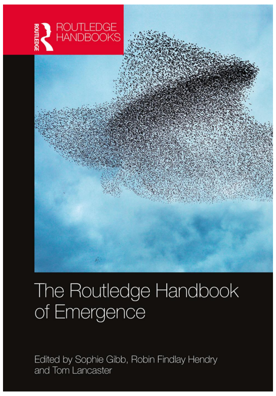

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Sophie Gibb, Robin Findlay Hendry, Tom Lancaster

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EMERGENCE

A personal perspective on a new paradigm for scientific research

David Pines

Introduction

Twenty years ago, in the physical sciences, the particle physics community was focused on a reductionist "top-down" paradigm whose success was embodied in the standard model of particle physics, in which one wrote down a model Hamiltonian for the so-called elementary particles – quarks and gluons – and pursued its consequences. There was heady talk of arriving at a "Theory of Everything" based on what was regarded as the fundamental approach to understanding the universe in which we live.

A contrary view had been expressed by P.W. Anderson in his seminal 1972 *Science* article on quantum matter, "More Is Different" (Anderson, 1972), in which he focused on broken symmetry and hierarchical organization and argued that these significant phenomena would never appear in a reductionist approach. Anderson wrote:

> The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.
>
> *(393)*

> The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.
>
> *(393)*

The past twenty years have seen a major shift away from the reductionist paradigm for carrying out scientific research to one that focuses on emergence and emergent behavior, terms that interestingly are not to be found in the Anderson article. When electrons or atoms or individuals in societies interact with one another or their environments, the collective behavior of the whole is strikingly different from that of its parts. We now 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. The study of emergent behavior at every level is as fundamental as work on the laws that govern the behavior of quarks and gluons.

In the study of inanimate and living matter, the Institute of Complex Adaptive Matter (ICAM), a distributed institute with its home on the Web (http:icam-i2cam.org), has played a significant role in bringing about this change. ICAM researchers focus on identifying the organizing principles responsible for the emergent behavior observed in the laboratory and, importantly, bring this research to the attention of the broader scientific and educational community.

In this chapter, I give a personal perspective on the role played by ICAM, which began in 1998 with six branches and now has twenty-six branches in North America and twenty-three branches in Asia, Europe, South America, and Israel. ICAM's message about emergence is communicated through a program of workshops, fellowships and exchange programs, and a significant outreach program of science, education, and engagement activities (Web 1). I describe the impact of a paper that served as ICAM's initial emergence manifesto, "The Theory of Everything", by me and R.B. Laughlin (Laughlin and Pines, 2000a) and the ICAM outreach efforts that led to the development of an online science museum devoted to emergent behavior (http://emergentuniverse.org). I then consider the role played by emergence in an online course, "Physics for the Twenty-First Century", and an emergence-based university course, "Gateways to Emergent Behavior in Science and Society". I conclude by describing a recent effort to teach eighth graders to "Think Like a Scientist", which uses a new approach, emergent scientific thinking, to introduce them to a broad spectrum of emergent behaviors.

ICAM begins

ICAM's origins may be traced to a 1996 conversation over lunch in which Zachary Fisk and I were discussing ways in which the many disparate research efforts on materials at Los Alamos might be more successful. We realized that finding a common theme would be a step forward, and I suggested that "complex adaptive matter" might offer that theme, since complex adaptive systems had proved to be a unifying theme for the Santa Fe Institute. We defined complex adaptive matter as the study of the generally unpredictable emergent behavior brought about by the interactions of the component parts found in living and inanimate matter. A succinct description of the results of those interactions had been provided earlier in Anderson's "More Is Different".

Zachary and I then proposed the idea to a number of senior Los Alamos National Laboratory officials, whose response was on the whole positive, sufficiently so that some two years later, in December 1998, the Center for Materials Research at LANL organized what proved to be the founding workshop for ICAM. Would-be participants in the workshop were asked to submit brief statements on the potential of such an institute, such that even before the workshop convened, it was already clear that a number of leaders in the condensed matter and biological physics communities were supportive of our idea of forming a distributed institute to study emergent behavior in matter.

