Simplicity and complexity

Research in complex systems can reveal the workings of everything from the human immune system and power grids to the social web. **James Crutchfield** and **Karoline Wiesner** wonder if there is a common theme to such work and ask where the field should go from here

James Crutchfield directs the Complexity Sciences Center in the Physics Department, University of California, Davis, US, and is a faculty member of the Santa Fe Institute in New Mexico, US. **Karoline Wiesner** is in the Centre for Complexity Sciences and School of Mathematics, University of Bristol, UK, e-mail k.wiesner@bristol.ac.uk

Is anything ever simple? When confronted with a complicated system, scientists typically strive to identify underlying simplicity, which we articulate as natural laws and fundamental principles. This simplicity is what makes nature appear so organized. Atomic physics, for example, approached a solid theoretical foundation when Niels Bohr uncovered the organization of electronic energy levels, which only later were redescribed as quantum wavefunctions. Charles Darwin's revolutionary idea about the "origin" of species emerged by mapping how species are organized and discovering why they came to be that way. And James Watson and Francis Crick's interpretation of DNA diffraction spectra was a discovery of the structural organization of genetic information – it was neither about the molecule's disorder (thermodynamic entropy) nor about the statistical randomness of its base-pair sequences.

In 1948 the mathematician Warren Weaver, who was then director of the Rockefeller Foundation, wrote a famous essay entitled "Science and complexity" in which he rather boldly claimed that while "the 19th century was the century of disorganized complexity…the 20th century must be that of organized complexity". Indeed, research on complex systems had progressed on many fronts during the 1940s and 1950s, which witnessed the temporary efflorescence of systems science, cybernetics and theoretical biology. In hindsight, however, we know that Weaver glimpsed only the beginning of a new era of science – what came to be known as the science of complex systems. Perhaps Weaver, who died in 1978, would be disappointed to learn that, at the start of the second decade of the 21st century, the exact nature of organized complexity remains the subject of ongoing debate.

What remains prescient, however, is Weaver's insight that organization plays a key role across the sciences. We think that the appearance of complex-systems science at the end of the 20th century was not an accident; rather, it was inevitable. The intense interest in complex systems – ensembles of dynamic, interacting elements that exhibit robust collective properties – and the struggles to define complexity reveal a trend in the broader scientific community to become explicitly focused on how nature is organized. That trend is driven by an enthusiasm for finally building a conceptual framework and experimental methods that directly acknowledge nature's diversity of form.

