Session 14

Towards a Systemic View of Complexity?

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General System Theory concept is close to theory of control systems. In this chapter, we try to find a systematic view of complexity from the viewpoint of system concepts. The first part of the chapter covers about General System Theory from Bertalanffy's book "General System Theory" [1]. In this book he shows that reductionism is completely wrong and modelling the system from the holistic viewpoint is the correct approach. One approach to looking at complex systems in a systemic perspective and a way to control the emerging patterns as well is demonstrated.

14.1 General System Theory

14.1.1 Introduction

"System Theory" represents a novel paradigm in scientific thinking [1]. General system theory is similar to "theory of evolution", which comprises about everything between fossils digging, anatomy and the mathematical theory of selection, or behavior theory extending from bird watching to sophisticated neurophysiological theories. Broadly speaking, three major aspects of the theory are: System science, system technology and system philosophy.

System science deals with scientific exploration and theory of *systems* in the various sciences, physics, biology, psychology, etc., and general system theory as doctrine of principles applying to all systems. Technology has been led to think not in terms of single machine but in those of systems. There is system philosophy, i.e. the reorientation of thought and worldview ensuring from the introduction of system as a new scientific paradigm. It has been learned that for an understanding not only the elements but their interrelations as well are required. This is the domain of “general system theory”. System thinking plays a dominant role in a wide range of fields from industrial enterprise and armaments to esoteric topics of pure science. Professions and jobs have appeared going under names such as system design, system analysis, system engineering and others. They are very nucleus of a new technology and technocracy.

14.1.2 History

The idea of general system theory was first introduced by the author of the book *General System Theory* by Ludwig von Bertalanffy prior to cybernetics, systems engineering and the emergence of related fields. There had been a few preliminary works in field of general system theory. Köhler’s “physical gestalten” (1924) pointed in this direction but did not deal with the problem in full generality, restricting its treatment to physics. Lotka (1925) dealt with a general concept of system but being himself a statistician his interests more lie in population problem than biological problem [1].

In early 20’s, Bertalanffy advocated an organismic conception in biology that emphasizes consideration of the organism as a whole or system, and sees the main objective of biological sciences in the discovery of the principles of organization at its various levels. His first statement goes back to Whitehead’s philosophy of “organic mechanism”, published in 1925. Canon’s work on homeostasis appeared in 1929 and 1932.

In the first year of the Center for Advanced Study in the Behavioral Sciences (Palo Alto), the biomathematician A. Rapoport, the physiologist Ralph Gerard and Bertalanffy found themselves together. The project of a Society for General System Theory was realized at the Annual Meeting of the American Association for the Advancement of Science (AAAS) in 1954 and its name is later changed to “Society for General System Research”, affiliated to AAAS. Local groups of the Society were established at various centers in United States and subsequently in Europe.

Meanwhile another development had taken place. Norbert Wiener’s *Cy-*

bernetics appeared in 1948, resulting from the then recent developments of computer technology, information theory, and self-regulating machines.

14.1.3 Trends in system theory

Miniskirt and long hair are called teenage revolution; any new styling of automobiles or drug introduced by the pharmaceutical industry can also termed so and in strictly technical sense one can speak of "scientific revolutions". A scientific revolution is defined by the appearance of new conceptual schemes or paradigms. These bring to the fore aspects, which previously were not seen or perceived, or even suppressed in "normal" science.

The system problem is essentially the problem of the limitations of analytical procedures in science. This used to be expressed by half-metaphysical statements such as emergent evolution or "the whole is more than a sum of its parts" but has a clear operational meaning. "Analytical procedure" means that an entity investigated be resolved into, and hence can be constituted or reconstituted from, the parts put together, these procedures being understood both in their material and conceptual sense. This is the basic principle of "classical" science, which can be circumscribed in different ways: resolution into isolable causal trains, seeking for "atomic" units in the various fields of science etc.

Application of analytical procedure depends on two conditions. The first is that interactions between "parts" be non-existent or weak enough to be neglected for certain research purposes. Only under this condition, the parts can actually be worked out, logically, and mathematically, and then be put together. The second condition is that the relations describing the behavior of parts be linear; only then is the condition of summativity given e.g. partial processes can be superimposed to obtain the total process etc.

