Chapter 1

Can there be a science of complex systems?

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At the outset of my remarks, I must apologize for appearing before you in this insubstantial form. We should expect that one important chapter in a theory of complexity, perhaps more than one chapter, will be devoted to describing the ways in which we may avoid complexity. Now the chief complexity in travel lies in the journey to and from the airport—threading your way through streets, highways, and airport ticket counters and passageways populated by other human beings and their vehicles, each intent on his or her own mission; meanwhile managing to keep track of your baggage and other possessions. That complexity is best avoided by not traveling.

Many years ago, when trains were the chief vehicle of inter-city travel, I had a fantasy of living in Cleveland, with an apartment in the city's main railroad terminal (which was, in fact, a combined terminal-hotel—perhaps still is). I would catch my train to New York, disembark in Penn Station, take a subway to my hotel or office destination, transact my business and return home: all without ever emerging into the open air of either city. Trips to Boston and many other cities could be managed in the same way. A truly ant-like, but quite simple, existence. Today I can realize my dream without moving to Cleveland, but with the help of PicTel, and the non-existent, hence simple, ether that transmits electromagnetic waves. True, I did have to walk to the Carnegie Mellon Campus, but that is only a half mile from my apartment, a pleasant leisurely trip, without baggage except for my lecture notes.

But let me get on with the task. If my topic—the possibility of a science of complexity—has caused you any anxiety, let me relieve you of it immediately. I am going to argue that there can be such a science—that the beginnings of one already exists—and I am going to try to sketch out some of its content, present and prospective. As you will see, the theory of complex systems is much concerned with the avoidance of complexity; or, to put the matter more precisely, the theory is concerned with how systems can be designed, by us or by nature, to be as simple as possible in structure and process for a given complexity of function. The task is to defeat complexity by removing it from mechanism.

1. General systems theory?

But before I turn to complex systems, let me say a few words about systems in general. The idea that there are systems in the world, and that somehow, they permit and even require special attention, is an old idea. In rather recent times, since the First World War, the idea has undergone three transformations. First, there was the holism of South Africa's President Smuts, with its insistence that new properties emerge with the growth of systems and that systems are not reducible to their parts.

One kind of emergence is hard to deny. If one doesn't have a system of at least two atoms, one can't have molecular forces. Emergence should have no terror for us, for we can recognize emergent properties as no more than new theoretical terms. Thus, if we are concerned with the temperature equilibria of mixtures of liquids, we simply average the temperatures of the component liquids multiplied by their masses. But if we now introduce two different liquids, generalizing our law of temperature equilibrium calls for a new property: specific heat. If we now include the specific heat of each kind of liquid as one of its properties, then there is nothing irreducible about the system. That property simply becomes an uninteresting parameter if we limit ourselves to a single kind of liquid.

My impression is that almost everyone today accepts reducibility in principle. Reducibility in practice is another matter; often we are quite unable to perform the computations that would represent a system in terms of its components, or to understand the reduced system without the aid of simplification by aggregation at the higher level. Hence, I think most biologists are quite unconcerned (and rightly so) at the possibility that they will be put out of work by particle physicists, or even by organic chemists. Later on, I will have more to say about "simplification by aggregation." By the time of the Second World War, the study of complex systems was taking on the form and name of general systems theory, which was built around such ideas as homeostasis, and around Wiener's cybernetic notions of information and control. After a promising start, general systems theory also began to die on the vine, through lack of nourishment from tangible scientific results. Homeostasis was largely absorbed by control theory. Information theory and control theory remain healthy enterprises, but they do not seem to have produced a general theory of systems. Instead, they became something much more specific, the former concerned with channel capacities of communications systems and the latter mainly with the design of feedback mechanisms to maintain the stability of dynamic systems.

