Five Questions on Complexity: Responses

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1. **Why did you begin working with complex systems?**

Why I began working with complex systems is much clearer to me now than during the 1970s when I started to work on nonlinear dynamical systems. The way I think about my original motivations is best expressed as a historical reconstruction, giving some insight to the times and how the field developed. Hopefully, it casts the answer in a way that highlights the intellectual challenges.

From this perspective, one can see the recent history of complex systems as two sides of the same coin. The first side was the discovery that simple systems can appear random (and high dimensional), even when consisting only of low-dimensional, but nonlinear coupled components (aka "deterministic chaos"). Despite our intuitively negative reaction to unpredictability, deterministic chaos was great news at the time. Could much of the randomness that we see around us in the natural world be, underneath, hidden away, simple nonlinear dynamical systems? If so, we might be able to extract the hidden simplicity—states and dynamic—from a few, or even one, variable. Answering this question led to the introduction of the idea of reconstructing "Geometry from a Times Series" by Norman Packard, myself, Doyne Farmer, and Rob Shaw in 1979. By the mid-1980s that idea had spawned much work on nonlinear time series analysis, which provided an important push against the then-dominant focus on linear, stationary, independent, identically distributed processes.

However, success in analyzing how chaos arises set up a second, more problematic side of the coin—the attempt to answer a complementary puzzle. If simple systems can spontaneously generate random-appearing behavior, why do large-scale systems with many components appear ordered? In short, what is the origin of organization in a chaotic world? This question led me to explore the mechanisms of pattern formation in spatially extended dynamical systems by introducing the prototype class of map lattices and experimenting with video feedback, chemical oscillators, and ferrofluids. Quite a bit of groundwork on spatial systems had been laid decades before by statistical physicists studying phase transitions and critical phenomena. But their approach was not very "dynamical" and relied on assumptions of ergodicity to explore spatial organization through random samples of spatial configurations. To my mind, this use of ergodicity throws the baby out with the bath water, disregarding the question of the dynamical origins of organization. Exactly what mechanisms—state space structures—constrain and guide organization? Adding to the shortcomings with the statistical physics approach, spatial "structure" was often quantified only through correlation functions, which throw away almost all of what is unique and interesting in organized systems.

In looking back at this history, it becomes clear that randomness from simplicity and order from complication are two sides of the same coin and that coin was the concept of pattern and pattern emergence. So, in the historical evolution, the first intellectual innovation was to appreciate the mechanisms that led to randomness and the second was to understand the mechanisms that led to order. Today, we appreciate that much of what we call pattern, what we try to encode in theories and concepts, arises from the dynamical interplay of randomness and order. It's this middle ground that has been so hard to model, to predict, to explain. It fascinates us nonetheless, since it is in this middle ground where pattern (structural complexity) emerges.

So if you had asked me why I worked on complex systems in 1976, I would have only been able to answer that I was fascinated with chaotic dynamical systems: local determinism leading to long-term unpredictability; beautifully intricate attractor topologies; the rather deep concept of state (or configuration) space and a dynamic over it; and the like. I eventually came to call this "microdynamics" in the sense that one focused intently on very fine scale structures—homoclinic tangles, absolutely continuous invariant measures, uncountably many periodic orbits, fractals, self-similar basin separatrices, the spectrum of Lyapunov characteristic exponents, ... The origins of randomness were remarkably structured.

Exploring order and randomness has a long history and the first demonstration of deterministic chaos came through studying classical mechanics. The history goes back to the French mathematician Henri Poincaré in the 1890s and his tour-de-force analysis of the three-body problem in mechanics which led, after a famous false start, to his articulation of the mechanisms of deterministic chaos. Since Poincaré the study of nonlinear dynamics effectively departed from physics proper, being championed by the likes of Aleksandr Lyapunov, Balthasar van der Pol, Mary Cartwright and John Littlewood, Andrei Kolmogorov, Stanislaw Ulam, Edward Lorenz, Steve Smale, and many others in mathematics, engineering, and even biology. So, just as statistical physicists had studied "collective phenomena" for decades before the appearance of complex systems, the discovery of deterministic chaos itself had an important history —a history that predates much of statistical physics, in fact.

