Exploring system behavior in a system ontology

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Abstract

Understanding and modeling system behavior is a key aspect of many disciplines, and is crucial when systems are designed to manifest desirable behaviors. In order to grasp system behavior, it is inevitable to address how it emerges from the properties and behaviors of interrelated system components. In pursuit of an understanding of the emergence phenomenon and to account for the nature of emergent system behavior, this paper takes a first step in extending a system core ontology with behavioral aspects. The ontology extension is grounded on the Unified Foundational Ontology and also in system science definitions and disposition theories.

Keywords

Systems, System Behavior, Behavior Emergence, Ontologies, Conceptual Modeling

1. Introduction

As systems become larger and more complex over time, we have the emergence of intricate system behaviors that are challenging to comprehend. Such emergent behaviors are the result of a complex phenomenon through which the behavior of the whole *emerges* from the interactions of parts. Emergence typically cannot be explained by just one cause. It is a result of the way in which system parts are related, of the (intrinsic and relational) properties of these parts, constraints, among other factors [1, 2, 3, 4]. This phenomenon has been studied by system science researchers since the inception of the General Systems Theory (GST) [1, 5, 6].

Although the notion of *system* itself is ubiquitous in the areas of information technology (IT) and information systems, it is often not explicitly recognized in modeling languages [7]. The same can be said of related notions such as emergence and system behavior. The lack of proper constructs representing systems and their behavior with corresponding well-grounded definitions hinders these approaches with important representation deficiencies [8]. This gap motivates us to explore the ontology of systems, as a stepping stone towards the definition of well-founded (ontology-based) notations for systems modeling.

Although over the years many ontologies have been proposed to model different types of systems [9, 10, 11, 12, 13], these ontologies focus on solving technological and practical issues

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related to specific contexts and lack a broader understanding of the very notion of system.

In this paper, we move towards bridging this gap by investigating some aspects of *system science* [6, 14], GST [1, 5], and systems engineering (SE) [15]. We build on the *system core ontology* proposed in [16] in light of the Unified Foundational Ontology (UFO) [17]. However, that work focused on the structural aspects of systems, and behavior was not considered explicitly. Here, we take a first step exploring the behavioral aspects of the system core ontology.

The remainder of this paper is structured as follows: Section 2 briefly presents an overview of the literature related to system-theoretical concepts; Section 3 presents a small fragment of the UFO and of the System Ontology that forms our baseline. This ontology is then extended in Section 4 with behavioral notions; Section 5 presents related work and some final considerations.

2. Systems and emergence

The concept of "system" is strongly associated with the emergence of properties and behaviors. Very often, a system is defined as a whole composed of related parts that allows for the emergence of capabilities or behavior. The literature on GST [1, 5, 18] converges to an understanding of a system as a kind of "complex" (or "organized" whole) composed of "connected" (or interacting) elements. A system is then understood as a collection of things that, through their connections (or interactions), create something new, such as emergent behavior and properties [1, 15].

For Bunge [14, 18], *emergent properties* are those that, while related to the properties of parts, are not present in isolation in the separated parts [6]. For example, the buoyancy of a ship cannot be reduced to the buoyancy of its parts (an arbitrary piece of a steel hull is typically not buoyant by itself). According to [2, 19], the emergent properties are also the result of *system constraints*, which limit it on the one hand but enable the arising of new characteristics on the other. In the same way, according to [4], *emergent properties* are a direct consequence of *how* parts are related. According to system definitions, emergence is not only associated with properties (or capabilities) but also with behavior. In disposition theories [20, 21], dispositions (e.g., capabilities) and behavior (their manifestation through events) are closely related. According to those theories, a (complex) behavior can be seen as a result of the "interaction" of distinct dispositions, such as mutual activation, complementary activation, triggering, and blocking effects [20, 21]. In this context, a direct impact of a behavior is the change it causes. According to [5], system behavior is an event composed of other events (actions, reactions, responses) that cause *changes* whose "consequences are of interest", for example, changes of *system states*.

3. Ontological background

We take as a starting point the *Unified Foundational Ontology* [17], which defines a number of domain-independent notions that we will employ here. The topmost is the distinction between *individuals* (such as "John" and "Saturn") and their *types* (such as "Person" and "Planet").

Among the category of *individuals*, UFO distinguishes *endurants*, *situations*, and *events*. *Endurants* are *individuals* which persist in time, maintaining their identity (e.g.,"John", "The Beatles", "Spotify Technology S.A."). *Events* are *individuals* that manifest themselves through time (e.g., John's first birthday party, the inauguration of pope Francis) and have temporal parts [22]. *Situations* are individuals composed (possibly) of many other individuals (including other situations) that may trigger *events* and be brought about by them [23]. *Endurants* are divided into *objects* and *moments*. *Objects* are *endurants* that do not depend on other (external) *individuals* to exist (e.g., "John", an apple). In contrast, *moments* (or *aspects*) depend on their bearers to exist (i.e., Mary's age, Gerald's headache, the color of an apple, but also *relators* such as the marriage between John and Mary). *Moments* include *dispositions*, which are moments that can be manifested through *events* in certain *situations*. Examples of dispositions include John's ability to speak English, and an airplane's flying capability.