My own diagnosis of the demise of general systems theory is that it attempted to be just that: a theory that described all systems. But as there is very little that is true for all known systems, or even all known large systems, the theory found little content. It became little more than an injunction that in designing large systems, one should not try to design the individual parts without full consideration of their contexts. That is good advice, but hardly earns the honorific title of “Theory.” Today, interest in complex systems begins with some new ideas that can be added to those of general systems theory. In recent years, we have learned a great deal about a large and important class of systems, called chaotic. Then we have had the birth of genetic algorithms for the investigation of the origins of complexity, and the game of life for the study of self-replication. To these, I would add my own favorite candidate: nearly completely decomposable systems, that bear a kinship with the renormalizations of particle physics.

What is new in the situation is that we are no longer talking about systems in general, but about particular classes of systems that have specific properties (e.g., chaos or near-decomposability), or specific mechanisms for their generation (e.g., genetic algorithms or rules for a game of life). An interesting theory can arise out of these special cases. Or, if we don’t like special cases, we can put the matter as follows:

What properties of a system are conducive to an ability to perform complex functions, or to rapid development toward such an ability? The former might be termed the “efficiency question,” the latter the “attainability question.” To survive in difficult environments, systems must be capable of performing a wide range of adaptive functions, hence of economizing on the energy they devote to each. To acquire this capability in competition with other metamorphosing systems, they must be able to increase their efficiency, to evolve, relatively rapidly.

Putting matters still more simply, we are not really interested in large systems so much as in the mechanisms that allow them to manage multifunctionality efficiently and to increase their capacity to do so. When I express confidence about the prospects of a theory of complex systems, it is this kind of a system and the mechanisms that support it that I have in mind.

2. Some principles of complex system design

What, then, are the principles that must inform the design of a system of the sort I have just described? I will organize this part of my discussion under four headings: homeostasis, membranes, specialization, and temporal specialization. There are undoubtedly others, but I should like to begin by examining these four.

2.1. Homeostasis

Homeostasis is a venerable term in discussions of complex systems. By means of feedback mechanisms or by other methods (e.g., by screening inputs for homogeneity), a system may be able to hold the values of some of its important properties within narrow limits, and thereby greatly simplify internal processes that are sensitive to these properties. However complex the external environment, the internal environment becomes much simpler. A familiar example of homeostasis is temperature control. As the rates of various chemical reactions are differentially sensitive to temperature, maintenance of a system becomes very much simpler if the internal temperature is constant.

Maintenance of a stable internal temperature no doubt greatly facilitated the adaptation of birds and mammals to life outside the relatively uniform environment of a large body of water. (I'm afraid that I'll have to turn to others to explain how reptiles manage on land without that stability.) As our knowledge of genomes advances, it will be interesting to learn whether there is a connection between the very large amount of DNA possessed by most amphibians and their need to adapt to a wide range of habitats that have different and changing temperatures.

Homeostasis is facilitated if the system possesses some kind of skin that greatly attenuates the transmission of environmental changes into the interior of the system, and the same principle can be applied to insulate the various subsystems of a system from each other. I will have more to say about membranes in a moment.

A third mechanism of homeostasis is maintaining inventories of the inputs to internal processes. Inventories decrease the need for precision in timing inputs that are obtained from the external environment, or obtained from intermediate internal processes. Inventories are important to the degree that there is uncertainty about the time required to obtain required substances from the environment, and to the degree that the substances can be stored efficiently. Thus, biological organisms typically carry sizable inventories of food (for example, in the form of fat), but not of oxygen, which is used at too rapid a rate to be readily stored.

We see that both variability of the environment and its unpredictability impose a need for homeostasis, and we might conjecture, therefore, that chaotic environments would call for especially powerful homeostatic mechanisms. Here again, feedback comes to the rescue, for appropriately contrived feedback devices can sometimes maintain a system within a specific small subregion of the strange attractor of a chaotic system; whereas without feedback, the system would be doomed to range over the whole area of the strange attractor, with consequent wide variability of its environment.

In general, we can think of homeostasis as a method of reducing system complexity at the cost of some new complexities in the form of the homeostatic mechanisms themselves. As in virtually all questions of design, there are tradeoffs here that put bounds on how much net reduction in complexity can be provided by homeostasis.