I'd like to think that what was different in my approach was realizing that something much more profound underpinned our study of each new nonlinear system than just the specific behaviors of each system. Despite rather active discouragement from senior colleagues, I became focused on generalizing studies of nonlinear systems to understand the very basic principles of modeling, that is, how we build theories, how we discover new patterns in nature.

So I can now say that I started to work in complex systems due to the realization that the focus of study should be patterns and how we discover them and not particular nonlinear systems in this or that application. To me, this is what complex systems is all about. And it is a very necessary activity, even if it smacks of a certain level of abstraction and philosophy. Acknowledging the latter, I came to call it experimental epistemology. The essential motivation for the research program was a simple, direct consequence of the most basic lesson of nonlinear dynamical systems: each nonlinear system requires its own explanatory basis. At root, we cannot blindly apply Fourier analysis, perturbation theory, wavelets, or any one of a host of accepted “complete” representations. We must understand each nonlinear system on its own terms. This realization brought up the question of intrinsic representation, how to learn new representations, and how to measure the amount of patterned-ness or structural complexity. With this professional epiphany I quickly moved on from nonlinear dynamical systems—showing that this or that physical or biological or social system could be chaotic—to the question of pattern discovery.

I just framed the question of complexity in a slightly more abstract way than most would—as the process of pattern discovery rather than analyzing specific examples of complicated systems. Nonetheless, this framing leads to two very concrete and clear questions. What is pattern and can we quantify the amount of pattern in a system? I believe answering these questions is what studies of complexity are uniquely about. Analyzing particular complicated systems and developing applications of complex system tools are crucial activities that bridge the general study of complex systems to the sciences and engineering. However, this kind of modeling activity survives healthily even in traditional disciplines and they end up recasting and owning the ideas, ignoring their origins in complex systems theory.

2. **How would you define complexity?**

Although I have framed "complexity" in a specific way, the term “complexity” is used in many, even contradictory ways. In particular, without an adjective qualifying the word “complexity”, the question here induces confusion. Much of the controversy of what complexity is, if the issue really deserves such an exalted descriptor, has to do with folks looking to use a rich and important word in one and only one way—their way, without defining what they mean. Assuming they can define it for the problem domain that interests them, then all they have to do is use an informative adjective. A simple prescription, one would have thought. If it had been observed over the last twenty years, much redundancy and reinvention could have been avoided and we would probably be further along.

Putting superficial semantic confusions aside, I will answer the question by rephrasing it.

First, there are senses of the word that are now seen to be in tension. Many dictionaries give two definitions for “complexity”. Definition 1 is “complicated”, “noisy”, “random”, and so on; Definition 2 is “sophisticated”, “intricate”, “consisting of related parts”, “structured”, and the like. The first means “without organization” and the second, “replete with organization”. And, worse, there’s even the limit in which the latter turns into the former: as one dictionary puts it “complicated in structure”. So we can see why some confusion was inevitable: our very reference documents conflate distinct properties.

Second, the mathematics of randomness is fairly well understood, thanks to such luminaries as Andrei Kolmogorov, Richard von Mises, Claude Shannon, Alan Turing, Ray Solomonoff, and Gregory Chaitin. Thus, I do not use “complexity” in the sense of Definition 1; rather I use “random” or “unpredictable” to describe this property of a system. Instead, I use “complexity” to describe the properties of a system captured by Definition 2. These choices are a simple, personal shorthand. It seems like a waste and redundancy to take a rich word like “complexity” to mean randomness. “Random” is a perfectly good label for its referent. Nonetheless, a confusion could arise with a shorthand and so when trying to be completely clear I say “structural complexity”, trying to adhere to the adjective dictum above.

