Session 2

Complex Systems — A New World View

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Because of the rapid increase of computational power, many numerical methods has been widely used in the complex system research. In addition to that the development of information processing and networked systems like the Internet has also effect to the field of complex systems. This chapter gives introduction to the ongoing change and possible promises.

2.1 Introduction

After the development of microprocessor the computational capacity started to increase rapidly. This has enabled totally new world to the modelling and simulation of complex systems — systems that are difficult or impossible to analyze by using traditional mathematical methods, like analysis. That has also generated several questions. It has been shown that it is possible to imitate complex system behaviour by using computer programs, but how useful and valid that kind of imitations finally are? Shall we get something useful out of it, or does the intuitive similarity only confuse us? Is it possible to find something that reshapes our picture of systems called "complex" by using different type of computer programs and number crunching methods, or are we just operating with new tools in old field?

2.2 Wolfram's "New Kind of Science"

2.2.1 About the book and author

Stephen Wolfram has recently generated a lot of discussion by publishing a book A New Kind of Science [1]. Wolfram was born in London and educated at Eton, Oxford and Caltech. He received his Ph.D. in theoretical physics on 1979 at the age of 20 having already made lasting contributions to particle physics and cosmology. In 1986, he founded Wolfram Research, Inc. [2], and developed computer algebra program Mathematica that was also, according to Wolfram, important instrument when he made the simulations and calculations presented in the book. Over the past decade Wolfram has divided his time between the leadership of his company and his pursuit of basic science.

2.2.2 Basic ideas

The crucial point in Wolfram's thinking is that computing capacity is today so huge, that simple computer programs with simple rules should be enough for understanding complex behaviour. He presents several examples, how complex behaviour is generated based on simple rules, and he points out several similarities between nature and systems generated by simple computer programs. This leads him to the conclusion that there are often simple rules behind complex behaviour. Wolfram formulates his main idea as the principle of computational equivalence: whenever one sees behaviour that is not obviously simple, it can be taught of as corresponding to a computation of equivalent sophistication [1].

2.2.3 Cellular Automaton

One important instrument in Wolfram's work is cellular automaton. One of the first predecessors of cellular automata was so-called Turing Machine, developed by Alan Turing in the 1930's. Turing machine is formulated by giving a set of rules how it should operate and change its states. Turing proved that whatever computing process can be repeated by Turing machine.

In the 1950's John von Neumann formulated cellular automaton. There are cells located somewhere in space, and in each step of time the state of a single cell is determined based on the states of neighbouring cells one step earlier.

One of the most well-known cellular automata was so-called Game of Life, a two-dimensional cellular automaton presented by John Conway in the 1960's.

Stephen Wolfram start to work with cellular automata in the 1980's, and found soon out that even cellular automata generated by very simple rules have interesting properties. By using computer programs including Mathematica he and his company developed, Wolfram made numerous different types of simulations with different types of cellular automata. He found out interesting variations of chaotic and regular patterns in cellular automata, nested structures, evolutionary structures and also interactions between different types of structures. Wolfram used cellular automata to investigate the system sensitivity to the different initial values, and he used cellular automata-like substitution systems to imitate some natural processes, like fluid vortexes, formation of snowflakes and growth of plants and animals. He built different classifications to cellular automata types based on his findings, and found also analogies between cellular automata and traditional mathematics [1].

2.2.4 Wolfram's conclusions

Based on his investigations, Wolfram claims that most of the complex natural processes are based on the same type of simple rules that he implemented in cellular automata. He goes even further, and postulates that even the laws of fundamental physics could be based on similar types of simple rules, and underneath all the complex phenomena we see in physics there could be some simple program, which, if run long enough, would reproduce our universe in every detail. As a comment for these postulates Wolfram writes: "The discovery of such subprogram would certainly be an exiting event — as well as dramatic endorsement for the new kind of science that I have developed on this book". Furthermore, he suggests that by combining this with a certain amount of mathematical and logical deduction, it will be possible at least as far as reproducing the known laws of physics [1].

After huge amount of examples and comments Wolfram returns to the main idea of his "New Kind of Science", what he calls the Principle of Computational Equivalence: "All processes, weather they are produced by human effort or occur spontaneously in nature, can be viewed as computations" [1]. This raises the question whether there is need for traditional mathematical analysis any more; is traditional mathematical analysis even valid tool in some cases?

2.2.5 Criticism

Wolfram presents several examples of how to generate complex behaviour based on simple rules, but in many cases reader gets a feeling that something is missing. The big question — especially from the system theoretic and control point of view — is how to go *backwards*? In real life situations the problem is usually that we already have a complex system, and we are trying to find rules for handling it. This task is much demanding that just showing that it is possible to generate complex behaviour with simple rules. There exist also some contradictions in Wolfram's presentation: In some cases he argues that it is important to take all the details into account, but in some other cases he says it should be enough just to follow the main lines and forget the details [1].

Another weakness is that the comparisons between traditional methods and methods based on Wolfram's methods are missing. In many examples presented in the book (concerning vortexes, for example) it would have been interesting to see the model of the same system based on traditional methods.