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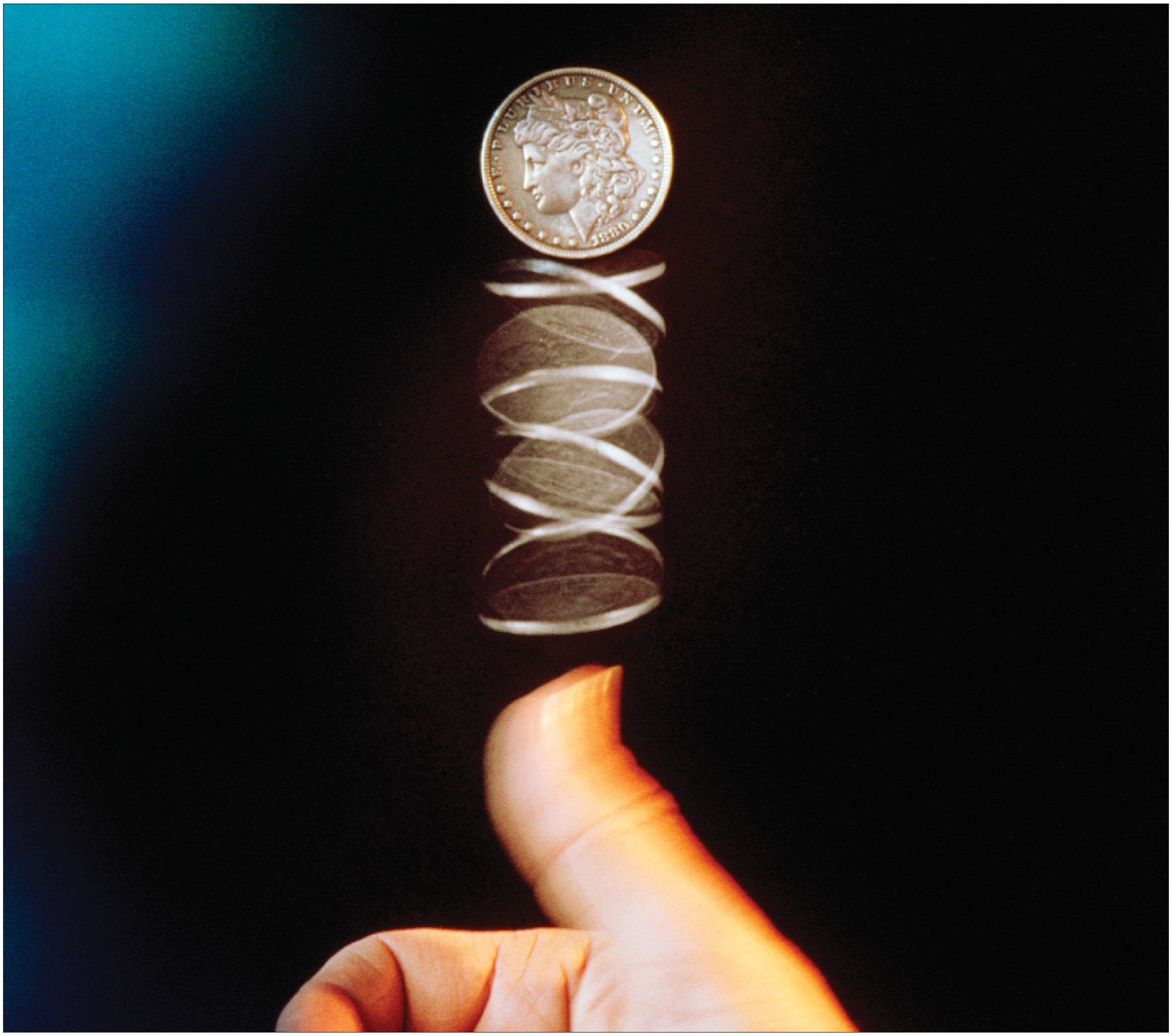
Defining complexity

The fact that nature exhibits robust organization is a familiar one. From inanimate complex systems (such as critical phenomena in condensed-matter systems) to animate systems (such as the collective nest-building of wasps) to the fragility of today's engineered systems (such as the "route-flapping" that plagued Internet bandwidth in the early 1990s), organized complex systems appear almost everywhere.

Yet although we know it when we see it, have we made progress in defining organized complexity? Is identifying simplicity with organization anything more than a tautology? More practically, do we understand these concepts well enough to measure their associated properties? A quick review of the literature reveals that there is no shortage of answers. Indeed, the list of possible ways of measuring complexity grows longer with every decade. These range from new proposals to finally nail down the field's earliest challenge – which boiled down to the question of how random is a coin flip really? – to a plethora of ways to capture concepts of organization, such as "regularity", "sophistication", "hierarchy" and even "semantic content". Is this diversity real and necessary or only apparent?

This seeming Tower of Babel is a liability, having led to criticism of the field both from within and outside. A closer look, though, reveals a good deal of progress. It turns out that some measures of complexity are better defined than others, some are more revealing than others, while some are easier to estimate from data. One accepted milestone is that we already have well-defined (and closely related) measures of randomness, such as entropy (in the field of thermodynamics, measuring degrees of disorder), Shannon information (in communication, measuring degrees of unpredictability) and Kolmogorov–Chaitin complexity (in computation, measuring the size of the minimal computer program required to produce an object). Weaver acknowledged this progress when coining the phrase "disorganized complexity".

