Published in: Dubitzky, W./ Wolkenhauer, O./ Cho, K.-H./ Yokota, H. (2013) (eds.): *Encyclopedia of Systems Biology*, Vol. X. New York: Springer, 456-460.

Complexity

Marie I. Kaiser, University of Cologne, Department of Philosophy, Germany,
kaiser.m@uni-koeln.de

Synonyms

complication, intricacy

Definition

Complex systems are associated with a range of different characteristics like the multiplicity of their parts, the non-linearity and non-additivity of the interactions between their parts, the sensitivity of their behavior to initial conditions, their hierarchical organization, their self-organization, and the robustness and the emergence of their behavior. Some of these characteristics are necessary conditions for a system to be complex; others are just typical for many complex systems. The latter is due to the fact that nature exhibits a variety of different kinds of complexity.

Characteristics

In recent decades the focus of scientific research has shifted more and more to trying to understand and handle the complexity of nature. In biology, for instance, the reductionistic assumptions (reduction) that there is a neat, simple gene-protein-trait-fitness relationship and that the behavior of a biological system can be understood merely by studying the parts of the system in isolation have been rejected. Instead, contemporary biologists try to account for the complexity of nature by recognizing the "wholeness" (holism) of biological systems (e.g. Chong and Ray 2002), that is, by paying attention to the various interactions between the parts of a system and to how these parts are integrated to the system as a whole. For example, rather than examining the isolated functions of genes biologists study the dynamics of entire gene regulatory networks. This focus shift towards complexity issues is not restricted to the biological sciences. Rather, it is a quite general trend, which is why some authors speak of a "complex system revolution" (Hooker 2011, 6) that has been and still takes place in contemporary science.

1. What Is a Complex System?

Despite the fact that complexity issues more and more gain center stage in several research fields there exists neither a unified science of complex systems, nor a consensus about what complexity is and what makes a system complex. Rather, the characterizations of complexity partially vary from field to field and from author to author. There are two different ways of how one could react to this situation. On the one hand, one could argue that there is still much empirical and conceptual work left to do, and that sometime in the next future scientists and philosophers will have figured out how to specify what a complex system is. On the other hand, one could point out that the actual disagreement on how to characterize complexity is not due to our insufficient knowledge. Rather, it arises from the actual variety of ways that systems are complex. In other words, nature exhibits different kinds of complexity that cannot be captured by a single definition.

Depending on which claim an author subscribes to, he will favor one of two strategies for characterizing complexity: first, several authors try to specify what complexity is by proposing a list of features, each of which is necessary and all together are sufficient for a system to be complex (e.g. Hooker 2011; Ladyman et al. 2012); the second strategy consists in distinguishing different kinds of complexity (e.g. Mitchell 2003; Kuhlmann 2011). In this section some crucial insights of pursuing the first strategy will be revealed, whereas Section 2 introduces some classifications of complexity (second strategy).

Before doing so it should be stressed that the two strategies are neither opposite nor incompatible. What distinguishes them is the emphasis they put on the diversity of complexity. Those who aim at a definition of complexity which identifies necessary and together sufficient conditions for a system to be complex (first strategy) focus on the similarities among different cases of complexity. On the contrary, those who pursue the second strategy and distinguish different kinds of complexity put more emphasis on the actual variety of ways that systems are complex. However, it is also possible to seek after a list of core features of complex systems and at the same time account for their diversity. For instance, one could abandon the requirement that these features must be necessary and allow also features on the list that are only typical for many (but not for all) complex systems. Furthermore, one could also combine the first and the second strategy by, at first, distinguishing different kinds of complexity, and then specifying these types of complexity by identifying different sets of features that are associated with these different kinds of complexity.

What are the features that are said to be necessary for complexity or that are at least typical for many complex systems? The following main features are widely associated with complex systems (which is not to say that this list is exhaustive; for alternative approaches see Hooker 2011 or Ladyman et al. 2012):

Multiplicity of parts

Complex systems typically consist of a *large number of parts*. In some cases, many of these parts are of the same or of similar kind (e.g. a swarm of birds is composed of birds of the same species). Other complex systems are made of components that belong to several different kinds (e.g. organ systems like the cardiovascular system consist of different kinds of tissues and cells).