ICAM began operating as an independent unit of the University of California, located at Los Alamos, reporting to the UC Office of the president, on March 4, 1999, with founding meetings in Oakland, California, of its board of trustees, chaired by Zachary Fisk (Florida State) and Alexandra Navrotsky (UC Davis), and its Science Steering Committee, chaired by Robert Laughlin (Stanford) and Peter Wolynes (UIUC).

It began as a joint project of the University of California's Office of the President (UCOP) and Los Alamos National Laboratory with support and oversight being provided by Robert Shelton, the UCOP Vice-President for Research, and Bill Press, the LANL Deputy Laboratory Director. Don Parkin, leader of LANL's Center for Materials Science, and I were asked to become

ICAM's founding co-directors. I accepted a five-year appointment as a LANL staff member to help ICAM emerge.

The first ICAM workshop was on "Adaptive Atoms in Physics, Chemistry, Biology, and the Environment". Co-chaired by Daniel Cox (UC Davis), Zachary Fisk, Andrew Shreve, and John Kazuba (Los Alamos), the workshop examined a broad range of systems in which adaptive atoms (atoms whose valency is determined through their interaction with their environment) play a key role in bringing about their observed emergent behavior. The participants concluded that there was so much to be gained by bringing physical scientists, biologists, and environmental scientists together to tackle problems at the frontier in this field that the study of adaptive atoms and their role in electron transfer reactions, broadly defined, could be regarded as a grand scientific challenge for the ICAM scientific community. The workshop soon gave rise to ICAM's first scientific paper (Cox, 1999) and to some seven nascent research groups – scientists from different fields and institutions who sought bridging support to initiate collaborations on problems identified at the workshop. The workshop also served to stimulate the formation of ICAM nodes in this and related areas at UC Davis, Rice University, Oxford University, and Los Alamos. This first success was soon followed by the workshop on "Mesoscopic Organization in Matter" described later.

The Theory of Everything

On January 1, 2000, *Proceedings of the National Academy of Sciences* (PNAS) published an article written by Bob Laughlin and David Pines, "The Theory of Everything" (Laughlin and Pines, 2000a), that, *inter alia*, served as an *emergent manifesto* for ICAM. Although Bob and I had been collaborating on bringing ICAM into existence during the previous two-year period, it had not occurred to us to write a paper about emergent behavior. Matters changed in March 1999, when my newly diagnosed cancer was being treated at UCSF, and I realized that by scheduling an early morning dosage of radiation, I could be free to do science the rest of the day. I wrote to Bob asking whether I might spend a few days each week during the seven-week course of treatment visiting him at Stanford and received a positive response.

As the visits took place, we realized we had a mutual antipathy to the then-popular idea that out of the reductionist approach of particle physics there might emerge a "Theory of Everything". We shared as well the belief that it was timely to call the attention of the scientific community to the importance of starting with an emergent paradigm in which the key ingredient was the realization that we live in an emergent universe in which the interactions between the fundamental components lead to unpredicted emergent behavior at every scale.

In "The Theory of Everything", we demolished the idea that there could ever be a theory of everything in which the behavior of complex adaptive matter could be derived from a set of "fundamental laws" in the traditional reductionist sense. We introduced the concept of *protectorates* to characterize emergent physical phenomena governed by emergent rules that are insensitive to microscopics.