2.2. Membranes

I have already referred to the insulation of a system from its environment: by means of skins in organisms, or their counterparts, like walls in houses, or the ozone layer of our Earth. But there is much more to membranes than insulation. In particular, membranes may contain specialized transport mechanisms that move particular substances or information from the external to the internal environment, or vice versa. Sensory organs can be regarded as one form of transfer agent, motor organs as another, and specialized systems for transport of substances between cells and between organelles within cells, a third.

All of these transfer agents represent specializations (and consequent complications) in the boundary surfaces. Instead of adjusting uniform surfaces to handle the complex mix of substances that have to enter and leave the system, particular regions of the surfaces are specialized for the transport of specific substances. Thus each of the sense organs has very specific sensitivities to particular kinds of stimuli. Each of the excretory surfaces (urinary, rectal, pores) are specialized to the removal of particular classes of substances. Perhaps the motor system appears less specialized than the other transfer mechanism—its task is to exert physical force on the environment—but we need only recall such specializations as the opposed thumb or the use of the tongue in speech to recognize that it is very specialized indeed.

The British biochemist, Peter Mitchell, and others following him have demonstrated a most remarkable variety of very specific membrane transport systems between and within cells. The mind boggles at what a homogeneous membrane would be like that could effect all of these kinds of transfer at any point in its surface without destroying the homeostasis of the interior. The design problem is simplified to the point of realizability by requiring each transport mechanism to transfer only one or a small number of substances, at the expense of restricting specific kinds of transfer to particular membrane locations. Again we see a tradeoff between a simplification, on the one hand, in boundary structures and complexity, on the other hand, in the additional mechanisms that are required to perform specific functions.

2.3. Specialization

We have already seen several examples of specializations that at the same time contribute to simplification of a system, viewed as a whole, but add new complexities in the form of the specialized mechanisms themselves. Can anything of a general kind be said about the tradeoff?

We can think of specialization within a system as an application of the principle of divide-and-conquer. If the task is to design a system that must perform many functions in order to operate successfully in its environment, then design a set of subsystems, each capable of performing one (or a few) of these functions, and connect them appropriately so that they can cooperate with each other. Clearly, the ease with which this strategy can be executed depends on the number and nature of the connections among the functions. If there are few connections, it should be easy both to design the components and to connect them. As the numbers of connections increases, the task becomes more difficult.

A first requirement for any successful system is that it be dynamically stable. R. L. May has shown that, if we represent the presence or absence of connections between pairs of elements in a linear system by a matrix of 1's and 0's and choose these elements at random, the system will very probably be stable if the percentage of 1's is sufficiently small, and highly probably unstable if the percentage of 1's is sufficiently large. Moreover, the shift from the stable to the unstable condition occurs quite suddenly as the percentage of 1's increases. This simple result gives us an important cue to the feasibility of specialization: specialization should be carried out in such a way as to keep the interactions between the specialized components at as low a level as possible.

Effective specialization is a central topic in the literature on human organizations. In fact, in the so-called "classical" literature of the 1930's (and in some of books and papers published even now), the advice is given to specialize: by function, by process, by area, and by clientele (and perhaps along other dimensions as well). As a checklist of possible bases of specialization, the advice is useful, but only as a first step, for it is internally inconsistent. If we put all of the marketing activities of a company in one department, and all of the financial activities in another (specialization by function), then we will not put all of the stenographers (specialization by process) in the same department. Hence choices must be made, at each level of the organization, as to which dimensions of specialization are the more important for the sets of heterogeneous tasks that are grouped together at that level.

2.4. Near-decomposability

Determining the degree of interconnection among various subsets of the elements of a system is not a trivial task. We must consider not only the number of different kinds of interactions, but also with the complexity of each, as well as its frequency and duration. One principle that has emerged from observation of the kinds of complex systems that actually occur in the world is that most such systems have a hierarchical structure. By hierarchy I do not mean a structure of power, although that may be present, but a boxes-within-boxes arrangement of subsystems and sub-subsystems This kind of structure is as visible in physical and biological systems as it is in human organizations. A much higher frequency and intensity of interaction takes place between components belonging to a single sub-system than between components belonging to different sub-systems; and this principle holds for all levels of the hierarchy.