These conditions are not fulfilled in entities called systems, i.e., consisting of parts in interaction. The prototype of their description is a set of simultaneous differential equations which are nonlinear in the general case. A system or "organised complexity" may be circumscribed by the existence of "strong interactions" or interactions which are nontrivial, i.e., nonlinear. The methodological problem of system theory, therefore, is to provide for problems which, compared with the analytical-summative ones of classical science, are of a more general nature.

There are various approaches to deal with such problems. The more important approaches are as follows [1]:

- Classical system theory
- Computerization and simulation
- Compartment theory
- Set theory
- Graph theory
- Net theory
- Cybernetics
- Information theory
- Theory of automata
- Game theory
- Decision theory
- Queuing theory.

A verbal model is better than no model at all. Mathematics essentially means the existence of an algorithm which is more precise than that of ordinary language. It may be preferable first to have some non-mathematical model with its shortcomings but expressing some previously unnoticed aspect, hoping for future development of a suitable algorithm, than to start with premature mathematical models following known algorithms and, therefore possibly restricting the field of vision. Models in ordinary language have their place in system theory, the system idea retains its value even where it cannot be formulated mathematically.

There are, within system approach, mechanistic and organismic trends and models, trying to master systems either by "analysis", "linear causality", "automata" or else by "wholeness", "interaction", "dynamics". These models are not mutually exclusive and the same phenomena may even be approached by different models. The fundamental statement of automata theory is that happenings that can be defined in a "finite" number of words, can be realized by an automaton (e.g., Turing machine). The automaton can, by definition, realize a finite series of events (however large), but not an infinite one. What if numbers of steps required is immense? To map them in a Turing machine, a tape of immense length would be required, i.e., one exceeding not only practical but physical limitations.

These considerations pertain particularly to a concept or complex of concepts which indubitably is fundamental in the general theory of systems: That of hierarchic order. The universe is seen as a tremendous hierarchy, from elementary particles to atomic nuclei, to atoms, molecules, high-molecular compounds, to the wealth of structures between molecules and cells to cells, organisms and beyond to supra-individual organizations. A general theory of hierarchic order obviously will be a main stay of general system theory.

"General System Theories" extended by Bertalanffy in the 1950's is one of the existing classification frameworks that has been examined and tested in the list of complex systems of interest. The list as presented by Bertalanffy had a strong orientation towards his discipline of biology and is summarized as below [1,8].

This is the systems classification according to Bertalanffy:

- Static structures
- Clock works
- Control mechanisms
- Open systems
- Lower organisms
- Animals
- Man
- Socio-cultural systems
- Symbolic systems.

In this list, each successive item is meant to be more complex and to some degree to incorporate the preceding entries. In addition, Bertanlaffy suggests the "theories and models" useful in each level of the hierarchy.

14.1.4 Ideas in general system theory

There exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relations or forces between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to system in general. In this way, General System Theory is postulated, and its subject matter is the formulation and derivation of those principles which are valid for systems in general.

A consequence of the existence of general system properties is the appearance of structural similarities or isomorphism in different fields. For example, an exponential law of growth applies to certain bacterial cells, to populations of scientific research measured by the number of publications of bacteria, of animals or humans, and to the progress of scientific research measured by the number of publications in genetics or science in general. The entities such as bacteria, animals, men, books etc. are completely different, and so are the causal mechanisms involved whereas the mathematical law is the same. Or there are systems of equations describing the competition of animal and plant species in nature. But the same systems of equations apply in certain fields in physical chemistry and in economics as well. This correspondence is due to the fact that the entities concerned can be considered, in certain aspects, as "systems", i.e., complexes of elements standing in interaction.

Similar concepts models and laws have often appeared in widely different fields, independently and based upon totally different facts. There are many instances where identical principles were discovered several times because the workers in one field were unaware that the theoretical structure required was already well developed in some other field. General system theory will go a long way towards avoiding such unnecessary duplication of labor.

Major aims of general system theory are [1]:

1. There is a general tendency towards integration in the various sciences, natural and social.
2. Such integration seems to be centered in a general theory of systems.
3. Such theory may be an important means for aiming at exact theory in the non-physical fields of science.
4. Developing unifying principles running "vertically" through the universe of the individual sciences, this theory brings us nearer to the goal of the unity of science.
5. This can lead to a much-needed integration in scientific education.