There are many of these protectorates, with the first to be recognized being the Landau Fermi liquid, the state of matter represented by conventional metals and normal ^{3}He, the lighter-weight isotope of helium. Landau realized that the existence of well-defined fermionic quasiparticles at a Fermi surface was a universal property of such systems that is independent of microscopic details. Landau eventually abstracted this to the more general idea that low-energy elementary excitation spectra were generic and characteristic of distinct stable states of matter. Other important quantum protectorates include conventional superconductors; superfluid Bose liquids such as ^{4}He; and the newly discovered atomic condensates, band insulators, ferromagnets, antiferromagnets, and the quantum Hall states. The low-energy excited quantum states of these systems are particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle. These quantum protectorates, with their associated emergent behavior, provide us with explicit demonstrations that the underlying microscopic theory can easily have no measurable consequences whatsoever at low energies. The nature of the underlying theory is unknowable until one raises the energy scale sufficiently to escape protection.

As Laughlin and Pines tell us,

> [L]iving with emergence means, among other things, focusing on what experiment tells us about candidate scenarios for the way a given system might behave before attempting to explore the consequences of any specific model. This contrasts sharply with the imperative of reductionism, which requires us never to use experiment, as its objective is to construct a deductive path from the ultimate equations to the experiment without cheating. But this is unreasonable when the behavior in question is emergent, for the higher organizing principles – the core physical ideas on which the model is based – would have to be deduced from the underlying equations, and this is, in general, impossible. Repudiation of this physically unreasonable constraint is the first step down the road to fundamental discovery.
>
> *(2000: 30)*

Perhaps the best way to get a sense of the continuing impact of the article is to go to Google Scholar. Here one finds that each year during the past decade some forty authors have cited "The Theory of Everything". If 2015 is a reasonable sampling, some 25% of their papers deal with physics and about the same number deal with the philosophical issues relating to emergence; the remainder cover a remarkably broad area of science that includes as a few unusual examples biological autonomy, business ecosystem dynamics, mental states as emergent properties, interferometric probes of Planckian quantum geometry (Kwon, 2015), crime as a complex system, "cupping" therapy, proteins as nanomachines, materials aging at the mesoscale, quantized orbits in weakly coupled Belousov-Zhabotinsky reactors (Weiss and Deegan, 2015), agent-based modeling, language as a values-realizing activity, and biological emergence and inter-level causation.

The range of topics suggests that our message about emergence and protected behavior is spreading throughout the world of science and is turning up in some quite unexpected places.

Workshop II: "Mesoscopic Organization in Matter"

Chaired by Robert Laughlin, Peter Wolynes, David Pines, and Alexander Balatsky (Los Alamos), a second ICAM workshop brought together thirty-three senior scientists, three postdocs, and three graduate students for an in-depth discussion of "Mesoscopic Organization in Matter". "Mesoscopic" describes a length scale intermediate between microscopic and the human scale, and organization of matter on the mesoscopic scale is a fascinating example of the emergent behavior found in both living and inanimate matter. There was unanimous agreement among the participants that the mesoscopic world is a key frontier in science, and that one of the grand scientific challenges in the study of matter is establishing the existence or non-existence of mesoscopic protectorates, rules of organization of matter on this scale that transcend details. A second grand scientific challenge identified at the workshop was establishing the connection in biology between structure, energy landscapes, dynamics, and function that make possible the predictive design and synthesis of biomolecules. There was agreement that sharp disciplinary boundaries are counterproductive in pursuing these challenges and that great and largely untapped research opportunities lie at the interface between the cultures of the physical and biological sciences.

Immediately after the workshop a group of us spent four days at my home working on the draft of a paper that would tell a PNAS audience about what we had learned at the workshop. "The Middle Way", by R.B. Laughlin, D. Pines. J. Schmalian, B. Stojkovic, and P.G. Wolynes (Laughlin et al., 2000b), was intended to provide an in-depth overview of mesoscopic organization in matter. (The "Buddhist" title was proposed by Wolynes.) We suggested to PNAS that it appear as a companion article to "The Theory of Everything", and the two papers appeared together in PNAS in its inaugural issue for this century.

The workshop also led to nine requests for bridging support to assist in the formation of multidisciplinary, multi-institutional research groups devoted to examining specific aspects of emerging macroscopic order in both living and quantum matter and to the establishment of ICAM research nodes at UCSB, UCLA, UCSD, UCB, UIUC, Stanford, Rutgers, Iowa State, and the University of Chicago.