Thanks to these advances, when defining disorganized complexity, we can now refer to it as "randomness", reserving the term "complexity" to mean structure,



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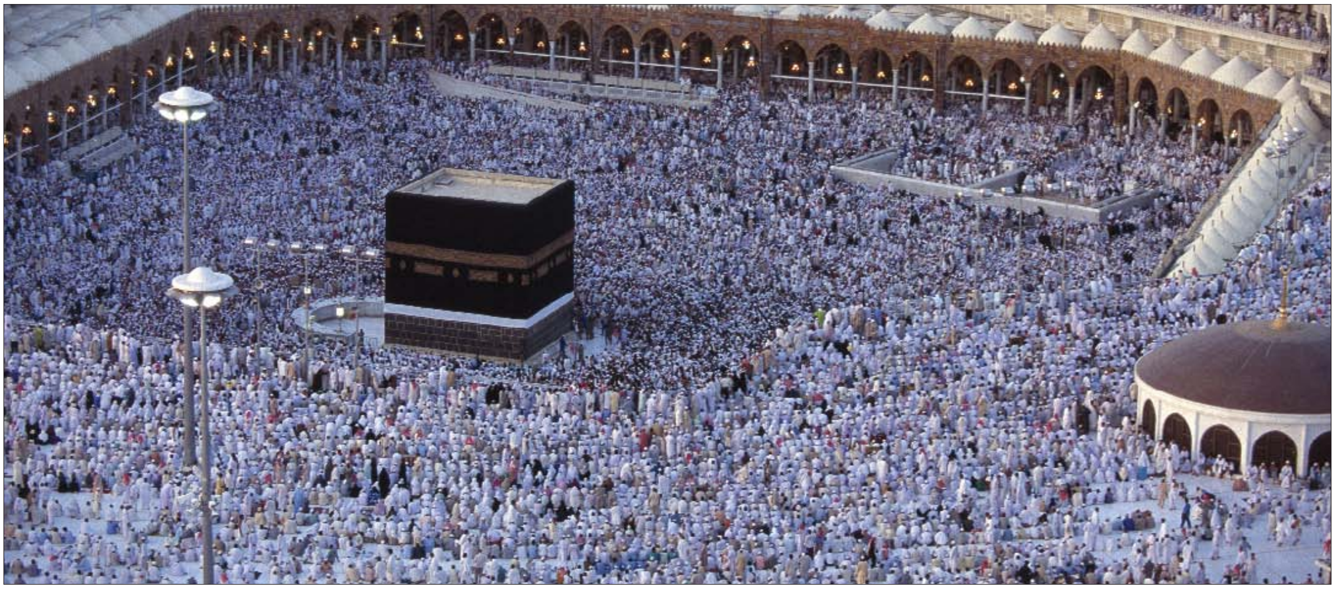
Disorganized complexity
Even deciding the exact randomness of a coin flip is subtle.

pattern and regularity. More to the point, a good measure of complexity captures kinds of organization. This is a necessary complement to understanding randomness, as it enables us to ask questions like how much organization does a system use to produce its randomness? That organization and randomness are complementary properties is familiar to computational physicists, who use pseudo-random number generators to emulate fair coin flips – ideal randomness. While giving similar degrees of effective randomness, though, different generators can be very differently organized. That is, they are different algorithmic structures that use different amounts of memory organized in different ways.

So, would Weaver be disappointed? Will "organized complexity" forever evade understanding, as some suggest? A number of recent experimental and theoretical successes demonstrate otherwise: measures of complexity can be calculated, estimated and interpreted in ways that are meaningful to specific scientific problems. For example, Chun-Biu Li and colleagues at the University of Chicago recently mapped the number of different possible conformations that a long-chain protein molecule can adopt – what is known as its "landscape" – using concepts from complex systems. The degeneracy of structurally distinct physical states was resolved using network analysis and information theory. In particular, the researchers found that measuring the structural complexity of a protein's conformational fluctuations gave new insight into the memory that proteins store (2008 *Proc. Natl Acad. Sci. USA* **105** 536).

