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System-of-systems support — A bigraph approach to interoperability and emergent behavior

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ABSTRACT

When designing highly interactive distributed systems such as e-learning environments, a system-of-systems (SoS) perspective enables dynamic adaptation to situations of use and thus user-centeredness during operation. Each system, e.g., a mobile device for accessing a learning management system, can still be operated as a separate system, e.g., displaying the latest feedback from peers, while being run as part of a federated system, e.g., synchronizing a learning group for a tutoring session taking into account individual availability of participants. This type of coupling requires interoperability assurance of systems, in particular federating various devices and cross-over features (e.g., linking learning content to posts on social media platforms) in dynamically evolving environments. We demonstrate the utility of bigraph-based handling of SoS. Abstract relationships allow not only the representation of dynamic interaction but also the re-specification of these systems through behavior adaptations. This abstraction supports cross-system decomposition as well as composition of interaction patterns for the purpose of emergent behavior. We show the potential of this approach orchestrating two distributed and independent systems, with orchestration enabling directly respondence to changes in a federated system's context.

1. Introduction

Once interactive distributed systems are expected to reconfigure and adapt themselves according to changing environmental conditions and requirements, respective dedicated services need to be available for composition and orchestration (cf. [1]). Increasingly, such systems are composed of various operationally and managerially independent sub-systems, revealing semantic heterogenity [2]. Typical examples in this context are enterprise portals that aim to enable the integration and linking of information resources across different systems in real time [3]. On the one hand, users want to use features or entire systems they are familiar with even in novel contexts. A typical example is Facebook as its functionality can be of use in private, work, and business contexts. On the other hand, different application contexts require different compositions of features or systems, such as a portal for market research differs from an accountant's workplace, referring to competitor or customer information, respectively, even if both provide analytics.

Rather than compiling such systems to inseparable entities, those systems are interconnected with respect to serving a common objective [4]. This particular class of systems is referred to as system-of-systems (SoS) and is increasingly investigated in the context of digitizing complex systems [5]. For instance, consider a supply network that integrates different systems, each managing a single transport modality, such as air cargo, sea freight, or road freight transport. Those systems are operated autonomously, but at the same time are all part of a bigger whole leading to emergent functionality and system behavior. For instance, the transport of goods by combining air cargo and sea freight might allow the optimization of delivery routes and therefore a decrease in delivery time and costs. Another class of systems featuring emergent behavior is e-learning systems.

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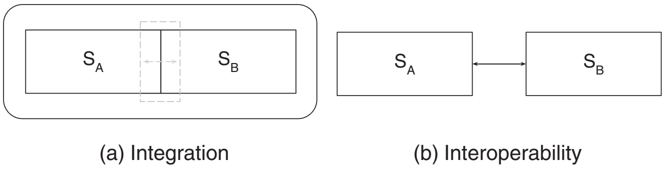

Fig. 1. System integration vs. interoperability.

Such systems couple content management and social media dynamically, depending on individual or collaborative learning processes (cf. [6]). Hereby, 'emergence occurs when interactions among objects at one level give rise to different types of objects at another level. More precisely, a phenomenon is emergent if it requires new categories to describe it which are not required to describe the behaviors of the underlying components' [7]. The provided added value, which cannot be attributed to a single system, is given through adjusting system properties for higher-level use, such as sharing context-sensitive annotations among learners for mutual feedback. The overall system therefore reveals some behavior that is more than the sum of its parts or component-systems (cf. [8]).

Although there is still no consensus on a distinct definition of SoS,[1] certain characteristics, namely *operational independence of elements*, *managerial independence of elements*, *evolutionary development*, *emergent behavior*, and *geographic distribution* are considered as inherent to systems-of-systems [10]. A more recent but similar taxonomy proposed by Ref. [11] introduces the characteristics of autonomy, belonging, connectivity, diversity, as well as emergence. The first three characteristics are considered as core properties and therefore fundamental to SoS [12]. Accordingly, systems are described and represented as being autonomous while being interconnected with each other in order to contribute to a goal at a higher level (cf. Fig. 2). Although systems are considered as autonomous in terms of their functionality and operation, they collaborate with other systems in order to contribute to the superior system's goals. Interoperability among those systems therefore is required to recognize and overcome their autonomous nature meaning that they are required for systems to be diverse and emergent in behavior.

Interoperability as an inherent part of system connectivity is crucial when it comes to system interaction and collaboration [13]. In case of autonomous systems being not interoperable, neither connectivity nor diversity or emergence is enabled. Of particular importance is semantic interoperability beyond functional alignment to achieve a common goal [14, 15]. Semantically relevant components (systems) interact while operating separately [16]. The involved systems have no functional dependencies but rather the ability to cooperate with each other in order to accomplish a common goal. Involved systems agree upon a common way of interaction in order to collaborate and exchange information (cf. [17]). As such they are distinct from integrated systems (cf. Fig. 1 showing two systems S_A and S_B).

In the case shown in Fig. 1a, both systems are integrated as they share common parts of their functionality with each other, such as content elements for annotations of different users. In the second case (cf. Fig. 1b), however, both systems have agreed on a common way of interaction retaining their independency in terms of operation. Hence, in case of interoperable content management and social media systems text entries can represent both, annotations linked to content elements (being part of a content management system), and social media entries, such as blog elements (being part of a blog system). Q4

Various definitions of interoperability can be found in the literature, leaving room for different interpretations and expectations [18]. Two well-known definitions are the one of the Standards Glossary of the IEEE and the one from Ref. [19].

> "Ability of a system or a product to work with other systems or products without special effort on the part of the customer. Interoperability is made possible by the implementation of standards."
>
> IEEE [17]

> "Interoperability characterizes the extent by which two implementations of systems or components from different manufacturers can co-exist and work together by merely relying on each other's services as specified by a common standard."
>
> Tanenbaum & van Steen [19]

Interoperability is essential not only to overcome system isolation, but also to enable systems to be diverse and emergent in behavior. As a consequence, both the static representation of interaction patterns as well as the representation of behavior in terms of structural changes are necessary (cf. Fig. 2). Changes that are related to the overall system behavior can become visible on this basis ($B_1 = \{b_1, b_2, b_3\}$ vs. $B_2 = \{b_1, b_3, b_4\}$).

System interoperability is required for SoS behavior to be emergent (cf. [11] and [12]). Bigraphs, in that context, allow preserving interoperability among systems, both from structural and behavior perspectives (cf. [20] and [21]). Hence, SoS behavior can emerge in a concerted way. We explore this bigraph capability in the following. In Section 2 we review existing approaches Q5 to ensure interoperability before introducing and detailing bigraph-based federation of features. Section 3 introduces a sample case of SoS providing a frame of reference for learning support systems. Section 4 outlines the idea of bigraphs after briefly

[1] A more detailed discourse on the definition of SoS is given in Refs. [4] and [9].

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