In some cases there exist quite courageous conclusions about the equivalence between cellular automata based systems and processes in real nature. It is hard to believe that it is enough that the behaviour only looks similar at some level [1].

2.2.6 Provocation?

It is not a miracle that Wolfram's book has evoked a lot of discussion — and also furious criticism — in the scientific community. What in any case is widely accepted and important point in this book is that it presents how rapidly the computational power has increased and that the possibilities of many simulation and computer algebra programs are becoming better and better. Many methods which were recently shot down immediately because of their huge demand of computation capacity are part of the normal practice today. There are more computational power in many cheap and simple calculators, than there were in building-size machines 25 years ago.

Could one of the motivations of Wolfram's courageous text be provocation?

When talking about big basic things in science, the scientific community is today so smug that many radical new ideas are immediately shot down without any further discussion, if presented conventionally. Hence, more provocative style is needed for generating active debate.

2.3 Networked systems

2.3.1 New findings and inventions

The basic principles of the neural system in biological organism have been known relatively long time, and during the latest decades a lot of new knowledge has been gathered in the area of neurosciences. In addition to that, the development of computers and the rapid growth of computing recourses have enabled the creation of different networked systems. Probably two most well-known network categories are the Internet and artificial neural network algorithms developed for modelling and simulation.

The success of those two network types and the rapid increase in the number of users has also generated new viewpoints to the complex systems, and, generally, to the universe around us.

2.3.2 From hierarchy to network

The traditional way to see many complex systems has been as a hierarchical structure. Even in modern quantum physics there exist different electron energy levels in the basic structure, and furthermore each of those stages is split to hierarchical structure in lower level. In macroscale, space consists of solar systems, galaxies and so on. There are of course a lot of hypotheses and different types of theories concerning those models, but the traditional way how the things have been seen is some kind of hierarchical structure.

Because of the traditional hierarchical way of thinking and relatively simple structure of hierarchical models, those types of models have been widely used in control engineering when trying to model and control complex systems. In many cases this approach has been useful or at least good enough when controlling industrial processes, for example.

2.3.3 Networked structures

In his book “Emergence” [3], Steven Johnson presents the idea that everything is linked rather than hierarchically structured. Furthermore, Johnson weights the importance of local low-level interactions in the network. He found analogies for example in the behaviour of ant colonies, economical systems and in the growth of cities. The structure of all of those systems is network-type, and there seems to be a lot of local interactions that are not centralized controlled. It could be possible that some general trends in the behaviour are initially or centrally set, like rules in the markets and city and instincts in the ant behaviour. Anyway, local interactions and decisions that cannot be centrally controlled have still crucial effect to the development of the whole system.

Thus, Johnson sees many systems as being constructed from bottom to up. He also presents some discussion about the development of local structures and local decision making clusters [3]. In his book “Linked” [4], Albert-Lazlo Barabasi presents similar types of thoughts about network-structured systems, and he formulates Agents as a functional objects in the network.

2.3.4 Nodes or only connections?

Two interesting issues concerning network structures are the importance of nodes and the importance of node connections. From one point of view, the locations of single nodes do not matter so much or they even do not matter at all; how the nodes are connected to each other matters, because it determines the possibilities how information can be transferred in the network. One can, for example, think the cellular phone system. It is not necessary to know the exact location of single cellular phone to make the system work; cellular accuracy has been enough to built robust communications system.

When talking about the Internet, it is a fact that it has made the World smaller during the last 10 years, but there have not been big changes in the physical travelling times since the beginning of 1990’s until the beginning of new millennium. The change that has made the World smaller is the change in information transferring time and capacity. When in Euclidian space the distance between two points is calculated using the Euclidian norm, in the networked space it can be, for example, the number of hops between two nodes, or the time that it takes to send information from node to another [1, 2, 4].

2.4 Conclusions: A way to the New World?

Since the development of mathematical analysis, the theoretical research based on differential computation and algorithm development has had the leading rule in the area of system research. Such complex systems that were difficult or impossible to model were seen as exceptions from general uniform rules. Recently the achieved computational resources and continuous increase of it has started to shake this balance.

Different methods based on numerical algorithms and other unstandard methods have given interesting and in some cases also promising results in the complex system research, and also in many traditional problems simulators based in numeric methods have became widely used. Many critics argue that because of the rapid development the possibilities of new methods are still not understood well enough. For example, some of the driving computers installed in the basic models of 1990's cars have the same computational capacity as the computers used in the first Moon flight had.

During the revolution of physics at the beginning of 1900's the research of phenomena earlier usually just regarded as a holes in uniform physical picture created radically new physical world. Could it be so that, similarly, the use of new computational methods in the research of complex systems will radically renew the field of systems research? If it is so, mathematical analysis in the form it developed in the 1600's will be just a part of system modelling valid in some restricted area — just like the results and methods of classical physics are special cases in the field of modern physics. Furthermore, when the new capabilities of information processing and networked systems are connected to new science, the change could be even more radical and in the near future we can deal with many systems taken earlier as too difficult or even impossible to model and control.

Bibliography

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