

Dynamical Hierarchies

Tom Lenaerts

IRIDIA

Université Libre de Bruxelles

CP 194/6

1050 Brussels, Belgium

Dominique Chu

Senter for Vitskapsteori

Universitetet i Bergen 5020

Bergen, Norway

Richard Watson

School of Electronics and

Computer Science

University of Southampton,

Southampton, UK

In [2], Mark Bedau et al. proposed a set of fourteen open problems in artificial life. The content of this special issue specifically addresses one of those suggested problems: *How can we create a formal framework for synthesizing dynamical hierarchies at all scales?* The dynamical hierarchy concept refers to a system that consists of multiple levels of organization having dynamics within and between the entities described at each of the different levels. An important aspect of this concept is the fact that entities at different levels can have different functionalities that emerge from the interactions of the lower-level units. In other words, dynamical hierarchies define a system that is structured by part-whole relationships between objects, where each whole can exhibit properties and can interact in ways different from its parts. As a consequence, the complete system needs to be modeled as structures relating different description levels of dynamical systems and their interconnectedness. A typical example in this context is the functional differences between proteins and their building blocks, amino acids. The functionality of proteins is not directly the result of the properties of the individual amino acids. The overall protein structure plays a crucial role here. As a consequence, properties that amino acids do not exhibit in their solitary state can be exhibited collectively. The same observations can be made when moving from solitary proteins to the level of protein-protein interactions. New functionalities emerge as a result of the different complexes produced by these interactions. It is the combination of all these dynamical levels from amino acids to multicellular organisms that makes it a dynamical hierarchy and not merely some simple single-level emergent phenomenon.

Though dynamical hierarchies are ubiquitous in living systems and fundamental to concepts of self-organization, recreating dynamical hierarchies spontaneously in artificial life systems has proved difficult. Although it is often arguable that a single level of emergent structure may arise in various artificial life simulations, demonstrations of more than one hierarchical level of emergent structure are rare, as are formal synthetic frameworks [1, 8, 5, 7, 3, 4]. A complete synthetic framework for dynamical hierarchies will not only provide an understanding of the organization and origin of the complexity in biological systems, but also influence all fields that have adopted biological theories or appeal to some form of emergence to create complexity out of simplicity.

This special issue (like the previously organized workshop at Alife VIII in Sydney [6]) attempts to provide background information and initial steps toward addressing this fundamental topic in

artificial life research. In this special issue, you will find a collection of articles that cover different issues on the road toward a formal framework for dynamical hierarchies. Briefly introduced below, the six articles in this issue deal with the identification of second- and third-level structures in sensor communication networks, the role of structured populations in the evolution of far-sighted adaptations, the notion of modularity and its importance in evolvability, the definition of transitions between descriptive levels of a dynamical system, the formation of wholes from the interaction of the parts, and the description of dynamical hierarchies based on information theory.

Mikhail Prokopenko and his colleagues describe in their article a new example of dynamical hierarchies in the context of multicellular sensing and communicating networks embedded in an ageless aerospace vehicle. They discuss in this particular context the emergence of second-level structures (i.e., chains of simple cells) and third-level structures (i.e., the combination of cell chains and the elementary cells they enclose). They argue that these higher-level structures possess novel properties, and they analyze their results using graph-theoretic and information-theoretic techniques.

In the second article, Lee Altenberg discusses, from an evolutionary perspective, the difference between simple dynamics in panmictic populations and hierarchical dynamics in structured populations. An important aspect of this discussion is the effect these hierarchical dynamics have on the evolvability of a biological system. Altenberg investigates how hierarchical population dynamics can protect a population from the invasion of pathologies (i.e., traits that promote the extinction of the population) and potentially prevent pathological genes arising in the first place. This example illustrates the effect higher-level components may have on the persistent properties of lower-level entities.

In the previous paragraph it was discussed how modular populations influence lower-level (individual) dynamics. Yet, as explained in the beginning of this editorial, the dynamics do not end there. In the third article Richard Watson and Jordan Pollack discuss the effect of the interconnectedness of such modules on the dynamics of the overall system. Their discussion is based on Herbert Simon's work on the evolution of complexity in modular systems and the concept of nearly decomposable systems [9, 10]. They argue that modular systems that are decomposable but not separable (systems with modular interdependency) can form hierarchical systems where all levels of organization are significant. They further show that such systems can cause problems for evolution and provide an alternative that can improve on them.

The three remaining articles provide models from the perspective of dynamical systems theory. Simon McGregor and Chrisantha Fernando discuss an alternative to the hyperstructure model that was developed in [1, 8]. Their work was triggered by certain problems that may exist in that model and its adaptations. As a solution they propose to define dynamical hierarchies through information theory, as was originally suggested in [3]. Concretely, they define the concept of hyperdescriptions, that is, dynamical systems' descriptions of other dynamical systems.

A similar approach is taken in the contribution by John Rowe and coauthors. These authors argue that higher-level units should be structured in a way that is compatible with the dynamics of the underlying system. They provide necessary and sufficient conditions for this compatibility in linear systems. This argument is clarified using a formal model and some artificial life examples.

The final article, provided by Martin Jacobi, also addresses these issues. He uses a differential geometry formalism and finds results in agreement with Rowe. He focuses particularly on the relations that need to exist between the degrees of freedom used at different levels and the dynamics that are observable at each level. To identify new levels, Jacobi requires the emergence of novelty in the dynamics at the higher level. Thus novelty, as argued in other definitions, plays again a crucial role for identification of new levels. He draws an interesting relation with interaction networks (also called complex networks) as an intermediate step toward the construction of a dynamical hierarchy.

Together these six articles provide a next step toward exploring the many facets of dynamical hierarchies in artificial life research. We hope that, given the importance of the subject, this work will raise its profile and stimulate future work on this topic.

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