Non-linearity and non-additivity of interactions

The parts of a complex system causally interact (causality) with each other in order to bring about a particular behavior of the overall system. It is characteristic for many complex systems that these interactions are *non-linear*, more precisely, that the behavior of the system is described by a mathematical function that is non-linear (e.g. because the variable of interest is squared). Non-linear interactions frequently involve positive or negative feedback.

Non-linear dynamical equations are characterized by *non-additivity*, which means that numerical combinations of solutions are in general not solutions. The feature of non-additivity is one reason why complex systems are said to be "more than the sums of their parts". To put it another way, complex systems are not *aggregative systems* (Wimsatt 2007) because their behavior does not remain invariant under interchanging their parts, under changes in the number of parts, and under decomposing and rearranging their parts, and the interactions among their parts are not linear.

Sensitivity to initial conditions

The behavior of some complex systems is *sensitive to initial conditions*. This is due to the fact that the non-linearity of the interactions between the system's parts allows small differences in the system state to be amplified (amplification) into large differences in the subsequent system trajectory.

Hierarchical organization

Complex systems typically possess a *hierarchical nature* (hierarchy), that is, they are parts of higher-level systems and they consist of parts that are themselves (lower-level) systems which, in turn, may also be composed of subsystems, and so on. For instance, organisms consist of organ systems that are composed of tissues which consist of cells, etc. This feature is also referred to as the *multi-level character* of complex systems. Recognizing the hierarchical nature of complex systems is important for understanding how complexity can evolve (Simon 1962).

Self-organization

Complex systems are *self-organizing systems*. Self-organization means that an initially disordered system becomes more organized or ordered because of the interactions of the parts of the system. The process of self-organization is spontaneous, that is, it is not centrally controlled by any agent or subsystem.

Robustness

The organization or order of a complex system is said to be *robust* (robustness), that is, it remains stable under a certain range of disturbances of the parts of the system.

Emergence

The behavior of complex systems is often said to be emergent (emergence) in the sense of being unexpected, unpredictable, or unexplainable on basis of the knowledge about the parts of the system in isolation (more on this in Section 3.3).

2. Different Kinds of Complexity

A second way to characterize the phenomenon of complexity is to distinguish different kinds of complexity. At least two classifications of complexity are worth being mentioned here. The first one has been introduced by Mitchell (2003, 2009). She distinguishes three different kinds of complexity in biology: constitutive complexity, dynamic complexity, and evolved complexity. '*Constitutive complexity*' refers to the complexity of the structure that biological systems (like organisms) display. The structure of biological systems is complex if the system as a whole is being formed of numerous parts in non-random, non-simple organization (see also Simon 1962; Wimsatt 2007). '*Dynamic complexity*' concerns the complexity of the processes that biological systems are engaged in, for instance the developmental or evolutionary processes that organisms undergo. Finally, '*evolving complexity*' refers to the domain of alternative adaptive solutions that are available for certain adaptive problems. If there exists a wide diversity of forms in life which have evolved as solutions to the same adaptive problem there is said to be much evolving complexity.

More recently, Kuhlmann (2011) has argued that it is important to distinguish compositional complexity from dynamical complexity. Although he uses similar words as Mitchell, the two kinds of complexity he identifies are different from hers. This difference might (at least partly) be due to the fact that Kuhlmann is more interested in complex systems from physics and socio-economics, rather than from biology. What Kuhlmann means by *compositional complexity* of a system is the complicated organization of the set-up conditions of a system, that is, the fact that a system consists of many parts and that the individual behaviors of the parts as well as their organization determine the overall behavior of a system. Somehow surprisingly, Kuhlmann emphasizes that the parts of compositionally complex systems interact with each other in a linear fashion, which is why the behavior of the system is a summation of the behaviors of its parts. Contrary to this, in case of *dynamical complexity* most facts about the nature of the parts of the system as well as their initial arrangement have no bearing on the behavior of the system. Rather, what makes these kinds of systems complex is that, although they are compositionally simple and the rules that determine their dynamics are simple (but non-linear), they show patterns that are factually unpredictable and qualitatively unexpectable.

