Complexity and the Future of Science

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"It makes me so happy. To be at the beginning again..."
—Tom Stoppard, *Arcadia*

A recurring theme in the history of science is the announcement of its demise. The specter of the "end of science" periodically appears in the scientific and popular literature, often at the end of one scientific era (e.g., Newtonian mechanics), before the beginning of a new one (e.g., quantum mechanics). Indeed, we are now living in an era of great knowledge about nature—the structure of elementary particles, the genetic code, and even the possible long-term future of the universe have all been cracked by scientists. It may seem like the scientific advances of the future will be but icing on this foundational cake.

But in truth, in spite of these glorious accomplishments, a fundamental ignorance remains about the workings of the world, especially in the realm of living systems. How is it that a group of cells can come together and organize themselves to be a brain? How did the intricate machinery of the immune system evolve, and how does it fight disease? How do independent members of an economy, each working chiefly for their own gain, produce efficient global markets? Despite great advances in understanding such systems, it would be generally agreed that these questions have not nearly been fully answered. An understanding of the phenomenon of self-organization, in which large numbers of simple entities organize themselves into a collective whole that creates intricate patterns, uses information, and adapts and learns, is (to my mind at least) *the* central problem in biology, economics, and society (and increasingly in technology, with the advent of huge distributed and decentralized computer networks). This problem remains almost completely unsolved.

Complex Systems

It is plausible that the problem of self-organization is, in some interesting sense, the same problem in all disciplines, though the details differ considerably. In general, we must ask how and under what conditions large-scale complex structure and behavior arises from relatively simple components that interact with one another in complicated ways. Such questions require the domain-independent definition of the still-colloquial notions "complex", "structure", and "behavior", and domain-independent laws governing their emergence. For better or worse, the study of self-organization across disciplines has been labeled the study of "complexity" or "complex systems". The methodology of what might be called the "complex systems movement" in science is both to study individual complex systems in order to infer commonalties and to develop general theories and tools that apply to many or all complex systems.

The complex systems movement was born of frustration over the specialization and isolation of scientific disciplines that has gradually occurred during the last two centuries, since the time when science—"natural philosophy"—was of one piece. Specialization in science has certainly produced great advances, but the problems of complex systems demand approaches that span disciplines; for these problems, the old boundaries are no longer appropriate. In response to this realization, several interdisciplinary centers for the study of complex systems have been organized, and the number of such centers continues to grow.

Dangers of Integrative Approaches

To be sure, great care must be taken in attempting an integrative approach to scientific problems. It is important to be passionate about big ideas, but in casting ones net for grand, far-reaching principles, one risks becoming entangled in grandiose pronouncements that are too vague to be meaningful ("life is driven toward complexity"). In searching for commonalties among disciplines, it is helpful to find suggestive analogies, but one must be careful about taking them too literally ("learning in the brain works just like adaptation in evolution"). One must be careful not to use "trendy" mathematical tools inappropriately (e.g., measuring the "fractal dimension" of everything in sight without a clear notion of when such measures meaningfully apply), and one must be aware that uncareful statements can lead to media hype ("SFI scientists create life inside computers").

Potential of Integrative Approaches

Such overreaching can lead to the kind of glib dismissal seen in a recent article in this magazine ("From Complexity to Perplexity", June, 1995) of all work on complex systems. However, such glib dismissals miss the other side of the coin—the imperative for integrative approaches to understanding complex systems and the potential that such approaches have for scientific advances of the highest order. This potential is for no less than the development of new languages (e.g., extensions of the theories of dynamical systems, information, and computation) and new methodologies (e.g., computer simulation, maligned unfairly in the aforementioned *Scientific American* article) that can be used across disciplines to explain how complex organization arises in nature, and to harness the principles of self organization for technology. The complex systems movement has already taken some major steps in these directions. Recent examples include the development of computational models of organization and evolution that may shed new light on the origin of life and on information processing in living systems, and the abstraction of immunological function in information-processing terms that may lead to immune systems for computers. There are many more examples of how work in complex systems is affecting science; it is ironic that the very same issue of this magazine whose cover asked, "Is complexity a sham?" also carried a major article and an "Amateur Scientist" column describing results from computer-simulation research coming out of the complex systems movement.

Prospects for a Theory of Complex Systems

I have used the phrase "complex systems movement" here to describe a loosely coherent collection of scientific efforts. Phrases like "complex systems theory" or "complexity theory", while used by some, seem premature to me; our enterprises have not yet earned the right to terms like "theory". Could there be a grand unified theory of complex systems? I personally do not believe there will ever be a single theory that explains and predicts all aspects of all complex systems in nature. However, I do believe in (and am actively pursuing with my colleagues) the possibility of general theories that explain the emergence of high-level information-processing structures from low-level interacting components, and that predict aspects of the types of structures that can arise and the conditions under which such structures will arise. Such theories—ones that explain and predict aspects of "emergent phenomena" across disciplines—are, I believe, vital to the future of science, which is, from the point of view of complexity, not at its end but at its beginning.