The property of near-decomposability has important consequences for the behavior of a system that possesses it. Suppose that a system has a number of layers of subsystems. Because of the hierarchical arrangement of interactions, if the system is disturbed, subsystems at the lowest level will come to their internal steady states before the systems of which they are components at the next level above. Because their subsystems return rapidly to a steady state, the system above can be described in terms of the average behavior of the subsystems—specifically their principal eigenvalues. Broadly speaking, the principal eigenvalues at the various levels of the hierarchy will represent the dynamic behavior of the system in different temporal ranges: the eigenvalues at the lowest level, determine the very short-term behavior; at the successive levels above, the eigenvalues determine the dynamics over longer time intervals; and the principal eigenvalue on the highest level determines the system's long-term dynamic behavior.

This mathematical structure of a nearly decomposable system allows us to fix our attention on particular system levels if we are interested in dynamics within a specified frequency range. Even more important, it allows us to factor the system, so that we do not have to deal with all of its complexity at once. Having determined the behavior of subunits at one level, we can replace the details of these subunits by a small number of aggregate parameters, and use these to represent the system at the next level above. Or, looking from the top down, we can say that the behavior of the units at any given level does not depend on the detail of structure at the next level below, but only upon the steady state behavior, in which the detail can be replaced by a few aggregated parameters.

It is also easy to show that systems composed of stable subsystems can be composed into larger systems orders of magnitude more rapidly than can systems lacking this underlying structure. We can use this fact to explain, for example, the evolution of the hierarchy that leads from quarks to elementary particles, to atoms to molecules, and further up the biological hierarchy at least to unicellular organisms. There is no obvious way, however, in which the argument explains how multi-celled organisms achieved similar hierarchical structure. They are not formed by composition of simpler organisms, but through specialization of cells during maturation. In trying to understand the development of multi-celled organisms as specialized hierarchical structures we will need to invoke new principles that are not yet understood.

One direction the exploration can take is to ask whether hierarchy allows the various components of the system to evolve relatively independently of each other, obtaining feedback, through natural selection of the entire organism, of the particular contribution to increased fitness that is provided by each component. Near-independence of the several component functions of the system should greatly simplify its fitness landscape, so that, at least in the small, the optimum (or good) values of parameters of one subsystem would be rather insensitive to the values for the other subsystems This insensitivity, in turn, should accelerate improvement of fitness through natural selection.

Perhaps these remarks are sufficient to persuade you that near-decomposability is a property that supports complexity of function, and that nearly-decomposable systems are important objects for study in a theory of complexity.

3. Organizations and markets

Finally, I would like to discuss two kinds of systems that play a dominant role in the complex human systems we call economies: organizations (chiefly business and governmental) and markets. Between them, organizations and markets handle substantially all of the economic production and exchange that takes place, as well as the decision making that controls it. Because their components are human beings, these institutions have peculiarities, particularly in the motivations of their participants. Motivation is not usually a topic we think about in connection with the interactions of parts of organisms or the behavior of automated mechanical or electronic systems. Hence some issues arise here that are not prominent in discussions of other kinds of complexity.

3.1. The market bias of contemporary economic theory

So-called neoclassical theory devotes most of its attention to markets and puts forth several arguments as to why they generally perform their functions better than organizations do. The first argument for markets is that they are thrifty in their use of information. Each actor (consumer or business firm) can make its decisions with a minimum of information about the other actors—essentially, it needs only a knowledge of the market prices of its inputs and outputs. This is Adam Smith's "Invisible Hand." The second argument is that they make effective use of the most reliable of human motivations (some would say, "the only motivation"): self-interest.

Modern economics usually gets along with a minimalist theory of organizations, or if it enlarges this theory (as does the so-called "new institutional economics"), it does so by postulating a large array of contracts to characterize the relations between the owners of organizations and their employees—that is, it redescribes intraorganizational relations as contractual market relations., and tries to compare organizations with markets largely in terms of the relative costs of transactions in the two systems under various circumstances.

