Hundreds is a good number, but thousands


SFI ARCHIVES

SFI's signature education program, the Complex Systems Summer School, provides graduate students and postdocs an intensive four-week introduction to complex behavior in mathematical, physical, living, and social systems in Santa Fe.

would be better. Our growing reputation fills our schools and residencies, but face-to-face educational experiences are ultimately limited. Course schedules are routine but episodic. SFI's campus is spectacular, but it offers no classrooms or residential facilities.

Once again digital innovation has changed the game, this time with MOOCs (massive open online courses). In 2013 Melanie Mitchell taught the Institute's first MOOC. The 16-week "Introduction to Complexity" drew more than 7,000 students. It marked the debut of a growing series of free online SFI courses designed to cover a range of complexity science topics and to appeal to students at variety of levels. Since this inaugural, introductory MOOC, we've rolled out three more courses (offered throughout the year), each of which has garnered several thousand students. MOOCs probably will not replace the Institute's on-campus courses, but they may prove to be transformational. Already they have struck down the historical barrier between SFI and its potential global student body. A campus has become less relevant.

We're not a traditional university, so virtual courses won't siphon students off our campus. MOOCs may indeed bring students to us. Onsite schools and fellowships could become capstone experiences rounding out preliminary online study. Our MOOCs are already required introductory material for CSSS and undergrad fellowships. They will likely also drive more flipped formats (lectures online/hands-on "homework" exercises in class) across our course spectrum. Ultimately we want to develop a full-scale complexity science certificate program on our MOOC platform.

A canonical business model for online education has yet to emerge, but a definite requirement for SFI's MOOC courses will be financial sustainability. In 2011 the education program ceased to be supported by internal funds. Fortunately, we were able to transition successfully from underwritten support to tuition-based programs without losing enrollment or diluting student quality. All direct education costs are now covered

SFI ARCHIVES

GUTS y Girls is a science, technology, math, and engineering program for 6th-8th grade girls in New Mexico. GUTS y Girls features a series of Saturday workshops held once a month and a private online social network where participants interact with each other and professional scientists.

by course tuition, program-specific grant awards, or externally supported scholarship programs. Financial autonomy, now and in the future, will generate program stability as well as backstop experiment and innovation.

A near-term experiment that interests us is how to forge stronger connections between our student bodies and SFI's research as it happens. We're exploring having Learning Lab staff consult with Institute researchers before, not after, they submit research proposals. Collaboration at the pre-proposal stage results in awards that move beyond boilerplate to incorporate meaningful educational outreach that matches content. We also want to actively encourage researchers to produce short, informal MOOCs chronicling their real-time work on specific projects. Not only would this offer a fascinating glimpse into science practice, it would give researchers a chance to hone their teaching and communication skills.

Twenty-six years after George Cowan and Murray Gell-Mann first imagined SFI educational outreach, we're still not a Rockefeller University. Our education program instead is the serendipitous product of both intent and surprise. Yet it has successfully created a unique and robust learning community that we think the founders would find true to their purpose. And just as the founders did in 1984, we look forward to inspiring the next generation of learners and leaders in complexity – in the spirit of their original vision. ◀

Ginger Richardson is the McKinnon Family Vice President for Education and Outreach at the Santa Fe Institute. During her 28-year career at SFI, she has been the driving force and steady hand behind the gradual development of the world's first, and foremost, complex systems education program. SFI's programs now serve learners and teachers from middle school through adult professional education, providing a continuous learning path through all stages of education. She plans to retire from SFI in December 2014.

MINESH BACRANIA PHOTOGRAPHY

INDEX OF SFI-AFFILIATED PEOPLE MENTIONED THIS ISSUE

Robert McCormick Adams. Former Trustee, Santa Fe Institute; Secretary Emeritus, Smithsonian Institution; Adjunct Professor, Department of Anthropology, University of California, San Diego

Philip Anderson. Science Board Emeritus, Santa Fe Institute; Professor Emeritus, Department of Physics, Princeton University; 1977 Nobel Prize, Physics

Kenneth Arrow. Science Board, Santa Fe Institute; Joan Kenney Professor of Economics and Professor of Operations Research Emeritus, Department of Economics, Stanford University; 1972 Nobel Prize, Economics

Rob Axtell. Former External Professor, Santa Fe Institute; Department Chair, Department of Computational Social Science, Krasnow Institute for Advanced Study, George Mason University

George Bell. Former Director, T Division, Los Alamos National Laboratory

Luis Bettencourt. Professor, Santa Fe Institute

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$$=\left(\sum_{j\neq i} X_j^2 - X_j(\bar{X}+\bar{Y}) + \bar{X}\bar{Y}\right) + X_i Y_i - X_i$$

$$\sum X_j^2 - (\bar{X}+\bar{Y})\sum_{j\neq i} X_j + (n-1)\bar{X}\bar{Y} + X_i Y_i - X$$

$$\frac{\partial f}{\partial x} = 0 \Rightarrow$$

$$1$$

$$\Longrightarrow x = \frac{1}{2}$$

$$M_{\Delta T} = N M_{\Delta x}$$

$$\frac{\partial f}{\partial y} = 0 \Rightarrow x =$$

$$f = \frac{J_{t+1}}{J_t} = 1 - s$$

$$N^{pr.} = \frac{dE}{dt} = -p\frac{dv}{dt}$$

$$ds =$$