14.1.5 Open vs. closed systems

In any *closed* system, the final state is unequivocally determined by the initial conditions, e.g., the motion in a planetary system where the position of the planet at a time is equivocally determined by its position at time T_0. In equilibrium, the final concentrations of the reactants depend on the initial concentration. If either the initial conditions or the process is altered, the final state will also be changed. This is not so in an *open* system. Hence the same final state may be reached from different initial conditions and in different ways.

An open system is defined as a system exchanging matter with its environment, presenting import and export, building up and breaking down of its material components. Living systems are basically open system.

14.1.6 The system concept

Three different kind of distinctions may be made when dealing with complexities of elements: Distinctions according to *number*, *species* and *relations* of elements. In first and second types, complexity can be understood as the sum of elements in isolation (*summative* and *constitutive*, respectively). In summative case the characteristics of elements within and outside the system are the same. In the third type, not only the elements should be known, but also the relations between them. Constitutive characteristics are those which are dependent on the specific relations within the complex. The example for the first type is weight or molecular weight. An example in second type is chemical characteristics (isomorphism). The meaning of the somewhat mystical expression "the whole is more than the sum of the parts" is simply that constitutive characteristics are not explainable from the characteristics of isolated parts. The characteristics of the complex, therefore compared to those of the elements, appear as *new* or *emergent*.

A system can be defined as a set of elements standing in interrelations. In mathematics a system can be defined in various ways. We can choose a system of simultaneous differential equations for different applications, e.g, law of mass action, demographic problems, kinetics of cellular processes and the theory of competition within an organism, etc. The differential equations can be used in describing the "growth" of the system. A solution of the equation, the "exponential law" is useful in various different fields. As we talk about the system or whole, every whole is based on the competition of its elements, and presupposes the "struggle between parts". The systems of differential equations also indicate *competition* between parts. One characteristic in the system can be described as the power function of another characteristic (e.g., allometric equations).

Summativity in mathematical sense means that the change in the total system obeys an equation of the same form as the equations for the parts. This is only possible in the linear case. There is a further case that appears to be unusual in physical systems but is common and basic in biological, psychological and sociological systems, in which the interactions between the elements decrease with time. In this case the system passes from wholeness to a state of independence of elements. We may call this *progressive segregation.* Progress is possible only by passing from a state of undifferentiated wholeness to differentiation of parts. This implies that parts become fixed with respect to a certain action. Therefore progressive segregation also means *progressive mechanization.* In a differential equation, if the coefficient of a quantity is large and all others are very small then the system is centered around the leading element, called *principle of centralization.* The differential equations can have different kind of solutions that describe the *finality* of the system.

The system concept asks for an important addition. Systems are frequently structured in a way so that their individual members again are systems of the next lower level. Such superposition of systems is called “hierarchical order”. For its individual levels, again the aspects of *wholeness*, and *summativity*, *progressive mechanization*, *centralization, finality*, etc., apply [1].

14.2 Towards a New Science of industrial automation

There are still plenty of challenges we have to face in the field of automation and system engineering. Because of the new devices and technologies, there is an “information explosion” what comes to available process data. The process models are also becoming more and sophisticated. We need new approaches to cope with the wealth of data and models. Theory of complex systems promises wonderful solutions to such problems [2].

The properties of a complex system can also be pointed as below:

- It consists of a large assemblage of interconnected nonlinearly interacting parts.
- Parts evolve over time, adapting to the environment.