In the light of this subordination of organizations to markets in much economic theorizing, it might surprise an observer of a modern economy to note that most of the activities of members of organizations, perhaps eighty per cent as a rough guess, are not market transactions at all, but decision-making and communication activities that involve extensive problem solving, using data that go far beyond market prices, and often also incorporating authority relations among the participants. It might surprise the same observer to note that many of the interactions between different firms involve the exchange of far more information than prices, and carrying out transactions quite different from contracting for purchase or sale. In fact, these interactions often resemble the within-organization interactions to an extent that makes the boundary between the organizations fuzzy. It is a small step from a franchised retailer to a branch of a large retail chain. The interactions in real markets are something quite distinct from arms-length market transactions.

Given the important role of markets and organizations in economies, a high priority needs to be given, in research on complex systems, to deepening our understanding of the real nature of these two kinds of structure. Many topics will appear on this agenda. We will have to learn why the exchanges in markets frequently call for information about many things besides prices. We will have to take account of the motives besides self-interest, especially organizational identification and loyalty, that play a central role in the decisions of members of organizations. We will have to reassess the circumstances under which markets exhibit greater effectiveness than organizations, and the circumstances under which they are less effective. In particular, we will have to understand how bounded rationality—limits on knowledge and computation (whether by humans or computers)—affects these relative advantages and disadvantages. In sum, the theory of markets and organizations, and of their mutual relations, deserves a high place on the agenda of the study of complexity.

3.2. Motivations in organizations

I will not try to survey this whole domain, but will focus on the motivational issues; for without a correct, empirically grounded picture of the goals and values that direct human choices in organizational settings, it is hard to understand why so much of our economic activity should take place inside the skins of organizations. Notice that the advantages of specialization do not necessarily give organizations an advantage over markets.

Adam Smith was quite clear on this matter, for although he was a staunch advocate of specialization (witness his celebrated example of pin making), he conceived it as being accomplished through something like the putting-out system, where the farmer grows the flax, which he sells to the spinner, who sells the yarn to the weaver, who sells the cloth to the mercer. In fact, Adam Smith was wholly skeptical that corporations could be relied upon to represent their owners' interests, and confident that they would be operated (inefficiently) as to line the pockets of their managers and employees. He took Oxford and Cambridge Universities as prime examples of the gross inefficiencies that inevitably accompanied corporate organization.

What Adam Smith did not take into account (partly for lack of experience in his era with large organizational forms other than armies), was that human selfishness is far from synonymous with the desire to maximize personal wealth. On the contrary, there is voluminous evidence that humans, in any situation, tend to identify with a "we," and to make their decisions in terms of the consequences (including economic consequences) for the "we," and not just the "I." In some circumstances, the unit of identification is the family, in other circumstances, the nation or an ethnic group. And in many circumstances in modern society, the unit is the company or government agency that employs the individual. The decisions, and the behaviors they lead to, that we may expect from someone who is employed by and identified with an organization are often totally different from the decisions and behaviors the same person exhibits in roles that evoke a different "we"—the family, say.

It is not hard to build the case that loyalty to groups, even to the point of many sacrifices of the "I" to the "we," are exactly what we would expect as a result of the workings of evolution. I made that case, in one form, in a paper that appeared in Science in December 1990, which employs a standard neo-Darwinian argument that does not challenge the doctrine of the "selfish gene."

The introduction of group loyalties instantly changes all discussion of incentives in organization. Direct economic incentives may continue to play an important role (and they undoubtedly do in fact); but the organization where loyalties are present can be far less preoccupied with the problems of measuring the marginal contribution of employees or guarding against their opportunism that it would have to be if personal economic motives were the only bond of the employee to the organization. Personal motives play a much larger role in the decisions to join or leave organizations than they do in behavior while employed.

But the issue goes far beyond motivation. There is not merely organizational loyalty, but also organizational identification, a more inclusive mechanism. Working in an organization exposes the employee to a daily environment of beliefs and information that is vastly different from what would be encountered in other environments, including other organizations and other positions in the same organization. As creatures of bounded rationality, the decisions we reach are strongly influenced by the social environment of information that surrounds us. Most of the time, in our daily jobs, the tasks we are doing are tasks that take their meaning directly from organizational objectives (objectives of the whole organization or of the particular units in which we work), and only very indirectly (in terms of the wages and other perquisites of the employment relation) from our personal objectives.