3. Further Philosophical Issues

3.1. Explaining Complexity

One important philosophical question that arises in the context of complex system research concerns the nature of scientific explanation. Do the explanations of the behavior of complex systems constitute a *special kind of explanations*, as for instance Mitchell (2009) and Kuhlmann (2011) argue? Or do they belong to one or more of the established kinds of explanation (like causal-mechanistic explanation, covering-law explanation, functional explanation, mathematical explanation, etc.)?

A good starting point for addressing this question is the widespread claim of biologists that reductionistic-mechanistic research strategies (reduction; mechanism) are inappropriate or, at least, insufficient to investigate and explain the behavior of complex systems (e.g. Gallagher and Appenzeller 1999). This suggests that explanations that are developed in sciences of complex systems are *non-reductive* (explanation, reductive) and *non-mechanistic*. However, it is far from clear what exactly this claim amounts to and whether it is true for all explanations in this field (e.g., whether it also applies to computational explanations that can be found for instance in systems biology). One reason why the explanation of the behavior of complex systems might be non-reductive is that these explanations frequently appeal not only to the parts of the system, but also to contextual factors and higher-level factors (which is why they are said to be multi-level explanations; Mitchell 2009). Moreover, the behavior of complex systems cannot be explained by referring only to the parts of the system in isolation (which is, in turn, typical for reductive explanations; Kaiser 2011). However, in the last 15 years several accounts of mechanistic explanation have been developed which decouple the concept of a mechanistic explanation from the concept of a reductive explanation because they allow higher-level and contextual factors to figure center stage in a mechanistic explanation (e.g. Bechtel 2008).

3.2. Causality and Complex Systems

A second philosophical question concerns the *causal structure* of complex systems (causality). Do any challenges and constraints for a philosophical theory of causation arise from the peculiarities of the causal structure of complex systems?

A possible challenge might be the existence of downward causation, which is a topic that is also frequently discussed in science itself. Downward causation encompasses cases, in which entities from a higher level of organization causally affects entities from a lower level (interlevel causation). Downward causation between a whole (i.e. the higher-level entity) and its parts (i.e. the lower-level entities) is regarded as particularly problematic because a central assumption in most theories of causation is that cause and effect must not be identical. However, if it is true that the relation between a whole and the set of its organized parts is one of identity, as one could argue, the whole cannot be causally related to its parts.

Other challenges and constraints of a theory of causation that may arise from the investigation of complex systems concern the context-sensitivity of their behavior and the non-linearity of the interactions between their parts. The latter often involve cyclic causal relations like feedback which constitute a challenge for some theories of causation (e.g., for causal graph theories).

3.3 Emergence and the Limits of Reductionism

One of the features that are characteristic of complex systems is that their behavior is said to be *emergent* (see Section 1). However, despite its ubiquity the notion of emergence is left notoriously vague. Most scientists use the term 'emergence' in an epistemic sense, that is, they call a behavior (or property) of a system emergent if it is unpredictable, unexpectable, or unexplainable on basis of knowledge about the behavior (or properties) of its parts in isolation.

Studying emergent behaviors of complex systems reveals the *limits of reductionism* (reduction). More precisely, it discloses the conditions under which the (exclusive) application of reductive research strategies (like decomposition, simplification of the system's context, and investigating parts in isolation; Wimsatt 2007; Kaiser 2011) is not adequate any more. In other words, the emergent behavior of a complex system cannot be understood by decomposing it into its parts, by examining the parts in isolation (i.e. separated from the original system), and by ignoring the context of the system. This is, for instance, due to the fact that the parts of a complex system are organized or "integrated" (Bechtel/Richardson 2010) in such a complicated way that their behavior is co-determined by the system's organization. Furthermore, the behavior of several complex systems heavily depends on certain parts of their context (i.e. it is non-robust under variations of these contextual factors), which is why the context of the system cannot be ignored altogether or simplified.

Cross-references

amplification; causality; classification; emergence; explanation; explanation, reductive; feedback; gene regulatory networks; hierarchy; holism; interlevel causation; mechanism; organization; reduction; robustness; self-organization

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