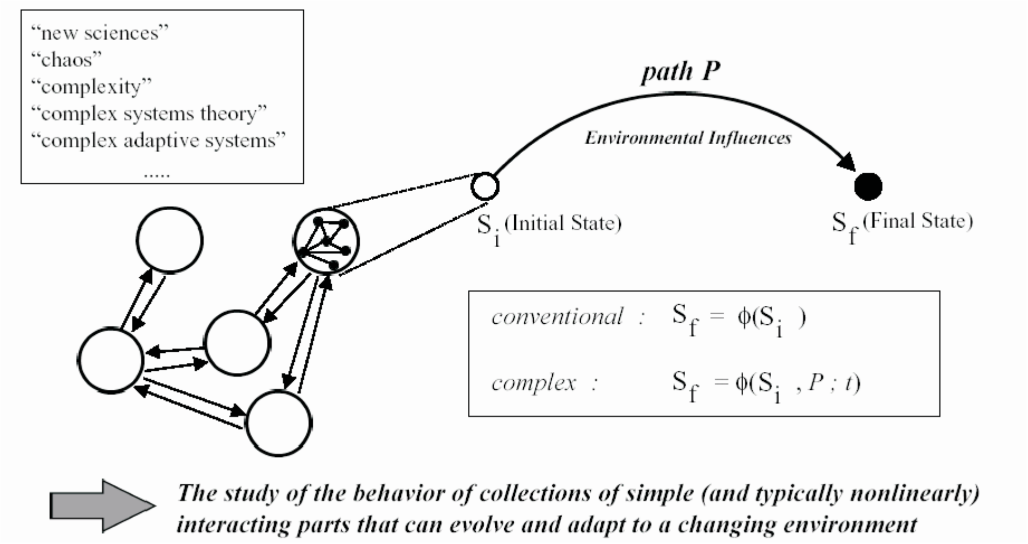

Figure 14.1: An illustration of complexity [12]

- They tend to be organized hierarchically
- They obey decentralized control
- Dynamics is basically top down and bottom up.
- Overall behavior is
  - self-organized
  - emergent
  - consists of a new-equilibrium order.

As someone speaks very loosely, he can describe chaos as the study of how simple systems can generate complex behavior whereas the study of complexity is the study of how a complicated systems can generate simple behavior [12]. There are various different approaches in defining the complexities. It is tried here to visualize some of them:

> *Malanson states that "the goal of the science of complexity is to understand how simple, fundamental processes, derived from reductionism, can combine to produce complex holistic systems . . . "* [9]
>
> *. . . A system that is complex, in the sense that a great many independent agents are interacting with each other in a great many ways. (Waldrop 1993:11)* [7]

> *... To understand the behavior of a complex system we must understand not only the behavior of the parts but how they act together to form the whole. (Bar-Yam, 1997:1)* [7].

> *... You generally find that the basic components and the basic laws are quite simple; the complexity arises because you have a great many of these simple components interacting simultaneously. The complexity is actually in the organization—the myriad possible ways that the components of the system can interact. (Stephen Wolfram, quoted in Waldrop 1993:86)* [7]

Let us try to figure out some of the examples of complex system.

- Predator-prey relationships of natural ecologies
- Economic dynamics of world market
- Turbulence in fluid flow
- Chaotic dynamics of global weather pattern
- Firing patterns of neurons in a human brain
- Information flow in the Internet
- Apparently goal-directed behavior of an ant colony
- Competing strategies of a nation's political infrastructure.

So, there are various examples of complex system around us and we can notice something fundamentally similar beneath the surface. However, the systems are so multifaceted that it is difficult to see what this underlying similarity is. It is assumed that there exist some underlying simple processes, so that when we iterate them massively, something qualitatively different comes out. The observed complexity is just an emergent phenomenon, and it is enough just to reveal the underlying simple single function to completely understand the fundamentals [2,3]. Emergence is appearance of higher level properties and behaviors that, while obviously originating from the collective dynamics of the system's components, are neither found in or nor are directly deducible from lower level properties [12].

Wolfram's claim is his cellular automata are the means to deal perfectly with any complexities [10]. We could say this is only the one approach to deal with and might also say a bad modelling technique because everything is reduced to elementary units as it is always allowed to avoid metaphysical questions away and to take only the fruitful issues in developing the model [2]. System thinking approach may help in dealing complexities. System thinking is a better way to deal with our most difficult problems [11].

14.2.1 Towards new paradigm?

Thomas Kuhn put it forward that there are paradigm shifts within a science [1] — things are seen from another point of view, and new conceptual tools are introduced. Systematic thinking may help in understanding complex systems, and may visualize new challenges. A new, data-centered world issuing to general system theory is trying to be demonstrated [2].

Theory of complex system may give new tools when searching for new tools for mastering complicated automation systems. At different level of abstraction, the appropriate way of looking at the whole system changes altogether. A good example can be *modelling of gases* [2]:

- Elementary particles of gas behave stochastically (quantum theory to be applied)
- Atoms behave deterministically (Newtonian ideal gas model)
- Atom groups behave stochastically (statistical mechanics)
- Large volumes behave deterministically (states described by pressure and temperature)
- Still larger volumes behave stochastically (turbulence and fluctuations becoming acute)
- Perfectly stirred volume behaves deterministically (ideal mixer model).