Of course we should not be so naive as to believe that self interest does not influence the way in which employees handle organizational matters, but, in the context of a stable employment relation, one can surely make better predictions of the daily behaviors of a manager or employee from knowing what his or her job is than from knowing his or her private needs or wants. We make such predictions all the time: the bus driver will collect our fares and drive the bus along the prescribed route, and which driver is on the bus on a particular day makes only a marginal difference.

The human propensity to acquire organizational loyalties and identifications, which change both motivation and cognitive outlook, is a powerful force toward enabling organizations to accomplish certain kinds of tasks that markets perform badly or not at all. In building our theories of that complex system called the economy, we will need to incorporate identification as an important component in the explanation of organizational performance, thereby changing substantially our view of the relative roles of markets and organizations.

In introducing this exceedingly complicated topic, my aim is to warn against excessive generality in our theories of complexity. The complexity of biological systems is not going to resemble, in all aspects, the complexity of geophysical structures and processes; and both of these are going to differ in many fundamental ways from the complexity of human institutions. The theory of complex systems is perhaps going to look more like biology, with its myriad of species and of proteins, than physics, with its overreaching generalizations.

3.3. Adaptive production systems

The most common way, today, in computer science for representing processes is in the form of production systems: systems of if-then, or condition-action, relations. Whenever the conditions of a production are satisfied, its action is taken.

(There must also be rules of precedence to choose between several productions whose conditions are satisfied simultaneously.) It has been shown that production systems are as general as Turing Machines. It would be a good exercise for a biologist to show how the Krebs cycle could be represented as a production system ("If such and such proteins, etcetera, are present, then synthesize the following protein: —".) In fact, the MECHEM program of Raul Valdes-Perez represents chemical reaction paths in precisely this way, by sets of productions.

Production systems may be adaptive, that is, they may have the capability of constructing new productions (new condition-action pairs) and adding them to the system—to themselves. One way this learning can be accomplished is by presenting to the production system an example of the steps in a process and allowing it to determine what actions were taken at each step, and what conditions were present that triggered the actions. The system then forms the conditions into the left-hand side of a new production, and the actions into the right-hand (action) side. The system must have available a set of detectable features that can be encoded as conditions, and a set of executable actions that can be encoded as actions. The complete conditions and actions for any production can be assembled, in tinker-toy fashion, from members of the sets of primitive features and actions.

Learning in this manner, from worked-out examples, is widely used by human learners, and often even incorporated explicitly in such instructional procedures as homework or classroom exercises. It is an extremely powerful and very general learning technique, and probably at the core of most human learning that is more complex than the acquisition of simple reflexes (and perhaps even of that). Adoptive production systems could provide a promising model of emerging biological systems, with the introduction of mutation and crossover. I am not aware that any models of this kind have been constructed.

4. Conclusion

Perhaps I have surveyed enough specific topics that are highly relevant to the behavior of complex systems to show that the theory of complex systems, if pursued correctly, is unlikely to suffer the fate of general systems theory. Complex systems are not just any old systems. They possess a number of characteristic properties, because without these properties they would be unlikely to come into existence, or to survive even if they were born. We would expect them to be homeostatic; to have membranes separating them from their environments, and internal membranes between their parts; to specialize, so that complex functions tend to be performed in few locations; and generally, we would expect them to be nearly decomposable. When they exist in chaotic environments, we would expect them to possess special mechanisms for dealing with that chaos. We would expect to identify a number of generic forms of complexity, of which markets and organizations are examples, and systems that learn (e.g., adaptive production systems) as another example.

At the present state of our knowledge, all of these expectations are possibilities, whose correctness, and whose causal and supporting mechanisms if they are correct, remain to be verified. And of course this is a very partial menu, for I should not like to claim that I have identified, much less described, all of the facets of complexity. For those of us who are engaged in research on complexity, life ahead looks very exciting indeed.