Emergence in Cyber-Physical Systems-of-Systems

In Cyber-Physical Systems-of-Systems (CPSoSs) the Constituent Systems (CSs) interact for the purpose to realize *emergent services* (e.g., optimal and dependable energy distribution in smart-grids) that cannot be provided by any of the CSs in isolation [1]. Key to these emergent services is the complex, non-linear composition of the behaviors of CSs which also bears the risk of *detrimental emergence*. An example of detrimental emergence is an energy-grid blackout which could be caused by a feedback-loop among the demand of energy consumers and failing producers. In an unfortunate fault scenario, the demand of energy consumers may put too much strain on some producers and cause them to fail. This further increases the strain on still operational producers until they fail as well, eventually resulting in a global energy-grid blackout. Consequently, for engineering, operating, and evolving possibly safety-critical CPSoSs there is tremendous need to understand and explain, as well as realize desired emergent behavior, while there is an even stronger demand to detect, predict, and prevent detrimental emergence. To this end the *AMADEOS Workshop on Emergence in Cyber-Physical Systems-of-Systems (March 10-11 2016, Vienna, Austria)* [2] has brought international experts from the domains of philosophy, biology, and computer science together. The purpose of the workshop has been to establish an *agreed definition of emergence in CPSoSs*, to clarify the issues around *the occurrence of emergent phenomena*, and to arrive at *design guidelines for the control of emergence*.

The following agreed definition of emergence in CPSoSs is based on the deep investigation of emergence throughout the entire project and the many interdisciplinary discussions at the workshop:
A phenomenon of a whole at the macro-level is emergent if and only if it is of a new kind with respect to the non-relational phenomena of any of its proper parts at the micro level.
Unlike many others, this definition of emergence objectively classifies a phenomenon as emergent if it is *conceptually novel* (a new kind) with respect to its parts.

During the workshop the AMADEOS research about *multi-level hierarchies* and *Holons* as a framework to study emergence has been presented. A Holon [3] introduces *interaction-relations* on the same hierarchical level and *level-relations* among neighboring hierarchical levels in a multi-level hierarchy. At the level above, a Holon appears as a *whole* that can interact with other Holons on the same hierarchical level. At the level below a Holon is composed of its interacting *parts* which are other Holons (recursive definition).
In Figure 2, a Holon (large outer triangle) is visualized at two neighboring hierarchical levels – the level of the whole (e.g., the CPSoS emergent service) and the level of the parts (e.g., interacting CSs). Interactions are only allowed among Holons of the same hierarchical level, visualized in the figure by the green surface of a Holon, while interactions between Holons of different hierarchical levels is forbidden (red surface). Level-relations are for instance control- or containment relations, while interaction-relations in the context of CPSoSs are stigmergic (physical) and message-based cyber interactions. The concept of a Holon has been used to describe many interaction- and level-relations in the sciences (e.g., in material hierarchies where biological cells are composed of chemical molecules which are in return composed of atoms).
In regard to the study of emergence it is important to model how the emergent effect comes about over time at the macro-level. Along the level-relations, the free behavior of the parts (see Figure 2, right) at the micro-level

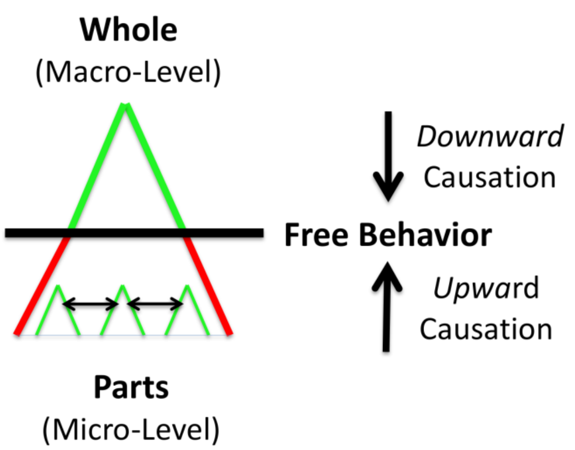

Figure 2: Holons and Causation of Emergence

is dictated by upward and downward causation. Upward causation consists of the universe of possible behavior (e.g, natural laws in physics), and downward causation is imposed by the whole which constrains the possible behavior of its parts. Take for example the fault-tolerant clock synchronization in distributed systems where a set of node-local clocks realize the emergent phenomenon of a fault tolerant global time. Upward causation is exerted by the physical properties of each of the node-local clocks (oscillator). They determine the fundamental behavior of the single clocks, e.g., in the fault-free case none of the clocks will run backwards. Downward causation takes into effect by the fault tolerant clock algorithm which adjusts the node-local clock according to the outlier-filtered mean of all other node-local clocks.

For managing emergence in CPSoSs the identification of level-relations, interaction-relations, conceptual novelty, and how the conceptual novelty as a whole exerts on its parts (downward causation) is of utmost relevance and represents a significant challenge in the general case.

In AMADEOS we have recognized the importance of realizing and handling emergence in CPSoSs and proposed a sound conceptualization of emergence based on multi-level hierarchies and Holons. This result among others (see the upcoming AMADEOS deliverable D2.3 and the AMADEOS book) has been presented and thoroughly discussed at an internationally organized workshop where experts from several disciplines participated and provided valuable contributions.

[1] Kopetz, H., et al. "Towards an understanding of emergence in systems-of-systems." System of Systems Engineering Conference (SoSE), 2015 10th. IEEE, 2015.

[2] Hoeftberger, O. Report on the AMADEOS Workshop on Emergence in Cyber Physical-Systems of Systems. Vienna University of Technology. May 2016

[3] Koestler, A. The Ghost in the Machine. Hutchinson. London, 1967. 19