Emergent macrosimplicity

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At Home in the Universe: The Search for Laws of Self-Organization and Complexity. By Stuart Kauffman. *Oxford University Press/Viking: 1995. Pp. 321. $25, £20.*

THIS is a courageous book. It has a distinct spiritual focus, not in the religious sense, but in the sense of 'why are we here?' When coupled with an unorthodox message that is unavoidably critical of much mainstream science, the combination is dynamite; and that is what makes it a courageous book.

The topic is complexity theory *à la* Santa Fe Institute, with an emphasis on developmental and evolutionary biology. The conventional biologist sees evolution as the result of random mutations in DNA sequences, mediated by natural selection, and abhors suggestions that, evolution has any kind of inherent direction. Similarly, the conventional biologist sees development as a program written in DNA, a simple matter of assembling the right proteins. Stuart Kauffman argues that, in both areas, the conventional biologists have got the wrong end of the stick. He tells us that in adaptive complex systems a great deal of order and structure is often obtained 'for free'. It isn't built in; it emerges. He says that such systems can self-organize and self-complicate in a way that makes no sense to much conventional theorizing. He looks for a new kind of mathematics, one capable of dealing with emergence, that fits the breathtaking diversity of the natural world far better than the sterile rundown predicted by thermodynamics. And he thinks he knows where such a theory might be found.

Lost perspectives

To my mind, the conventional view of evolution loses an important perspective because it places too much emphasis on the least interesting features. Imagine a theory of the flow of water founded on the molecular nature of the liquid rather than the conventional continuum model favoured by fluid dynamicists. Suppose further that the only observations available are those of water in its natural habitat — streams and rivers, rainstorms and lakes — and that the surrounding landscape is invisible. We observe the water and try to explain its patterns as it meanders past a randomly strewn boulder or drops off an eroded ledge in a waterfall. And the story we tell is one of contingency and selection. At root, the flow of water is merely the random wanderings of molecules. There is no purpose, no goal, no order; just stochastic jiggling. But as the molecules jiggle around, some of them tend to accumulate, whereas others tend not to. So the first kind do accumulate, whereas the second rapidly jiggle themselves elsewhere until eventually they accumulate too. As a consequence of this random jiggling plus selection based on the purely contingent factor of accumulation, the mass of water moves. It could, it seems, go anywhere.

But things look very different when we can see the landscape. The places where water molecules tend to accumulate are contingent on their surroundings, for sure, but once we know the surroundings we can predict what will happen. Water accumulates where the potential energy is lower — in short, it runs downhill. The geography of the surrounding landscape imparts a definite direction. The random jigglings are important for only one reason: they render the water fluid, so that it can flow into the lower regions. Without the random jigglings, motion would be only potential, but with them it becomes actual. And although the mechanism whereby individual molecules select where to accumulate is also contingent, it inherits direction from the landscape. (Individual molecules can climb uphill, but on the whole they don't.)

Evolutionary biologists seem to have the wrong view of physics. They think that the flow of water is deterministic, and that the partial differential equations used by fluid dynamicists are actually implemented by the fluid itself. They thus derive a wholly misleading contrast between Darwinian principles and physical laws, and this confuses them when they start thinking about the global constraints that affect evolution. 'Goal' and 'purpose' are not the right words, to be sure, but there are dynamic effects in evolution, resulting from constraints. Mutations make phenotypes fluid enough to change, selection implements particular changes preferentially, but the overall result is more like water flowing through a landscape. It is an invisible landscape, however, formed out of the nearby 'potential' phenotypes and constrained by context — a mathematical 'phase space'. It includes not only what happens, but what could have happened instead.

It sounds metaphysical, but such imagery lies at the core of how physicists and mathematicians currently think about all dynamics. To them, phase space is just as real as ordinary space — it makes itself felt by constraining the potential dynamics into the behaviour that we actually observe.

What makes evolution particularly tricky is that the phase space is not fixed. It itself evolves, in response to the organisms that live in it. In *The Collapse of Chaos*, Jack Cohen and I coined the term 'complicity' for this kind of coevolution of content and context, but the words and concepts have not really been pinned down yet. We will never find them unless we recognize that there is some kind of global dynamic to evolution, and start trying to explore it. And that's one of the things that complexity theory is about: it shows that systems with a highly complex microstructure typically develop recognizable macrodynamics — usually in an emergent manner.

Topological constraints

One of Kauffman's basic examples is the Boolean network, a circuit of little light bulbs that are either on or off and that affect each other in an ever-changing way. Imagine a network with 100,000 bulbs. Mathematically such a system has only finitely many states — but vast, $2^{100,000}$ or about $10^{30,000}$ — so the only possible long-term dynamics is a periodic cycle. The question is: how long is the cycle? Short cycles are structured, very long ones might as well be random. Now, if all the bulbs connect together then the typical cycle has length about $10^{15,000}$. But if each connects to only two, then the typical cycle contains only 317 states. "I hope this blows your socks off", says Kauffman. Mine are well on their way to the Sahara. What this simple example tells us is that topology constrains dynamics. It quantifies one case where vast mirocomplexity gives rise to emergent macrosimplicity.

Kauffman's main message is that most of biology is like this. The path of evolution is far less contingent than Stephen Jay Gould in *Wonderful Life* would have us believe, because it is constrained by the topology of its own phase space. The same is true of development: the growing organism builds its own phase space along with its cellular structure.

Kauffman sings his song loud and long, from the origins of life to the emergence of a global civilization. It may not be a song that everybody wishes to hear, and it may be a song with many clashing harmonies and unscheduled pauses — but I sure hope he goes on singing it. And I guarantee that any reader whose imagination has survived an academic education — or has never been exposed to one — will learn a lot, and be changed forever. □

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