So, finally, the question becomes, What is structural complexity? This I can answer unambiguously and concisely: Structural complexity is the amount of historical information that a system stores. Without recounting the technical results, the upshot is that there is a deep connection between how a system stores and processes information —how it “intrinsically computes”—and how the system is structured.

Thus, within the computational mechanics framework I use, complicated systems are not necessarily complex. One has to show that a complicated system of interest actually stores and processes lots of information. Then it is structurally complex.

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

I like that one can use complex systems to understand, with a very small set of ideas, much of the natural and human-made world. In a nutshell these ideas come from studying the commonalities between dynamical systems theory, statistical mechanics, information theory, and computation theory.

They consist of (i) the geometric view that dynamical systems theory gives of the state space (and the structures there that drive and constrain behavior), (ii) the notion of structure captured in the theory of computation, and (iii) the concept of information (aka entropy in statistical physics) from communication theory. Pretty much everything else in complex systems is one or another solution strategy, algorithm extension, or optimization trick that builds on these three foundations.

The interest and fascination in discovering patterns in our world is as old as humanity. Now that we have new mathematical and computing tools appropriate to complex systems, we are in position to make profound progress in understanding natural and, even, engineered systems by analyzing their behaviors and organizations.

We should not, though, get too far from the intellectual innovations that led us to this point. There are many important lessons and even a sense of inevitability when one looks at the historical momentum behind the questions that complex systems pose. In particular, the recent interest in complex systems is, in many ways, a revival of Wiener's push for cybernetics in the 1940s and 1950s. It's not too much of a simplification, and perhaps it does some honor to him, to see complex systems as "nouveau cybernetics", as a rekindling of his and others' enthusiasm during that period. Unfortunately, the word "cybernetics" has a checkered past. For example, it is very hard to see cybernetics in contemporary computer science, though that field's founders played key roles in articulating the problems of complex systems.

An important, perhaps under-appreciated, aspect of complex systems is its novel contributions to scientific methodology. One of these you might call emergence analysis which attempts to address the question, By what mechanisms did behavior X or structure Y appear? This is fundamentally different from how questions were posed previously. Let's take an example from population genetics. It has been observed that genomic mutation rates vary over time and from gene to gene. One way to model this is to add a "modifier" gene that directly controls mutation rates. This gene too is subject to mutation and so one can analyze how mutation rates vary by solving the population dynamics problem of whether the modifier gene persists or atrophies as a population of genotypes evolves. This approach is very different from understanding why and how a modifier gene might appear in the first place. What improvement in survivability would lead evolution invent a gene that modulated the rate of change of other genes? How could such an innovation be encoded? This is a question of evolutionary innovation—the evolutionary analog of pattern discovery. Conventional population modeling assumes a specific sophisticated mechanism, whereas treating the question as a complex system allows one to investigate conditions promoting evolution of diverse sophisticated mechanisms.

Another of my favorite aspects of the research process for complex systems is that is it is very "geometric" and so, to me, visual, if you are willing to buy into a certain level of abstraction. That abstraction is the state space—a representation of the set of all possible configurations a system can be in. One's understanding of the emergent patterns in a complex system is expressed by delineating the geometric structures in the state space which lead to the system's behavior.

Over the years, my desire to view state space led to repeated searches for new kinds of exploratory tools. First, my graduate student colleagues and I at UC Santa Cruz used analog computers (this was the 1970s) to solve differential equations with chaotic solutions. We also made 16 mm films of, for example, the cross sections of strange attractors to understand their intricate topologies. Rob Shaw and I made a reel-to-reel video (1970s!), now apparently lost, of the chaotic dynamics and bifurcations in a dripping faucet. I also developed an experimental system for interactively exploring spatial pattern formation. This was based on the reaction-diffusion dynamics supported by an electronic-optical computer, commonly called "video feedback". These instruments were special purpose and speak rather directly to the technologies of their time. Today, of course, technological circumstances have changed immensely; we now regularly use massive Linux clusters for multiagent simulations and even immersive visualization (see KeckCAVES.org) to explore complex systems.

