

Understanding Complex Systems

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“Understanding complex systems” has become the overarching theme of a new approach to science. Promoting research that encourages a holistic perspective [1] to “understand complex systems” is a long term investment priority in the strategic plan of the National Science Foundation of the United States for the next five years [2]. In 2005 Springer Verlag started a book series entitled “Understanding Complex Systems” [3] and since 2001 the annual “Understanding Complex Systems” symposium is held at the University of Illinois at Urbana-Champaign [4]. The phrase “understanding complex systems” is often used, but its meaning is rarely defined. The phrase is a sequence of three words, where each word describes an abstract concept: understanding, complex, and system.

The Merriam-Webster Online Dictionary defines “Understanding” as “to grasp the meaning or reasonableness of something, to have thorough or technical acquaintance with or expertness in the practice of something, to be thoroughly familiar with the character and propensities of something”, and the current Wikipedia definition is “Understanding is a psychological process related to an abstract or physical object, such as, person, situation and message whereby one is able to think about it and use concepts to deal adequately with that object.” In a more colloquial way “understanding” can be defined as “being able to translate”. For instance, understanding a foreign language means being able to translate the foreign language into the mother tongue and back. Similarly, “Having a mathematical understanding” means “being able to translate everyday phenomena into the language of mathematics and back”. And someone, who can derive a concept, such as Newton’s second law, from more abstract concepts, such as conservation of energy, has an abstract understanding of Newton’s second law. Describing Biology with mathematical concepts leads to a mathematical understanding of Biology. Understanding means translating between two sets of knowledge, translating between two conceptual networks, a translation from common knowledge into disciplinary knowledge, a translation between disciplines, or a translation between more abstract and less abstract concepts within a discipline.

Why is “understanding complex systems” a difficult problem? The behavior of complex systems is often counter-intuitive. Traditional concepts in mathematics, science, and engineering do not help us in modeling such systems for prediction and control. Typical questions involving complex systems are: “What is the biological origin of human thought?” or “What is the role of humans in climate change?”. We are not talking about computational complexity theory which classifies the running time and memory requirements of the algorithm change, as a function the size of the input to an algorithm, and we are not talking about complex numbers, numbers with an imaginary part, but we are talking about systems with a large number of interacting parts and a large throughput

of energy, information, or material [1]. If the throughput is large enough it can induce emergent patterns, including fractal structures and emergent behavior, such as chaotic attractors. Since emergent phenomena can not be phrased in terms of traditional analytic scientific concepts[1], they require a different set of concepts, a set of holistic approaches, as mentioned in the strategic plan of the National Science Foundation [2]. Holistic approaches are rare in natural sciences. They are more commonly used in social sciences, as a descriptive tool, rather than a quantitative, tool.

Thus, “understanding complex systems” is a two-fold problem: (i) translating qualitative holistic social sciences concepts into Mathematics and natural sciences and back, and (ii) developing a conceptual network of holistic concepts, creating knowledge about complex systems. But what is a concept, what is knowledge, and how do we measure the amount of knowledge produced?

Historically, there have been multiple attempts to define knowledge. Plato's dialogues contain one of the earliest written theoretical descriptions of knowledge. Theaetetus rejects Pythagoras' view that all knowledge is perception [5]. Plato accepts Socrates' perspective that there can be knowledge in the sense of objective universally valid knowledge, such as the properties of numbers and geometrical objects [6]. In *The Republic*, Plato introduces the "levels of knowledge" of the development of the human mind on its way from ignorance to true knowledge [7]. Ironically, true knowledge exists only if a foundation of axioms or *a priori* knowledge is believed to be true. Defining a minimum set of *a priori* knowledge is still a subject of active research. For instance, Stephen Wolfram recently published a new minimal set of axioms for Boolean algebra [8]. Aristotle praises the most abstract knowledge and calls it wisdom [9], but he encourages testing knowledge with our senses [10]. St. Augustine emphasizes abstract knowledge too, in *De Beata Vita* [11] "only the wise man can be happy, and wisdom postulates knowledge of truth". For him 'a priori knowledge' has to be experiential either by our own senses or others [12]. With powerful digital computers, and computer assisted reasoning software, the creation of abstract knowledge has become fast and easy, whereas experimental verification is still comparatively expensive and slow. Because of the traditional preference for abstract work, abstract research results with very little experimental grounding are being published at an ever accelerating rate, whereas experimental work receives comparatively little attention and funding. This raises the question how much knowledge is being created by current complex systems research.

Assessment of knowledge is a regular concern in education. National and international standardized tests attempt to assess the knowledge of the students. Ausubel [13], Novak and Gowin [14] developed concept maps to measure the change of the structure and organization of an individual's knowledge during the learning process in many areas [15-18], but little is known about the statistical and topological properties, in particular individual reproducibility and the predictive power of test results. At this point, the philosophy of knowledge, and the assessment of knowledge in education appear to be quite disconnected.

Recently Durak et al. [19] published work which tries to bridge this gap. They introduce several quantities to measure the amount of knowledge of an agent, who can be a human or an expert system on a computer. One of these quantities is a measure for abstract knowledge in line with Plato and St. Augustine. Another quantity, called practical knowledge [20], is a measure for less abstract and a priori knowledge in line with Locke [21]. In this approach knowledge is classified in levels of abstraction, similar to Plato's classification. At each level of abstraction, knowledge is structured in terms of concepts, where each concept is referenced by an identifier, such as a name or a symbol and contains (i) an objective (ii) a definition complemented by (iii) a collection of "like-this"-examples [22] and "hands-on examples" [23], (iv) a collection of applications, and (v) a list of related concepts. Each component of a concept is given as one or several "trains of reasoning" [24]. A "train of reasoning" is a sequence of sentences in a spoken or a formal language, including cartoon-style illustrations or animations, which are comprehensible by an agent, either a human or a computer.

The concept objective specifies a task such as "this concept establishes a relation between force, mass and acceleration". This task is solved in the concept definition. The definition of an abstract concept is typically a list of other concepts or a short sequence of sentences and illustrations that define a quantity, such as "density" or describe a relationship between concepts. For example, Newton's law describes a relation between mass, force, and acceleration. Briefness can make concept definitions ambiguous. Examples are less abstract and resolve some of that ambiguity. The concept examples are problem-solution pairs, where the solution is derived from the definition of the concept. The concept applications are problem-solution pairs which require repeated use of the concept or illustrate relations to other disciplines. Some of the applications are typically hands-on [23]. Concept applications relate the concept to common knowledge [25].

An agent knows a concept, if it can tell the identifiers, reproduce the definition, give examples, applications, solve problems which are very similar to the given examples and applications, and can list related concepts. This implies that the agent knows a concept, if it knows all sub-concepts of the concept and can name, but does not necessarily know related concepts. Sub-concepts are those concepts, which are used in the definition, examples, and applications. Knowing a concept is a prerequisite for understanding. If the agent is able to give its own interpretations and translations of the concept, the agent has an understanding of the concept.

If two concepts have a relation, i.e. similarities in their facts, methods, explanation, or typical application, they are called related. The concepts and their relations form a hierarchical conceptual network. If two concepts have a strong relation, this relation is a concept by itself, an abstract concept [25].

We note that most work currently published under the rubric complex systems covers only some aspects of the definition of concepts. Complex systems research would be much more readily accepted if scientific publications present all components of a new concept. Further, the preference for abstract concepts leads to a rapid growth of abstract knowledge, whereas practical knowledge grows only slowly. This means that we may

have to wait for quite some time till we develop a 'practical' understanding of complex systems and see practical applications of complex systems research.

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