Workshop III: "Designing Emergent Matter"

"Designing Emergent Matter", the title of the third ICAM workshop, focused on the extent to which one could use well-established organizing principles for emergent behavior in matter to design new materials. It brought together chemists, biological physicists, and quantum physicists who discussed state-of the-art approaches toward achieving this goal. What made it different from earlier ICAM workshops was the inclusion of two major science writers among the invitees, Sandy Blakeslee and George Johnson of the *New York Times*. Sandy published a contemporaneous article about the workshop that conveyed to the general public the challenges of designing emergent matter. George waited some months before producing, in December 2002 for the *New York Times*, an account of the tensions in the scientific community associated with transition underway from reductionism to emergence.

The *New York Times* on emergence vs. reductionism

What George Johnson succeeded in doing in his lengthy and lucid article was to set the stage for a global debate on whether the reductionist paradigm would be overtaken by an emergence-based paradigm. In the physical sciences the hard-core reductionists were to be found in the theoretical particle physics community, who firmly believed in a top-down approach to understanding their field and, by inference, all of physics. Looking back, it appears likely that at this time, in 2002, their view was accepted by a significant portion of the physics community.

The minority view in the physics community – that we live in an emergent universe – was largely espoused by theorists who studied quantum matter, a field in which experiment seemed to provide an unending set of unexpected and unpredicted behaviors. (After all, as early as 1972 the battle was joined by Phil Anderson in "More Is Different.", in which he argued that the study of quantum matter [and matter more generally] was every bit as fundamental as the study of quarks and gluons.)

Those interested in science communication quickly picked up on the debate in progress. The day after George's essay was published, I was invited by Ira Flatow, host of the NPR show *Science Friday*, to debate Leon Lederman on the topic. As it turned out, in the *Science Friday* debate, Lederman was joined by a leading particle theorist, Chris Quigg. I like to think that I held my own against the two of them.

Bob Laughlin and I received an invitation from one of the leading scientific literary agents to write a book expanding the views we had expressed in "The Theory of Everything". Laughlin and I did start collaborating on a book, but it soon became clear that Bob's literary voice was sufficiently different from mine that it was better for him to write it alone. His book, *A Different Universe*, was published in 2004 (Laughlin, 2005).

The 115 materials and the two-fluid model

As part of its continuing focus on emergent behavior in quantum matter, ICAM held a workshop in December 2002 on some remarkable materials, the heavy electron family Ce*M*In5, where *M* could be Co, Rh, or Ir. At low temperatures, as the external pressure was varied, these "115" materials could be antiferromagnetic, superconducting, or both. At high temperatures they behaved like a collection of interacting local moments, but as the temperature was lowered the hybridization of the local moments against a background of conduction electrons led to the emergence of an itinerant heavy component with masses that could become as large as 200 free electron masses. It was this mixture of local moments and heavy electrons that displayed the remarkable low temperature behavior noted earlier.

But how to sort this out? The answer came shortly after the end of the workshop, as Zachary Fisk; his postdoc, Satoru Nakatsuji; and I were discussing experiments they had carried out by doping the cerium sites with lanthanum. We realized that a consistent phenomenological account of their results could be obtained with a two-fluid model in which an order parameter described the emergence of heavy electrons. What we were doing was carrying out the first step toward a physical understanding of the emergence of heavy electrons in these and other heavy electron materials.

What makes this interesting to those who are not quantum theorists is that this initial phenomenology was followed by another fifteen years of work developing the phenomenological two-fluid model in much more detail and using it to achieve a better understanding of the emergent behaviors turning up experimentally, while still not being able to solve the problem microscopically. This research can serve as a proof of concept for what can be achieved at a phenomenological level with emergent behavior.

