Session 4

Architecture of Complex Systems

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4.1 Conceptions of Complexity

Last century has seen strong interest in complexity and complex systems. There were three main waives of interest in complexity. The post-WWI interest in the topic was focusing on the claim that the whole is more than the sum of their parts, and was strongly anti-reductionistic in flavor. The post-WWII interest was rather focusing on the idea of feedback control and self-stabilization of complex systems. The current interest in complexity focuses mainly on mechanisms that create and sustain complexity, and analytical tools for describing and analyzing it.

4.1.1 Holism and Reductionism

"Holism" is a modern name for very old idea. In the words of its author, the South African statesman and philosopher, J.C. Smuts:

> "Holism regards natural objects as wholes ... It looks upon nature as consisting of discrete, concrete bodies and things ...

> which are not entirely resolvable into parts; and ... which are more than the sums of their parts, and the mechanical putting together of their parts will not produce them or account for their characters and behavior."

Two different interpretations can be given to this idea of holism — "weaker" or "stronger". The stronger one postulates new system properties and relations among subsystems that had no place in the system components; hence it calls for *emergence,* a creative principle. In a weaker interpretation, emergence simply means that the parts of a complex system have mutual relations that do not exist for the part in isolation. By adopting the weak interpretation of holism one can adhere to reductionism even though it is not easy to prove rigorously that the properties of the whole can be obtained from properties of parts. This is the usual concept of the science as building things form elementary parts.

4.1.2 Cybernetics and General System Theory

In the 30's and 40's of XX century Norbert Wiener defined "cybernetics" as being a combination of servomechanisms theory, information theory, and stored-program computers. His works provide new insight into complexity. The information theory explains organized complexity in terms of the reduction of the entropy that is achieved when systems absorb energy from external sources and convert it into a pattern or structure. In information theory, energy, information, and pattern, all correspond to negative entropy. Feedback control defines how a system can achieve a goal and adapt to changing environment.

4.1.3 Current interest in complexity

The current wave of interest in complexity has lots of common ideas with the second one. But other new ideas are considered, such as catastrophe theory, chaos theory, genetic algorithms, and cellular automata. The motivation for the current interest is the need to tackle with complexity in global and large-scale systems such as environment, society, organisms etc. Also, tools that were developed for system complexity management in the second wave are not appropriate for current systems under investigation due to their increased complexity.

4.2 The architecture of complexity

It is good to define the term of complex systems, before going to the architecture of complex system. There are many definitions of a system. But roughly, a complex system is made up of a large number of parts that have many interactions. In such systems the "whole is more than the sum of the parts". Given the properties of parts and the laws of their interactions, it is not a trivial thing to infer the properties of the whole.

4.2.1 Hierarchic systems

By a hierarchic system we can understand a system that is composed of interrelated subsystems, each of them being in turn hierarchic in structure until some lowest level of elementary subsystems is reached. The question is rising immediately "what is an elementary subsystem"? Probably, in different cases different types of elementary units can be chosen with respect to specific task's needs.

There are lots of examples of hierarchical systems in different domains such as social systems (governments, business firms), biological and physical systems (cells — tissues — organs) all having a clearly visible parts-within-parts structure.

4.2.2 The evolution of complex systems

Let us quote here the "watchmakers metaphor" that was presented in [4.3]:

> There once were two watchmakers, named Hora and Tempus, who manufactured very fine watches. They were making their watches in own premises, a phone was calling frequently – new customers were calling. Hora prospered and Tempus became poorer. What was the reason?
>
> The watches consisted of 1000 parts each. Tempus was assembling them part by part, and if his phone was ringing (the work process was interrupted) he had to put the not finished watch down, and it immediately fell to pieces and had to be reassembled from the elements.
>
> The watches that Hora made were not less complex. But he had designed them so that he could put together subassemblies

> of about ten elements each. Ten of these subassemblies could be put together into a larger subassembly; and so on until the ten last subassemblies would be combined into the whole watch. Hence, when he was interrupted, he had to put down th epartly assembled watch to answer the phone. He was losing only a small part of his work in comparison to Tempus.

If we take into account some ideas from biological evolution and other fields, a number of objections will arise against this metaphor.

- The complex forms can arise from the simple ones by purely random process. Direction is provided to the scheme by the stability of the complex forms, once these come into existence.
- Not all systems appear hierarchical. For example, most polymers are linear chains of large number of identical components.
- Multi-cellular organisms have evolved through multiplication and specialization of the cells of a single system, rather than through the merging of previously independent subsystems.

Hence, there are reasons to dismiss the metaphor. However, the systems that evolve by means of specialization have the same kind of boxes-within-boxes structures as well as systems that evolve by assembly of simple systems.

There are application were the metaphor works. Consider, for example, the theorems and their proofs. The process starts with axioms and previously proven theorems. Various transformations allow obtaining new expressions; this process goes on until the theorem are proven. Another good example is the development process of an empire:

> Philip assembled his Macedonian empire and gave it to his son, to be later combined with the Persian subassembly and others into Alexander's greater system. On Alexander's death his empire did not crumble into dust but fragmented into some of the major subsystems that had composed it.

4.2.3 Nearly decomposable systems

The interactions among subsystems and interaction within subsystems can be distinguished in hierarchic systems. The interactions at the different levels may be of different orders of magnitude. For example, in a formal organizations there will be more interactions between employees from the same department than from different departments. The system can be considered as decomposable if there are no interactions among the subsystems at all. In practice, these interactions can be weak but not negligible. Hence, one may move to the theory of nearly decomposable systems.