Meanwhile, Dowman Varn of the Sante Fe Institute in New Mexico and one of us (JC) discovered that structure embedded in disordered solids can be extracted directly from experimental X-ray diffraction spectra of quasi-1D materials, called polytypes (2006 *Acta Crystallogr.* B **63** 169). This "chaotic crystallography" of noisy spectral data revealed that polytype structure consists of systematic mixtures of multiple, competing crystal types and their faults.

On the mathematical front, recent work by the present authors and others has begun to show that complexity measures fall under the umbrella of communication and computation theories. It turns out that various underappreciated aspects of Shannon's ori-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Collective behaviour Pedestrian traffic flows, such as those during the "hajj" pilgrimage to Mecca, have been successfully analysed using tools from the science of complex systems.

ginal information theory are key to breaking a system's organization into degrees of information storage and degrees of communication capacity, and to monitoring the extent to which these are present but encrypted in a system's behaviour.

These results, and many others, suggest that organization – defined in terms of a system's structure and measurable using extensions of Shannon's information theory – is a unifying theme in the science of complex systems. It is now not only desirable but possible and practical to develop a systematic and implementable theory of organization. In addition to continuing experimental applications, the mathematical results suggest a range of future conceptual developments that delve more deeply into Shannon's communication theory and also his theory of secrecy systems. They will find important roles in analysing complex interacting networks, for example.

Forced integration?

Reflecting on nature's organization at different scales – from fundamental particles to biochemical and brain processes – is not such a new idea. Until recently, however, most work was focused on specific complex systems, such as the Internet. But now that we can quantitatively compare disparate complex systems – thanks to recent work on complexity measures – we are in a position to discover the mechanisms through which low levels of organization successively give rise to higher and higher levels – just as atoms form molecules, molecules coordinate to form cells, and cells cohere to form biological organisms.

We believe that the brave new frontier, however, is in applying complex-systems tools to the social sciences. There, complex-systems science may finally overcome the long-appreciated limitations of adapting the physical sciences lock, stock and barrel to a domain where observables are unclear and where energy – the currency of physical theory – is not a universal fundamental. A notable example is work by Dirk Helbing and colleagues at the ETH Zurich, who have successfully analysed pedestrian traffic flow using mathematical and computational tools from complex systems to gain quantitative and qualitative insights into collective group behaviour. Such work has even led to the development of strategies for controlling large numbers of people in panic situations, such as during fires in crowded buildings, and in the annual "hajj" pilgrimage to Mecca, where over two million faithful are in motion.

Tracking the focus on organization through the recent history of science, the field of complex systems itself appears much more organized than at first sight. We suspect that the field is ripe to take a substantial step forward, if its members are willing to identify common goals. Today, many scientific communities regularly do just this – be it astroparticle physicists vying for new facilities or semiconductor firms coordinating to develop ever-smaller and more powerful integrated circuits. The question is whether the complex-systems community should attempt such a road map. This effort would not only put past advances in new light, but crystallize goals and ways to reach them.

In July 1991 the Nobel-prize-winning condensed-matter physicist Philip Anderson wrote in *Physics Today* that "we complexity enthusiasts (perish the thought that we be called complexity scientists!) are talking, at least for the most part, about specific, testable schemes and specific mechanisms and concepts. Occasionally, we find that these schemes and concepts bridge subjects, but if we value our integrity, we do not attempt to force the integration".

Given the field's progress since then, which suggests that we can identify common themes, and its rapidly increasing diversity, which threatens to Balkanize the field, it is time for us "complexity enthusiasts" to revisit Anderson's concerns. We believe that an attempt now to integrate different schemes and concepts will not be forced at all, but will help researchers to make progress. We are particularly hopeful about the novel perspectives the field could lend to solving the daunting challenges that confront societies that construct ever-more complex socio-technical systems – systems with emergent properties, such as correlated risk, that we often do not anticipate, sometimes with disastrous effect.