Foreword
The Structure of Complexity in an Evolving World: The Role of Near Decomposability

In today's world, we pay a great deal of attention to complex systems, and with good reason. The phenomena we wish to understand, in all of the sciences, are increasingly complex, and the problems we need to solve in order to guarantee the future of our planet have complexity at their core.

Complex systems are usually big, but complexity means something more fundamental than bigness. A balloon, as big as you like, filled with hydrogen or helium gas would not usually be regarded as complex. We could build a theory of the balloon, quite satisfactory for many purposes, on the basis of the simple, fundamental law that relates pressure and volume to temperature of gases and the other laws of thermodynamics.

Of course, if we set the balloon loose in the atmosphere, all sorts of complexity may be observed in its behavior. But the source of this complexity is the balloon's interaction with a complex atmosphere; it is not intrinsic to the balloon.

Complexity arises, then, when we have a large system *and* when the system divides into a number of components that interact with each other in ways that amount to something more than uniform, frequent elastic collisions. Interactions among components can lead to all kinds of nonlinearities in behavior, and very often carry the system into the especially complex regions of phase space that we call chaos. For us humans, a principal symptom of complexity is that the complex system becomes harder and harder to understand and to predict. Our ordinary mathematical methods no longer lead to solutions in closed form, and the complexity can even carry us beyond the simulation capacities of our largest computers, present or prospective.

Even in the absence of chaos, the phase spaces of our complex systems may, and usually do, exhibit irregular surfaces of local minima and maxima of the variables of interest, preventing us from using our favorite mathematical tools to find the global maxima or minima that we often set as the goals of our search.

These difficulties of understanding and predicting the behavior of complex systems confront not only us human beings; they also confront, in a manner of speaking, the forces of inorganic and organic evolution. If we take the phrase "survival of the fittest" literally, then our theories of change and evolution, organic and inorganic, have force only in a world where maxima are attainable and the paths toward them are discoverable, conditions that are seldom satisfied in the real world. If Nature is unaware of these difficulties that confront it as it moves forward in time, we human beings who are observing the course of events are only too well aware of them.

The universe before the big bang apparently was not too unlike our hydrogen balloon—big, but perhaps not very complex—the universe immediately afterward, and from then on, became progressively more complex, with the rapid growth of components that were themselves increasingly complex. It becomes a fundamental problem of science, then, to explain why this growth in complexity came about and to observe and explain any commonalities of form that the resulting complex subsystems of the universe exhibit.

It has been noted for a long time that most of the complex systems we observe in the world, beginning with atoms and going on to stellar galaxies or galaxy clusters, have distinctly hierarchical structures: that is, they consist of (complex) subsystems, that consist of subsystems, and so forth, through many levels. The subsystems interact with each other (else they would not form systems), but the frequencies (and energy densities) associated with the interactions drop steadily as we go upward in the hierarchy—typically by an order of magnitude or two for each level that we ascend. Thus, quarks and other atomic particles jostle each other at speeds that are very hard to observe (the steady rise in cost of leading-edge accelerators being testimony to that), whereas the stars and even the planets revolve about each other at a majestic, solemn pace.

Another way to describe this structure is to state that the frequencies of interaction among elements in any particular subsystem of a system are an order of magnitude or two greater than the frequencies of interaction between the subsystems. We call systems with this property nearly completely decomposable systems, or for short, nearly decomposable (ND) systems (Simon and Ando, 1961).

The question, then, is, Why does complexity in our universe, at virtually all levels, generally take this hierarchical, nearly decomposable form? The first step toward answering the question is to observe that the complex systems had to evolve from simpler systems by processes of evolution. This leads to the second question: What is the connection between speed of evolution and near decomposability?

The answer to this second question is still far from complete, and the incomplete answer we have comes in several parts. First, it is easy to show that if large systems form by the agglomeration of smaller systems, and if the agglomeration process involves chance meetings between components that can form new, more or less stable, systems, then the probability is very high that large systems will consist of many layers, produced by successive meetings of components—and earlier still, of components of those components—and not by a single "reverse big bang" that instantly assembles a massive system from numerous tiny components.

Many of you are familiar with this argument of "The Two Watchmakers" (Simon, 1996, pp. 188–190), one of whom never succeeds in assembling a watch before the many independent components fall apart again, and the other of whom builds his watches in stages, putting together smaller, stable components into larger ones until the whole is complete.

But not all of the large systems we encounter in the world, especially biological organisms, appear to have been assembled by evolution from diverse smaller components. In particular, the formation of multicelled organisms has been quite different, based mostly on specialization of identical or similar units that are generated by cell division, but retain a lifetime's mutual attachment. Yet, the same ND architecture appears in these organisms, with their division into organs and tissues, and finally into (specialized) cells. What kind of evolutionary process could lead to the ubiquity of this particular hierarchical scheme?