From quantum criticality to "Music of the Quantum"

Among the fascinating emergent behaviors found in correlated electron materials is the quantum-critical behavior found when there exist two competing states of matter near absolute zero. This leads to a quantum-critical point that marks a transition from one state to the other and produces fluctuations that are called quantum critical. ICAM held a workshop on this topic at Columbia University in March 2003.

One of the workshop organizers, Piers Coleman, saw this as providing a unique opportunity to inform the greater New York City community about ICAM and emergence. His idea was to hold a combined musical and scientific event that would be of interest to both the scientific and musical communities in New York. He persuaded his brother, Jaz, a talented musician and composer, to write a piece, "Music of the Quantum", for the occasion, and I was able to obtain funding for the event.

Expectations for the concert and popular lectures on March 22 were high, but the timing was terrible, since that was the day the Gulf War began. As such, there was no possibility of coverage in the major newspapers, many potential listeners stayed home to follow the latest news of the war, and concert impact on the city was minimal. Those who were able to attend were rewarded by the world premiere of a science-inspired composition and two excellent popular lectures by Bob Laughlin and Piers Coleman.

Fortunately, the event was recorded and posted online at http://musicofthequantum.rutgers.edu, to include not only a recording of the concert but also a number of interviews on emergent behavior with scientists who came to the workshop. I strongly encourage readers of this chapter to relive the event online.

ICAM and emergence go global

The NSF held a competition in 2004 for awards to three institutions to establish international materials institutes. ICAM was encouraged to enter the competition and emerged as one of those selected. It used the award to establish I2CAM, the International Institute for Complex Adaptive Matter, which soon had as many branches abroad as it did on home soil. During the next decade (the period over which such NSF support was available) I2CAM was able to expand its emergence-based research, educational, and outreach program to some eighteen countries in Europe and Asia. The global expansion was so successful that, three years after the end of NSF support., ICAM has twenty-six North American branches, eleven Asian branches, eight European branches, two South American branches, and one branch each in the Middle East and Australia. Many of these latter branches are consortia of several institutions, so that, in fact, some forty-nine scientific institutions outside the United States are members of ICAM. This significant global presence translates into a major expansion in the number of scientists who have come to appreciate and embrace the emergent paradigm.

Estimating the impact of ICAM workshops on emergent thinking

State-of-the art workshops are a remarkably effective way of communicating new science and new ways of doing science. Not only are the participants informed, but as they return home, and in the months and years that follow, they spread the word through organizing new research initiatives and giving talks at meetings. The founding 1998 ICAM workshop and the three that followed involved some 200 participants. A conservative estimate of their impact would be to assume that each participant in turn introduced five students or colleagues to emergent thinking during the first three years of ICAM's existence. If we assume that during this period, "The Theory of Everything" had some 500 attentive readers, that the George Johnson piece in the *New York Times* added another 500 new readers, and that the *Science Friday* piece on the topic added another 1000 scientific listeners, we arrive at an estimate of some 3000 scientists whose thinking about emergent behavior may have begun to change. If then each of these scientists during the following decade influenced the thinking of say, 5 other scientists, we arrive at an impact factor of 75, from the 200 founding participants to some 15,000 emergence-oriented scientists today. This is likely a significant underestimate, as some fifty additional ICAM workshops were held and a number of other efforts, described later, also began to have an impact.

Emergentuniverse.org

The most ambitious emergence-based outreach program undertaken by ICAM was to inspire and find support for the establishment of a virtual science museum, emergentuniverse.org, that was aimed at an audience of millennials who are not scientists. ICAM was able to find the perfect person to carry out this ambitious project, Suzi Tucker, who had changed careers from being a successful statistical theorist with a tenured professorship to become a scientific exhibit and web designer.

