Five Questions

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1. Why did you begin working with complex systems?

The short answer is that the phenomena of "emergence" and "adaptation" were (and remain) absolutely fascinating to me. In nature we see many examples of huge numbers of simple elements, interacting with no central control, collectively producing sophisticated adaptive behavior that is far beyond the ability of any single or small group of component elements. Are there any general principles underlying this kind of emergent complex and adaptive behavior? And can we get machines to become intelligent and lifelike using those same principles? These questions are what got me hooked on complex systems.

In the early 1980s, after I graduated from college with a degree in math, I read Doug Hofstadter's book, Godel, Escher, Bach: an Eternal Golden Braid. That book was my introduction to some of the main ideas of complex systems, It presented a view of the mind as emerging from the brain via the decentralized interactions of large numbers of simple, low-level "agents", analogous to the emergent behavior of cells, ant colonies, and other such systems. I decided that I wanted to study artificial intelligence, and to try to work with Hofstadter on creating intelligent systems based on these ideas.

A year or so later I ended up going to graduate school in computer science at the University of Michigan in order to join Hofstadter's research group. Even at that time, Michigan was a hotbed of work on complex systems. It was the home of the so-called BACH group—named for its original members Arthur Burks, Bob Axelrod, Michael Cohen, and John Holland. These people are pioneers in the field of complexity. I took John Holland's course on "Adaptation in Natural and Artificial Systems", which put forward a view that (in my fellow student Chris Langton's words) "the proper domain of computer science is information processing writ large across all of nature." This really resonated with me. Holland became my co-advisor, along with Hofstadter. These two people have been the most important influences for me in my work.

When I was finishing up my Ph.D. in 1989, Hofstadter was invited to a conference at Los Alamos on "emergent computation". He was too busy to go, so sent me instead, which was a serendipitous opportunity for me. It was at that conference that I met many of the major players in complex systems, and found out about the Santa Fe Institute, a relatively new (at that time) center for research on complexity. After completing my Ph.D. I was invited to spend a summer there, and I was awed both by the beauty of Santa Fe and by the breadth, depth, and novelty of the science that was being done at SFI. I returned to SFI the following summer, and ended up being appointed to the Institute's research faculty. All in all I was there for about eight years, directing SFI's program in adaptive computation.

2. How would you define complexity?

I don't think there is a single good definition, just as there is no single good definition of "self-organization" or "emergence". People use words like this in different ways in different contexts. There is a well-known paper from 2001 by Seth Lloyd describing about 40 different definitions people had proposed, and there have been lots more since. None are really satisfactory, in my opinion.

A more useful approach, I think, is to ask what concepts are most appropriate to employ in characterizing the behavior of these so-called complex systems. My own view is that we will need a combination of concepts from the fields of nonlinear dynamics, information theory, computation, and evolution. People have long made connections among these various fields, but a real interdisciplinary language that captures all these aspects of complexity has not yet been formulated.

3. What is your favourite aspect/concept of complexity?

Given the complexity of "complexity", it's hard to isolate a single "favorite" concept. My current interests are largely focused on the pattern-recognition abilities of complex adaptive systems such as the brain, the immune system, insect colonies, individual cells. and genetic regulatory networks. Pattern recognition, at various levels of abstraction, is one of major activities of all living systems, and life-like pattern recognition has turned out to be rather difficult to capture in computers. I believe there are some general principles underlying the ability of large collections of agents to effect abstract pattern recognition in a decentralized way, and that these principles can help us in designing computer programs with similar pattern-recognition abilities.

4. In your opinion, what is the most problematic aspect/concept of complexity?

The concept of "emergence" is a tough one. It's central to complex systems, yet hard to define. For example, in cognitive science we might say that "concepts" are emergent properties of the activities of networks in the brain. What do we mean, exactly? One definition of emergence is "higher-level global behavior, arising from the collective actions of simple lower-level components, that is more complex than can be achieved by the lower-level components independently.". This leaves us to define "higher level", "global behavior", "collective actions", etc. Another definition might be "phenomena we don't yet understand, arising from the collective actions of components we do understand". Again, a rather unsatisfying definition for me, since my intuition is that "emergence" is not just a subjective property, dependent on what we do or don't currently understand.

Many people have tried to define "emergence" formally, but I haven't so far found a definition that is both correct and useful. Emergence is a phenomenon that I believe is "real" in some sense, and is key to understanding complex systems. However I don't think we yet have the conceptual framework or vocabulary to characterize more precisely what this phenomenon is.

5. How do you see the future of complexity?

I think that, as we increasingly understand complex systems, the concepts and vocabulary we use for describing them will become much more specific, quantifiable, and useful. That is, ill-defined terms such as "emergence", "self-organization", and "complexity" itself will be replaced by new, better-defined terms that reflect increased understanding of the phenomena in question.

One danger is that the field of complex systems might go the way of General Systems Theory or Cybernetics. These earlier disciplines were aimed at answering many of the same questions that complex systems addresses. However, they got a bad name for being, as one Nobel-prize winner described, "well-meant, but premature and intellectually lightweight". It's possible that in 50 years people will similarly criticize early 21st century complexity research.

This is indeed a risk. However, the possible payoffs for pursuing this area are great. In the life sciences, brain science, and social sciences, the more carefully scientists look, the more complex the phenomena are. A good example is the unexpected complexity that is being discovered in genetics and development. New technologies have enabled these discoveries, and what is being discovered is in dire need of a new kind of conceptual vocabulary for describing this complexity and a set of theories about how such complexity comes about and operates. That is something I think complex systems is gradually beginning to offer. As people in the field have joked, we're "waiting for Carnot"—that is, waiting for the right concepts to be formulated to describe what we see in nature. Who knows? It's possible that our Carnot is already among us.