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Exploring Complex Systems Through Computation

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Complex systems are abundant in our universe, especially in the form of biological and social systems. By complex system I refer to systems that are composed of local elements interacting with each other in a inhomogeneous, time-varying, specific, and often non-linear manner [1], ultimately leading to emergent behaviour. Exploring complex systems is essential to increase our knowledge about the universe. Since Newton and Galileo, we mostly approach this by looking at the system as a whole and thus from a macroscopic or global point of view and by formulating mathematical equations describing the system's behaviour from this viewpoint. The current mathematics of this approach becomes hard if not impossible to use for describing the kind of interactions we find in complex systems and although we know that, we still investigate complex systems as Newton and Galileo did – neglecting the way complex systems compute. In this abstract, based on an example from biology, I illustrate what structure complex systems have and how they operate or compute on their structure. I then propose a way of exploring complex systems exploiting computation in complex systems.

Biological systems develop and grow building almost exclusively *network structures* [1]. Local elements such as cells interact with each other in networks and form higher-level structures such as tissues. It might start small and simple but the interaction in such multilayer networks leads to the emergence of large and highly complex systems such as organisms and societies. Biological research mainly follows different pathways through the multilayer networks of biological systems. But such an isolated view of cellular and molecular interactions is misleading as beautifully illustrated by the *omnigenic hypothesis* [2], which suggests that all genes affect every complex trait. Additionally, knowing which elements interact with each other leads to a good approximation of the emergent behaviour despite the lack of detailed kinetics [3], highlighting the importance of interaction.

If we now look at a biological system in terms of computation, we can make use of the concepts of *structure* and *operation*. Complex systems and systems in general consist of at least one structure and one operation computing on this structure [4, 5]. E.g. a computable function is an operation and its input and output are structures. Accordingly, biological systems develop and grow starting from a few interconnected elements and repeatedly applied simple rules over time. The structure that forms is a network or, if including multiple length scales, a multilayer network. The operation is a simple rule or a set of rules determining whether a particular element is on or off at a particular discrete time step. This description is identical with Stuart Kauffman's *random Boolean networks* [6]. He was able to show that representing gene regulatory networks with simple Boolean rules iteratively applied to network structures leads to regulatory behaviour and network topologies also found in biological gene networks. The system's behaviour is thus emerging from the interacting elements based on rules applied repeatedly over time. It is also similar to Stephen Wolfram's elaborative work with *cellular automata* where he found that simple rules can lead to complex behaviour [7] and that cellular automata can been seen as models of complexity [8]. This allows us to generalise the described computation in complex biological systems to any other type of complex system. Most recently, Wolfram presented a new model [9] based on *hypergraphs* that is used in the same way but has a network structure, which makes it identical with the computation described above.

These observations suggest that computation in complex systems is based on network structures that start with few local elements and emerge as a result of iteratively applied simple rules over time. It is therefore a *rule-based bottom-up approach* and requires a device capable of performing an extremely large number of computations, which makes it *algorithmic* [1]. Instead of trying to come up with a mathematical equation describing the global or macroscopic behaviour of a complex system, complex system computation suggests to start with simple rules and small structures at the local or microscopic level. It also suggests that the system's structure needs to develop and grow and thus many computational experiments with different rules are required to get an impression of the system's behaviour. Instead of analytically solving mathematical equations, computational experiments are conducted. The computed data can of course be analysed and where computational reducibility permits it, equations and analytical solutions might be possible. Starting almost structureless and performing countless computational experiments is uncommon and seems tedious at first but it seems that through computation and by making as few assumptions as possible, the complexity of a system can unfold.

References

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