Her museum is divided into three main parts: (1) an introduction to emergence, with examples ranging from fish schooling to cars in traffic to the "Game of Life"; (2) "Resistance is futile" – an introduction to superconductivity, the poster child for emergent behavior in quantum matter; and

(3) an examination of Alzheimer's disease, from its origin in the formation of amyloid plaques in the brain to its onset and consequences. Among the many segments on the website are a flash dance group illustrating a key aspect of superconductivity, the highly correlated motion of electron pairs, and a moving illustration of the changes in personality that accompany Alzheimer's disease.

One can keep track of the number of visitors to emergentuniverse.org. As of January 2018, in its ninth year, it has had some 182,000 visitors. It lifetime may be limited, as it is based on flash technology, which is being abandoned by the industry. So ICAM and its outreach-based spin-off, described next, are exploring what might be done to preserve this online museum and develop a version addressed to eighth graders.

"Physics for the 21st Century"

I turn now to the role played by emergence in three educational experiments. "Physics for the 21st Century" (Web2) is an online course that explores the frontiers of physics. The eleven units, accompanied by videos, interactive simulations, and a comprehensive Facilitator's Guide, work together to present an overview of key areas of rapidly advancing knowledge in the field, arranged from the subatomic scale to the cosmological. The goal is to make the frontiers of physics accessible to anyone with an inquisitive mind who wants to experience the excitement, probe the mystery, and understand the human aspects of modern physics.

The course has been distributed free of charge on the Web since 2010. It was designed by Harvard Professor of Astronomy and Physics Christopher Stubbs, with units developed by a distinguished group of physicists from Harvard and other top universities and research centers. Produced by the Science Media Group at the Harvard-Smithsonian Center for Astrophysics and funded by Annenberg Media, it is intended to open the doors to an exciting world of ideas, to help bridge the gap between what is being taught in high school and college and what is exciting physics researchers.

Two of its eleven units in the course are devoted to emergent behavior: "Emergent Behavior in Quantum Matter", which I wrote and is based on a course with that title that I taught for a number of years at UC Davis, and "Biophysics", written by Princeton University Professor of Physics Robert W. Austin. Taken together, these provide a unique introduction for high school students and their teachers to emergent behavior in quantum and living matter.

"Gateways to Emergent Behavior in Science and Society"

A course with the title "Gateways to Emergent Behavior in Science and Society" was taught at UC Davis in 2012. The aim of the course was to provide students with the tools they need to develop an emergent perspective on problems in science and society by focusing on gateways to emergent behavior we have identified in the physical and biological sciences and on gateways that have been proposed for solving some of our major societal problems.

This new course was an experiment, stressing interdisciplinary and integrative learning at the upper undergraduate and graduate level. There are several aspects to the experiment: the topic of emergence as a unifying principle bringing together students in different sciences; the emphasis on emergent global problems and the science needed to assure clean, secure, and sustainable energy and food supplies to power and stabilize our world; the integration of high-profile guest lecturers who will also participate in other campus activities; and grading based on a website created by each student. This experiment will set the stage for other innovative, rigorous, and adventurous intellectual experiences for UC Davis students.

The course was organized and co-taught by David Pines and Alexandra Navrotsky (Distinguished Interdisciplinary Professor of Ceramic, Earth, and Environmental Chemistry at UC Davis).

They enlisted the help of a number of internal and external distinguished colleagues who are each world leaders in their respective fields and invited them to spend two days on campus, during which they gave a major public lecture that formed part of the course and met with our students.

The first guest lecturer was Ralph Cicerone, the then-president of the National Academy of Sciences. He was followed by Peter Littlewood, a past director of Argonne National Laboratory; University of Colorado physicist Ivan Smalyukh; MacArthur Fellow Shawn Carlson; the ecologist Simon Levin of Princeton University; Peter Smerud, the director of the Wolf Ridge Environmental Learning Center; the earth scientist Sue Kieffer of Princeton University; and the Carnegie Institution geophysicist, Robert Hazen. Their lectures were videotaped and may be viewed online (Web3).