Here we must return to the complexity of the fitness landscape, especially the proliferation of local maxima that make it extremely difficult to reach global maxima by any local hill-climbing, survival-of-the-fittest strategy. The solution to the dilemma appears when we recognize that those which survive need not be fittest, in the sense of occupying global maxima in the fitness landscape. The winners need not be "optimal" organisms. For an organism to survive and flourish requires only that it be *fitter* (in some niche) than the other extant organisms with which it competes. "Potential" organisms that have not yet been introduced by mutation or crossover or immigration offer no competition until they actually appear, as hares finally did in Australia. So local maxima, or even uplands that are not maxima, are all that the evolving organism need aspire to.

With this recognition, the process of evolution takes a new shape. Suppose that a large, complex system, with many interacting parts, is changing through the usual evolutionary mechanisms. Natural selection only evaluates the fitness of the organism as a whole, not the fitness of individual organs except as they contribute to the whole. But if the effectiveness of design of each organ depends on the design of the organs with which it interacts, then there is no guarantee that improvements of one organ will not worsen the performance of others. Natural selection will have to depend on the lucky chance that simultaneous, mutually beneficial changes in a number of different organs will occur to improve overall fitness. The probability of this coordination of events decreases rapidly with the amount of interdependence of design of the organs.

Suppose, instead, that the effectiveness of each organ depends very little on the design of the others, provided that the inputs each requires are supplied by the others. Then, up to a scale factor, the design of each organ can be improved independently of what is happening to the others; and it is easy to show that fitness will rise much more rapidly than when there is mutual dependence of design. The most convincing demonstration of this is the simulation by Frenken, Marengo, and Valente of the University of Trento (1999), using a genetic algorithm and simulated organisms, some of which were ND and some of which were not. The ND organisms soon reached higher fitnesses than the others, and displaced them.

I have omitted important details from this brief sketch. In particular, organs inhabiting a single organism would require some mutual balance of their relative capacities. However, one can describe a variety of allometric mechanisms that can balance capacities through an entire organism by size adjustments of component organs without damaging their basic independence of design (Simon, 1996, pp. 204–205).

The evolutionary scenario I have just described is not limited to organisms. Exciting explorations, some of them by the same group at Trento who demonstrated the superior growth of fitness of ND systems, have deepened our understanding of the evolutionary development of business firms with changing technology. The same ND property that facilitates rapid evolution provides the key to rapid adaptation to new technological opportunities. This is of particular interest in a society that uses a combination of markets and organizations to perform its economic functions.

Markets are basically simple systems, in the sense that our hydrogen balloon is simple. In fact, most of the arguments for their economic efficiency rest on their simplicity. However, historians of economics have noticed that when Adam Smith was writing, markets dominated the economy of Britain, but in the two succeeding centuries markets have been steadily and rapidly displaced by large organizations. Today, most people engaged in economically productive activity in the developed world work within organizations and not in the marketplace. Whether e-commerce will substantially shift that balance remains to be seen, but I, for one, see no compelling reason why it should. By lowering market costs, e-commerce may actually reduce the fraction of total productive effort required to operate the economy's markets.

Economic theory about the relative roles of markets and business firms in a modern economy is in a state of great flux. The neoclassical theory that had placed markets in the central role is being seriously challenged by the New Institutional Economics, by the theory of bounded rationality, and by evolutionary theories—the latter three viewpoints being complementary in complicated ways. I would not like to try to forecast how this will all work out, but I offer at least the conjecture that a theory of ND systems will be important to the outcome.

Near decomposability also plays a major role in the understandability of complex systems when we humans seek to investigate their properties and behavior. Because of the (incomplete) separation of frequencies between levels of an ND system, one can usually obtain good approximations to the short-run and middle-run behavior at any given level without considering the details of the higher-frequency movements at the levels below, and while taking the situation at the levels above as constant over the interval of interest. We have been using this divide-and-conquer strategy in science for many generations, and it is a principal basis for specialization of the sciences into levels, from sociology and economics through biology and chemistry, and ultimately to particle physics.

Improvements in our methods for approximating the behavior of ND systems (for example, renormalization in quantum electrodynamics, which depends on near decomposability) will continue to be an important task for applied mathematics, certainly requiring advances in pure mathematics as well.

I have touched on only a few aspects of complexity and complex systems that happen to have attracted my interest over the years. There are many other stories to be told about complexity, and I am sure that many of them will be told at this workshop. For example, we are still far from digesting all of the lessons of chaos, advancing our computational theories to explore it, or designing feedback devices that can constrain and manage it. I will not presume to speculate about all of the forms that complexity will take in the world and in our thoughts, or to enlarge further the brief account I have given of one of its very visible aspects, the near decomposability of most of the world's complex systems.

—Herbert A. Simon†

References

Frenken K, Marengo L, Valente M (1999) Interdependencies, nearly-decomposability and adaptation. In: Computational Techniques for Modelling Learning in Economics (Brenner T, ed), 145–165. Dordrecht: Kluwer.

Simon HA (1996) The Sciences of the Artificial, 3rd ed. Cambridge, MA: MIT Press.

Simon HA, Ando A (1961) Aggregation of variables in dynamic systems. Econometrica 29: 111–138.