A Unifying Theme

FOR 21st CENTURY SCIENCE

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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.

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

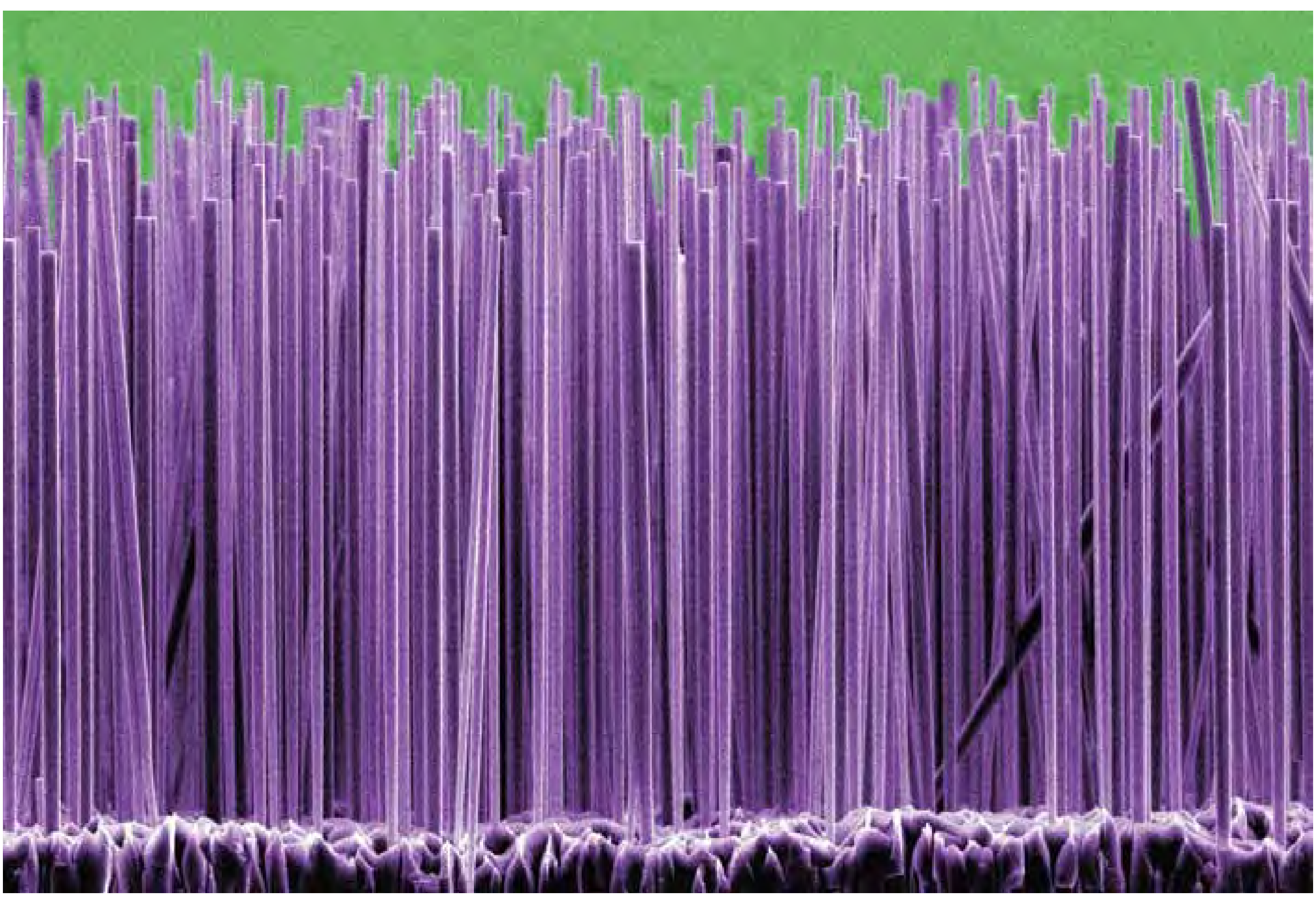
The Santa Fe Institute began exploring emergent behavior in science and society at its 1984 founding workshops, "Emerging Syntheses in Science," during which every speaker dealt with an aspect of emergent behavior as well as the search for the organizing principles that bring about that behavior[1]. 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.

RIGHT: MINESH BACRANIA PHOTOGRAPHY; ABOVE: DREAMSTIME.COM

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-



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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].

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:

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"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.

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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

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The Tiananmen Square protests in Beijing in 1989 arose from deep-seated and wide-spread 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.

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.

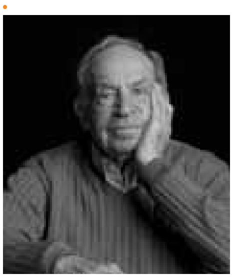
co-sponsored by ICAM (the Institute for Complex Adaptive Matter), a distributed institution with its home on the web. ICAM's scientific strategy for studying emergent behavior in quantum, soft, and living matter was informed by SFI and the article by Laughlin and myself cited above. ICAM last year joined 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].

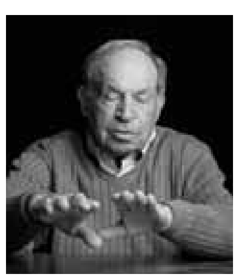
In the course of these workshops, many big questions about emergence were proposed for the scientific community. One of the most important questions concerned a science-based "emergent" approach to solving societal problems. The grand challenge is to develop an emergence-based

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





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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." ◀

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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).