There still remain the same underlying laws, but the lower level tools are not the most economical ones in describing the complexities. The key point is to look at the phenomena from a higher abstraction level, ignoring the details of the physical components. Rather than concentrating on the actual realizations of the dynamic signal, one looks at the statistical and static relationships between the "qualifiers" or the process parameters and corresponding "qualities", or process behaviors. It can be claimed that a higher-level statistical model emerges from the lower level deterministic behaviors.

Extensive Monte Carlo simulations with slightly varied operating conditions should deliver the necessary information. The key concept to get rid of the details or reaching the higher level of abstraction is presented in the figure below [2,3,4].

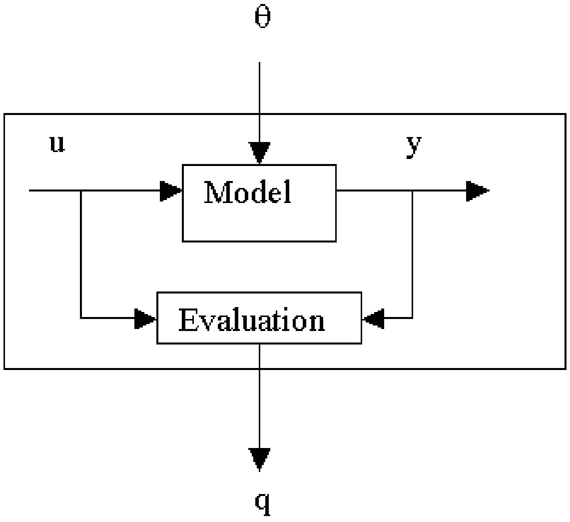

Figure 14.2: A more abstract level of looking at a dynamic system

Assuming that the necessary information are available, data is unimodal and the variations of data are normally distributed, then the data can be expressed by a multivariate Gussian distribution which can offer a nice mathematical model. Most of the information (variations) is captured in the subspace determined by most significant principle components.

Unfortunately, when studying a complex system, the unimodality assumption cannot be made. When studying the properties of a distribution in general, the data mining problem is being faced. There exists some structural properties that can be applied, and special assumptions about the distribution properties can be made. It can be claimed that sparse components are the best suited for modelling of natural, multimodal data representing a Gaussian mixture model.

So, the appropriate model is piecewise linear, consisting of linear substructures that are spanned by the individual data clusters each having separate normal distribution. Mixture modelling (clustering) concerns modelling a statistical distribution by a mixture of other distributions. The different Gussian mixtures can be motivated in a rather natural way as below [2]:

- *Continuous nonlinearity*: Smooth nonlinear functions can be approximated by locally linearising the function and using the nearest submodel to represent each sample.
- *Clustered data*: Assuming there exit different operating modes and fault conditions.
- *Independent components*: They are capable of nicely capturing physically relevant phenomena.

Linear representations are too weak to capture the real-life complexity. If the linear structures are summed or combined the resultant structure is still linear. But still the linear basic underlying structure (affine) is assumed and it is boosted with nonlinearity to make complex representations possible and to facilitate emergence of sparsity.

14.2.2 Theoretical issues concerning New Science

In complex system research, it is assumed that interesting patterns emerge from massive iterations. But there can arise some questions like when this is possible, what is interesting to begin with etc. To answer such questions, truly deep philosophical questions need to be studied. The key terms are *epistemology, ontology* and *semantics* [2].

To have something meaningful, non-trivial automatically emerge out from some mindless mechanical machinery, the domain specific meaning (*semantics*) must somehow be captured in the functions. The domain area expertise and understanding is traditionally hand coded into the model in symbolic form. However, if the models remain purely on syntactic level, no real semantics can be buried in the data structure. Rather than speaking of real semantics of the system one can speak of its behavior in an environment and its reactions Simulations supply for the grounding, hard data and the evaluation supplies for interpretation and expert understanding. This means the proposed structure can carry some *formalized semantics* or may be possibly *emergence* of something interesting.

14.3 Conclusion

General system theory should be, methodologically, an important means of controlling and investigating the transfer of principles from one field to another and it will no longer be necessary to duplicate or triplicate the discovery of the same principles in different fields isolated from each other. Bertanlaffy suggests the "theories and models" are useful in each level of the hierarchy of the system structure. Holistic view of understanding the system is that not only the parts but also the interactions in between them must be considered once the system is modelled.

The most natural way to connect low-level models to high-level tools is simulation. New data-centered world might be a new approach to be issued in "General System Theory". Mastering a complex large-scale system is to understand what is happening, what is relevant and what is not in the wealth of data.

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