Let me finish with a simple, personal favorite about complex systems. I enjoy the excuse that it gives for exploring different fields of science and the arts. This could very well be a product of my having an attention span of only about five years. But it is particularly rewarding to comparatively explore a general concept like emergence or pattern by delving into music, physics, psychophysics, biology, bioacoustics, and social science.

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

Early studies of complex systems became caught up in a difficult social change in the sciences in the 1980s and 1990s: increased public attention that led to increased self-consciousness. (This is not really unique to complexity, but it did play a key role in its development.) Never had there been so much interest in books on science and magazines devoted to it. One or two key books in the mid-1980s seem to have woken up publishers to a public hunger for news on science and technology. One manifestation of this was the hugely increased role of science journalism in the late 1980s.

There were many positive benefits to this. One was that your parents and relatives were much more appreciative of what you did, even if they admitted to not really understanding it. More broadly, the public and, very importantly, young students received a much more lively picture of contemporary science and mathematics. Chaos, fractals, emergence, and the like were all fantastic fodder, conceptually and graphically, for an intelligent lay audience.

The downside, of course, appeared as changes within the science community, including the occasional lack of warmth with which one's immediate colleagues greeted one, when a result got widespread press. In the 1980s and before, getting exposure through the press was largely new to most areas of science. In physics, anyway, people were downright skeptical of this shift. (We were faceless workers collectively building the edifice of science, through which society benefited and so paid our daily wages, right?) This was particularly true when journalists, desiring to interest a broad readership, would focus news articles on personality and lifestyle. As a journalistic strategy it was hugely successful and, for better or worse, now twenty years on, it is common practice; even one with which hard-nosed physical scientists seem to have come to terms.

The general area of complex systems was a prime beneficiary of this more-public exposure of science. Even if universities hesitated to accept changes to their curricula to teach complex systems, funding agencies, industry, and even private philanthropists were supportive. Without them, the field would be markedly much less advanced today.

But it also led to a level of self-consciousness that had a chilling effect on cooperation and the development of shared goals. A new kind of entrepreneurial attitude developed, somewhat spurred on by the increasing sophistication of computing technology. Computers, once only unacknowledged handmaidens to science, came to be seen as essential tools. In many cases, they were the only way to access and study many problems in complex systems. However, those tools had to be programmed, which was time consuming, very difficult, and expensive. So, if you could craft a tool that reduced the difficulty of modeling and simulating complex systems you could control the direction of science. More to the point, a useful tool was a product that could be sold by companies who determined the content.

Fortunately, this entrepreneurial period has stabilized and, many thanks to the emergence of global scientific collaboration via the Internet and the Open Source movement, the science of complex systems (and many other areas) is no longer hostage to the commercial entrepreneurial spirit. The upside, as one looks to the future, is an even greater rate of discovery and innovation as tools are collectively developed and as the tools' source code is there for all to see and to improve much more quickly.

So was this increased self-consciousness really a problem? It is hard to know. Perhaps the long view is that social dynamics, even in science, moves to the middle ground I described above, becoming truly complex as a result, as it swings from one extreme to another.

5. **How do you see the future of complexity? (including obstacles, dangers, promises, and relations with other areas)**

I’m very concerned about training and education in complex systems. I’m happy to see many of us developing books and specialty courses. However, I’m concerned that, given the central and broad importance of complex systems, there are very few appropriate multiyear graduate training programs. I’ve been working in this area for over thirty years now and, in that setting, I feel we, or at least I, have failed our students. To my taste, there has been too little synthesis and too much competition. The result is a dilution of the original spirit and insight. (How ironic for a field one of whose central goals is to understand emergence.) One central cost has been a lack of cooperation to build training programs.

