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Note on Complex Systems

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A view is presented which argues that hierarchically organized, complex systems are in no sense unlikely to come about in a world in which thermodynamics is operative, and that they, in fact, often represent states of greater entropy than unorganized systems of the same components. This view is also brought to bear on the problem of how qualitatively new behavior arises out of simple, interacting components.

1. Introduction

It has been a feature of some past studies of complex, organized systems to exploit an analogy between organization and "information" (in the information theoretic sense) with the result that organized systems seem to contain more "information" and thus lower "entropy" than simple ones (Dancoff & Quastler, 1953; Elsasser, 1964; Raven, 1961; Rothstein, 1952; among others). This point of view leads to the conclusion that complex, highly organized systems are an anomaly in a universe in which thermodynamics is operative. If we observe them at all, we must be in an unusual region of the universe. The region that includes life is strange indeed.

It is the purpose of this note to argue that this approach is mistaken, that the coming into being of complex, hierarchically organized systems is often a thermodynamically preferred situation, and that we should not be surprised that these systems are so prevalent.

2. Explanation for the Prevalence of Complex, Hierarchically Organized Systems

Some successes have recently been achieved in this direction. Prigogine & Nicholis (1967) have extended a line of analysis of Turing (1952) in their work on the spatially inhomogeneous steady states of model chemical systems. Kauffman (1969) has investigated computer simulated, randomly built binary switching networks, and has found a high degree of organization in networks whose components have certain connectivity relations among them. (An analytical explanation of this phenomenon, as well as extensions to continuous systems, is the subject of recent work by the present author, Newman, 1970.)

However the arguments here are somewhat different. Consider a collection of simple interacting components, each with a well-defined state. An example is a set of particles which obey the laws of quantum mechanics, each characterized by the values of its position and momentum vectors. The statement that they interact with one another is equivalent to saying that the state of one particle is influenced by the states of others. In other words, they can exchange dynamical information. (In quantum mechanics this means that the single particle states are no longer eigenstates for the system.)

Of all the configurations of particles consistent with the dynamics of the system, it is clear, that other influences being equal, those which remove a certain proportion of the total "state" from further change by interaction with the rest of the system are most likely to persist. This masking effect can be accomplished geometrically, for instance, by architectures which protect most of the "works" from outside influence. Part of the stability of atoms is certainly due to the shell-like construction that protects most of the constituent components from being perturbed.

Thus, if a subsystem is organized in the right way, there is a *smaller* exchange of dynamical information with the remainder of the system, or environment, than would be the case if the subsystem were unorganized. From this point of view, which is the only one relevant to the system itself, the "informational" entropy has increased. Furthermore, the organized entity will have a greater effect on the unorganized components (which will have their total state subject to change) than *vice versa,* and can thereby serve as a seed for even further organization. All this is accomplished through a limitation on information exchange in the total system. The view that identifies greater organization with more information fails to distinguish between the information that is available for *use* within a system and the information that we require to *characterize* a system.

The viewpoint presented here can also give us an insight into how qualitatively new forms can emerge by means of quantitative changes out of collections of old elements. As noted above, as soon as some fortuitous "organization" has the effect of concealing even a small proportion of the system's state from further interaction, there simultaneously exists the tendency for the organized part to exert a greater effect on the unorganized, than *vice versa.* If this effect is slight, we can go on treating the various interactions as if they were still among simple components. As the effect becomes quantitatively larger, this program often becomes unfeasible. What has emerged are qualitatively different "basic entities," the laws of whose interaction it is the new job of science to discover. (Examining the relations between the particles that obey the laws of quantum mechanics and those that obey the laws of chemistry, will help clarify this.)

This "new level" now has its own dynamics and state functions which can undergo similar processes of organization through internal information loss. In this scheme, hierarchically organized systems are only to be expected.

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