Complexity

Why the sudden fuss?

WALTER FONTANA AND SUSAN BALLATI

Walter Fontana is a research professor in residence at the Santa Fe Institute. He is working on a theory of molecular organization and on adaptive dynamics of RNA. Susan Ballati has a Masters in Public Administration with many years of experience in the semiconductor industry. She is Director of Marketing at the Santa Fe Institute.

Consider a single molecule of water. Many of its properties, such as bond lengths, bond angles, and energy levels, can be calculated from quantum mechanics, the appropriate theory at the atomic scale of matter. Add 10^{23} further molecules of water, and you've got a liquid, which is described by hydrodynamics—an altogether different ball game than quantum mechanics. Eddies and vortices don't exist at the level of a single molecule. Decrease the temperature, and the liquid freezes. Now you can push the rear side of a block of ice and the front side moves instantaneously along with it. Rigidity is hardly a property of a fluid or a gas. A very large number of water molecules thus constitute an "object" so rich that it needs a different theory at different temperatures!

In the early 1970s, Phil Anderson, a Nobel Laureate and member of the SFI Science Board, coined the slogan "*More is different*" (*Science,* 177:393–396, 1972). Emergence points to the fact that new properties come to dominate a system's behavior as we increase its degrees of freedom or as we tune a parameter to break a symmetry. There are different mechanisms for emergence. Yet they all depend on the fairly obvious fact that the components of a system interact. Increasing the number of interactions, or emphasizing certain interactions over others (breaking symmetry), triggers feedback loops among the components, giving rise to collective behavior. Components that are locked into such behavior can be treated together as a new unit. While the composition of a system has remained the same, its internal boundaries—which suggest how to parse a system into "parts"—have been redrawn from within. This forces a change in the way we describe that system and how we must think about it. For example, we do not think of the air over the U.S. as a flowing gas, but we think of it in terms of cold and warm fronts or huge vortices such as hurricanes.

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Those who emphasize the global view of a system say that "*the whole is more than the sum of its parts,*" where the "more" refers to properties deriving from

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interactions among the parts. Metallic sodium and chlorine gas are both poisons, but together they are table salt. Perhaps we should rather say that a system is a *function* of its parts. Reductionism is the scientific program aimed at understanding this function. It is a "bottom-up" approach that requires that one has already identified the relevant parts of a system and properly understood their interactions. Yet that just may be where the problem is, and it is by no means a trivial one. The parts of a system may be interdependent, and their boundaries may even shift over time in response to events affecting the system. Think (genetic) regulatory networks. In such a situation, a more global "top-down" approach may provide critical insight. Prior to explaining something, we need to know what is it that needs explanation. Reductionism and holism do not contradict each other. They are complementary strategies. We owe this framing to Henk Barendregt (www.cs.kun.nl/~henk), Universiteit Nijmegen, Netherlands.

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Complex systems are typically organizations made of many heterogenous parts interacting locally in the absence of a centralized pacemaker and control. Think, for example, of the economy, the brain, cellular metabolism, or the Los Angeles traffic basin. It may be easy to describe a system's composition, but it is far more difficult to describe its global behavior. Complex systems are said to be adaptive. Yet it deserves emphasis that an adaptive organization is *not* a tracking device; it does not adapt to everything. There may, in fact, be a tension between organization and the capacity to adapt. The very same internal organization that enables adaptation also channels change along specific directions while conveying resilience and vulnerability along others. It is precisely this definite directional response to random events that reveals the organization of a system.

Biologists have long appreciated that the idea of "organization" is linked to that of its history. The history of an organized system is not merely the series of events in which the system had been involved. It is the series of transformations by which the system was progressively formed. This means path dependence and frozen accidents. Early architectural decisions cannot be reversed if the functioning of many components depends on them. They are *de facto* standards. For example, provided the genetic code can be a different one, no such alternative could evolve from current organisms. From an evolutionary point of view, an adaptive organization is like a ship on the open sea that has to rebuild itself while staying afloat. Think transition economies. Think Russia.

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Approaching such mind-boggling systems will require the integration of multiple perspectives from physics, chemistry, biology, computer science, social science, economics, cognitive science, and mathematics in mixtures that vary as the nature of a particular class of systems is becoming better understood. This requires new kinds of environments, like the Santa Fe Institute, for doing research.

Advances in mathematics and the availability of computational tools for simulation permit the probing of complex systems in a way that was impossible only two decades ago. These studies have led an increasing number of people to think seriously about the possibility of deep similarities among seemingly different instances of complex systems across levels of nature and to search for a taxonomy of *classes* of complex systems that share structural and dynamical features at a qualitative level. Although the computer is a powerful tool, simulation alone does not provide a conceptual foundation; it rather presupposes one. To arrive at such a foundation is difficult, because real-world complex systems possess many distinct levels of description that must be taken into account simultaneously. Think of climate change, for example, which involves geology, oceanography, industrial development, and a host of other human activities. Approaching such mind-boggling systems will require the integration of multiple perspectives from physics, chemistry, biology, computer science, social science, economics, cognitive science, and mathematics in mixtures that vary as the nature of a particular class of systems is becoming better understood. This requires new kinds of environments, like the Santa Fe Institute, for doing research.

The other reason why complexity has transited from being an adjective to being a concept has to do with an emerging recognition of what lies ahead. We are facing a fundamental *conceptual* frontier, a major challenge to our capacity to imagine and to abstract. Consider that most theoretical studies focus on the dynamics of already-existing organizations, where the constituent entities and their interactions are known and fixed in advance. However, by the very process of adaptation, organizations participate in the construction and active maintenance of the world to which they are adapting. In changing that world, they set the stage for their own reorganization. Even a river continually redefines its own bed by transforming the materials and the terrain to which its flow adapts. The frontier, then, consists in framing processes in which organizations themselves change (their architecture), not just their state (some numerical value). We must come to understand the processes by which new classes of entities come into being—autonomous chemical systems, self-maintaining organisms, cognitive structures, societies. The frontier is a comprehensive theory of evolution.

Despite many specific approaches, some of them quite technical, there is, as yet, no single "theory of complexity." There is, however, an increasing appreciation of what that theory will have to be about. Science is not only about solving problems, but also—and, perhaps, even foremost—about posing them. There is no end to science.

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