Think Like a Scientist

Emergence is reaching a much younger audience through Think Like a Scientist (TLS), a global movement that recognizes, connects, and expands the efforts of individuals and organizations seeking to stimulate *all* students to think like scientists in the emergent universe in which they live. It is convening teams of engaged scientists, innovative educators, citizen science and science museum leaders, and game designers who use emerging technologies to create resources and activities that are designed to inspire and teach middle school students to think like scientists, provide teachers with new ways of thinking about the science they teach, and connect engaged teachers and students to mentors from the working scientist community.

To bring emergent behavior to an eighth-grade audience, TLS is focusing on *emergent scientific learning*, defined as a multifaceted approach using emerging technologies to learn about science. In emergent scientific learning, because of the many possible interactions and synergies between these different modes, the whole becomes much more than, and different from, its parts.

To help identify the skills of Thinking Like a Scientist, TLS has introduced *TLS/Concepts*, a summary of the skills that go into TLS. As may be seen next, emergence and emergent scientific thinking play a key role among these thirteen steps that enable an eighth grader to think like a scientist.

1. **Be curious – inquire!** Never accept that something is unexplainable. We just don't have the answer yet. Do not think there are black boxes; these are just boxes that we don't yet understand.
2. **Learn to look for patterns** in your data, whether they are obtained on the Web or by recording the results of your own hands-on experiments.
3. **Carry out experiments** or use the Web to study the result of using different probes to make measurements and ask how the results might be connected.
4. **Collaborate and communicate** through participation in group work on projects.
5. **In the emergent universe** in which we live, "More is different" because the interactions between people and matter and the environment in which they exist lead to unexpected consequences and unpredictable behavior at every scale. The whole is different from its parts, as everyone who has ever baked a cake knows full well.
6. **Know how to get science-based facts, experiments, observations, and data from the Web.**
7. **Know how to analyze and interpret data.**
8. **Begin to understand systematic and statistical errors in your data.**
9. **Begin to devise scenarios and logical alternatives to explain your observations.** For example, what is connected to what and how your observations change with the environment in which experiments are carried out.

10 **Understand that making mistakes is part of doing experiments** or carrying out observations, and mistakes can also advance science.
11 **Be skeptical** – Ask if the new fact you were told is science-based. Consider how the parts of the system interact – can you do an experiment, apply a mathematical principle, engineer a solution, or integrate technology to show that it is true?
12 **Be a complex problem solver,** recognizing that almost all problems are emergent in that there is no single cause and therefore no single solution. Therefore, to make progress, you need to experiment – try several solutions at once and then determine from observations which combination works best.
13 **Connect** – ask whether there are connections between different kinds of emergent collective behavior (e.g., birds flocking, fish schooling) or between the results of an experiment/observation and one of the big ideas in science.

In collaboration with the Smithsonian Institution's Science Education Center, TLS established ATLAS (Always Thinking Like a Scientist) as "A Journey into Your Emergent Universe". The first semester of ATLAS/Aspen, an experimental out-of-school program in which high school students act as lead explorers who expose a group of middle school students to ideas, concepts, and methods that help them learn to think like scientists, has just been completed. As measured by the enthusiasm displayed by the students in their eagerness to continue being part of ATLAS/Aspen, the experiment was an outstanding success.

Conclusion: emergent strategies

For the layman, perhaps the key takeaway that comes from recognizing that you live in an emergent universe is the realization that any problem you face, whether at home or in society, is likely to be emergent. This implies that it has no single cause and no single solution. So your emergent strategy is to experiment with many solutions at once, look for emergent synergies among these, and take advantage of these as they emerge.

For the scientist, it means building a physical understanding of your field based on experiment and using a phenomenological approach to explaining the emergent behaviors you study. Indeed, in many, if not most, cases, a detailed phenomenological description may be the best one can do. Recognizing this is the case requires abandoning the reductionist dream of being able to develop a microscopic model that captures all aspects of the emergent behavior one is studying and represents a key step toward making progress in understanding it.

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