On the up side, much progress has been made in the research arena. Now is the time to take the (perhaps substantial) effort to rework those results so that students can be introduced to the concepts systematically. The goal is that they learn deeply enough to extend them creatively to attack the many remaining, truly complex problems.

So, it’s time to move on from “complexity”. The heydays were in the early 1990s. Much progress was made; though, much of that progress is still being digested.

The label “complexity” was positively useful then. It was vague enough that people in very different disciplines working on their field’s hard problems could come together with a hope of learning something from others in other fields. They came with open minds and enough energy to get through the difficult disciplinary boundaries of vocabulary and research style. The label was also specific enough that an interest in “complexity” was an effective filter that kept more discipline-focused scientists at bay.

At this point, however, the word has entered a stage of overuse and so its meaning and utility have been diluted.

This is not to say that the problems that have fallen under this rubric are less interesting or less important. In fact, just the opposite. We have never faced problems of the level of complexity, either natural or of our own making, than we now do. For example, the age-old problem of individual action versus collective function is more present than ever. We see this in both the natural world, as affected by us, and in the artificial world, as engineering innovations allow us to assemble ever-larger and increasingly vulnerable socio-technological systems. I believe that the concepts and tools of complex systems will be key to understanding and solving such problems, including sustainability, social justice, and economic stability.

However, the field is a victim of its own success. It’s now time to start making finer distinctions than simply saying that this or that system is “complex”. How exactly is it complex? How much information processing does it do? What is the minimal dimension it lives in? What are the intrinsic coordinates for that space? What are the effective forces that drive its behavior? At what levels are different kinds of information processing embedded? How does collective function emerge from individual behavior? Can we design policies for individuals that lead to desired collective outcomes?

By definition, complex systems are some of the hardest problems to approach scientifically and mathematically. Frankly, I feel that modern mathematics, despite the amazing insights of our predecessors, is currently not up to the task, specifically the problem of representation. Very few nonlinear problems can be solved in closed form; that is, the underlying mechanisms and solutions cannot be expressed in mathematically tractable ways. We need a very new approach.

People today say computers can fill the mathematical void. I would agree with this only partially, since powerful computers can be programmed to simulate models that are as complicated as many natural systems. Beyond the conceptual hygiene that comes from porting the mathematics of an idea to a computer language, often little is gained. More to the point, having petabytes of simulation data is not the same thing as understanding emergent mechanisms and structures. We need to understand mechanisms and structures to build predictive theories—theories specific enough to be wrong. Perhaps even more troubling is the recurrent conflation of writing a 20,000-line LISP program as a model of machine intelligence and claiming that that program means you understand how intelligence works. This is far from the case, since such a program most likely is very complicated itself. In any case, it does not directly represent the emergent mechanisms that lead to its behavior. Without emergence analysis of the running program, for example, one can't say which portions interacted cooperatively to produce a successful solution to a learning task. A useful comparison is a program that simulates the famous Logistic Map, which need be only several lines of code long. It has taken decades to understand the rich chaotic behavior in that nonlinear system.

Very recently, this line of thinking reached a new nadir with marketing successes, in targeting online advertising, that rely on mining large empirical data sets. The successes led information technology leaders to claim that theory is no longer necessary. However, in devaluing theory the pure-simulation, pure-data, and pure-computing approaches sideline scientific understanding. Complex systems provide no better antidote to such thinking. We live in a very prosaic age as these examples show, nonetheless relying heavily on the conceptual insights of past great, innovative thinkers. To devalue theory is to preclude the future reduction-to-practice of today's conceptual insights. In light of this, I've often joked that my role is to make the world safe for theory. At the largest scale, it's really an ecology of pattern discovery. We should move away from the rhetorical extremes to the dynamic synthesis found in the middle ground.

These things said, I'm very optimistic about the future of the intellectual momentum that "complex systems" represents. There are many interesting and absolutely fundamental problems that, on the one hand, we don't understand and that, on the other, the new methods and thinking are ripe to solve. I hope to look back to this time and marvel at how naive we were.