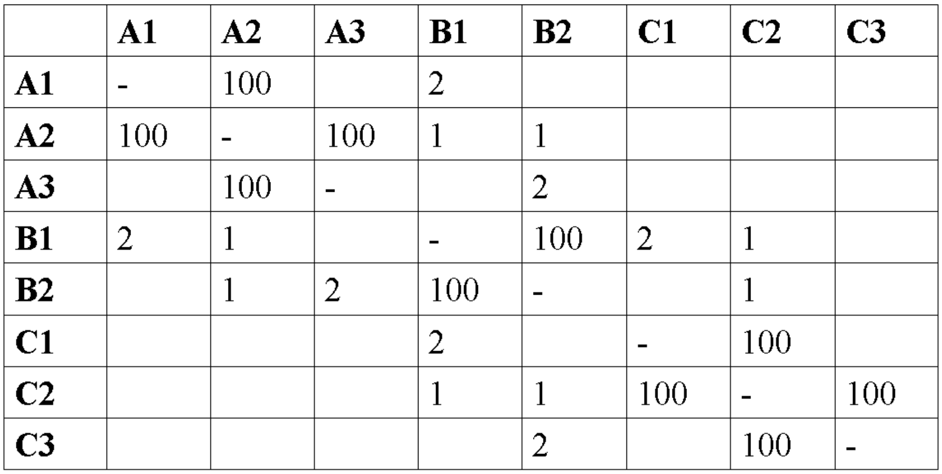
There are two main theoretical propositions found concerning nearly decomposable systems:

- In a nearly decomposable system the short-run behavior of each of the component subsystems is approximately independent of the short-run behavior of the other components.
- In the long run the long-run the behavior of any one of the components depends in only an aggregate way on the behavior of the other components.

These ideas can be described using an example. Consider a building whose outside walls (boundary of our system) provide perfect thermal isolation from the environment. The building is divided into a large number of rooms; the walls between them (subsystems boundaries) are not perfect isolators. Each room is divided in partitions — the cubicles being poorly isolated. A thermometer hangs in each cubicle. There is wide variation in temperature during the first observation. But a few hours later the temperature variation has become very small among rooms inside the building.

One can describe the process of reaching the equilibrium formally by setting up the usual equation of heat flow. The equations can be represented by the matrix of their coefficients: $\boldsymbol{r}ij$ is the rate at which heat flows from the ith cubicle to jth one. If cubicle i and j do not have a common wall then $\boldsymbol{r}ij$ will be zero. If cubicles i and j are in the same room then $\boldsymbol{r}ij$ will be large. If cubicles i and j are separated by the room's wall then $\boldsymbol{r}ij$ will be small but not zero. Hence, one can group together all these coefficients, getting a matrix where all of its large element will be located inside a string of square submatrices along the main diagonal. We shall call a matrix with this properties a nearly decomposable matrix (see Fig. 4.1).

Now it has been shown that a dynamic system that can be described in terms of a nearly decomposable matrix has the properties of nearly decomposable systems, stated earlier in this section. Hence, we have seen that hierarchies have the property of near decomposability. Intra-component linkages are generally stronger then inter-component linkages. This fact has the effect of



	A1	**A2**	**A3**	**B1**	**B2**	**C1**	**C2**	**C3**
A1	-	100		2				
A2	100	-	100	1	1			
A3		100	-		2			
B1	2	1		-	100	2	1	
B2		1	2	100	-		1	
C1				2		-	100	
C2				1	1	100	-	100
C3					2		100	-

Figure 4.1: The nearly decomposable matrix. The matrix coefficients rij are the rates at which heat flows from the cubicle ith to the cubicle jth (A, B, and C are rooms; A1 denotes the cubicle 1 in room A)

separating the high-frequency dynamics of a hierarchy (involving the internal structure of the components) from the low-frequency dynamics (involving interaction among components).

4.2.4 The description of complexity

Information about a complex object is arranged hierarchically like a topical outline. When information is put in outline form, it is easier to include information about the relations among the major parts and information about the internal relations of parts in each of the sub-outlines. Detailed information about the relations of subparts belonging to different parts has no place in the outline and is likely to be lost. From the discussion of dynamic properties of nearly decomposable systems, we have seen that comparatively little information is lost by representing them as hierarchies. Subparts belonging to different parts only interact in an aggregative fashion — the detail of their interaction can be ignored. For example, in studying the interaction between two molecules, generally we do not need to consider in detail the interactions of nuclei of the atoms belonging to the one molecule with the nuclei of atoms belonging to the other.

The fact then that many complex systems have a nearly decomposable hierarchic structure is a major facilitating factor enabling us to understand, describe and even see such systems and their parts. From another point of view, if there are important systems in the world that are complex without being hierarchic, they may to a considerable extent escape our observation and understanding. Analysis of their behavior would involve such detailed knowledge and calculation of the interactions of their elementary parts that it would be beyond our capacities of memory or computation.

There are two main types of description that seem to be available to us when seeking for understanding of complex systems:

- State description
  - “A circle is the locus of all points equidistant from a given point”.
  - Pictures, chemical structural formulas, blueprints, etc.
- Process description
  - “To construct a circle, rotate a compass with one arm fixed the other arm has returned to its starting point”.
  - Recipes, differential equations, etc.

4.3 Conclusions

Empirically a large proportion of the complex systems one can see have hierarchical structure. Or one perceives them as hierarchies in order to solve some complex problems. A complex system can be presented as a hierarchy in order to make proper control of the systems. This approach of presentation is very desirable in many cases due to the fact that it has many useful properties such as near decomposability that is simplifying description and analysis of the system.

Reference

- Herbert A. Simon: *The Sciences of the Artificial.* MIT press, Cambridge, Massachusetts, 1996 (third edition).