Types are repeatable predicative entities whose instances share common features. In the taxonomy of types in UFO, there are *object types*, *situation types*, *event types*, *moment types*, etc., according to the ontological nature of their instances. Endurant types (object types, moment types) are categorized by considering the formal meta-properties of *sortality* (whether all instances of that type obey the same principle of identity), *rigidity* (whether the instances of that type can cease to instantiate that type), and *(relational) dependence* (whether the instances of that type require the establishment of relations to other entities). By using these meta-properties, UFO proposes the following distinctions for types [24]: (a) *kinds* (e.g. "Person", "Car", but also "Marriage", "Enrollment") and *subkinds* ("Sedan", "Hatchback") are rigid sortals; (b) phases (e.g., "Adult" and "Child", but also "Active Enrollment" and "Suspended Enrollment") are anti-rigid, relationally independent sortals; (c) roles (e.g., "Student" and "Employee") are anti-rigid, relationally dependent sortals. Moreover, we have *non-sortal* types representing common properties of individuals of multiple *kinds*: (d) *categories* subsuming multiple kinds rigidly (e.g., "Mammal"); (e) *phase mixins* subsuming *phase* types with distinct *kinds* (e.g., "Adult Mammal"); (f) *role mixins* subsuming *roles* of distinct *kinds* (e.g., "Customer", subsuming "Personal Customer" and "Organizational Customer"); (g) *mixins* subsuming rigid and non-rigid types instantiated by instances of different kinds (e.g., "Insurable Item" when subsuming "Car" and "Building" in a domain in which cars are necessarily insured but buildings are only contingently insured). These types of types are represented in OntoUML [25, 24] with corresponding class stereotypes.

The system core ontology Figure 1 presents a fragment of the system core ontology [16] using OntoUML. "System" is a *category* of *objects*. *Systems* have proper parts called *components*. "Component" is a *mixin* whose instances are interrelated *objects* in a system. A *subsystem* is a *system* that is also a *component* of another system. System components can be *connected to* each other and/or to external entities, i.e., entities that are not part of the same system. These connections (material relations [26, 25]) are somewhat analogous to the notion of *bonding relation* in Bunge [18, 6]. Also in line with Bunge [14], we consider systems to have "global properties", which their parts do not exhibit in isolation. We call them *system moments*, as shown in Figure 1. "System Moment" is a *category* of *moments*, encompassing *dispositions*, *qualities*, *relators*, etc. As a simplification, our model focuses solely on *emergent* (as opposed to *resultant*) properties [14]. An (emergent) *system moment* "emerges from" *component moments*, in certain *system situations*.

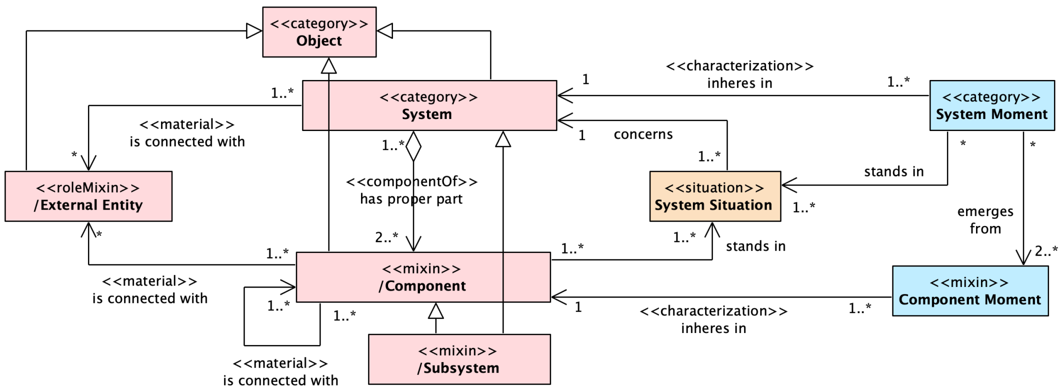

Figure 1: System Core Ontology (Fragment)

4. Addressing system emergent behavior

As depicted in Figure 2, we assume that an "emergent" behavior is *constituted by*[1] (causally interrelated) *system events*. In the proposed ontology, as depicted in Figure 2, a *system event* can be classified as (i) *system-environment event*; (ii) *system participation*, and (iii) *internal system event*. As illustrated, *system-environment event* represents "interactions" between the *system* and *external entities* and, for this reason, can be partitioned into *system participation* and *external entity participation* events. On the other hand, *internal system events* are those that do not involve *external entities* and are constituted by internal *component events* and internal component interactions as well. Based on UFO's notion of *functional parts* [27], both internal interactions (between *components*) and external ones (between *components*/*system* and *external entities*) are manifestations of (internal and external) *connection* relators (not shown in the Figure 1) grounding instances of "is connected with" (same figure).

These *connections* come about from the interrelation between dispositions (*component moments*), whose joint manifestation constitute *system events* (Figure 2) [16]. In other words, when these interrelated *component moments* manifest, they give rise to interrelated *component events* manifested "collectively" and "coordinately". That resulting complex event constitutes a *system event*. As *system moments* emerge from certain component moments, *mutatis mutandis*, *system events* are constituted by the combination of the corresponding *component events*[2]. Ultimately, *system behavior* is a consequence of *system moment* emergence phenomena.

This idea is illustrated in Figure 3. In this example, the chest *c* (*system*) is composed of interconnected components, such as the base *b*, lid *ld*, lock *lc*, and key *k*, as depicted on the lefthand side of Figure 3. These components are split into two main subsystems: the *base-lid* subsystem (*sub*1) and the *locking* subsystem (*sub*2). As shown in the center of the figure, the chest *c* is characterized by two emergent capabilities (*system moments*): "chest openability" and

[1] See [17] for a formal characterization of *constitution*.

[2] In OntoUML, kinds are mutually disjoint. Other sorts of types are not subject to the same restriction. Here, due to lack of space, we use the stereotype «event» simpliciter to represent event types that can possibly overlap. For example, a *system event* of system *X* can also be a *component event* when *X* is a subsystem of another system *Y*. As a *component event* it then constitutes *system events* of system *Y*.

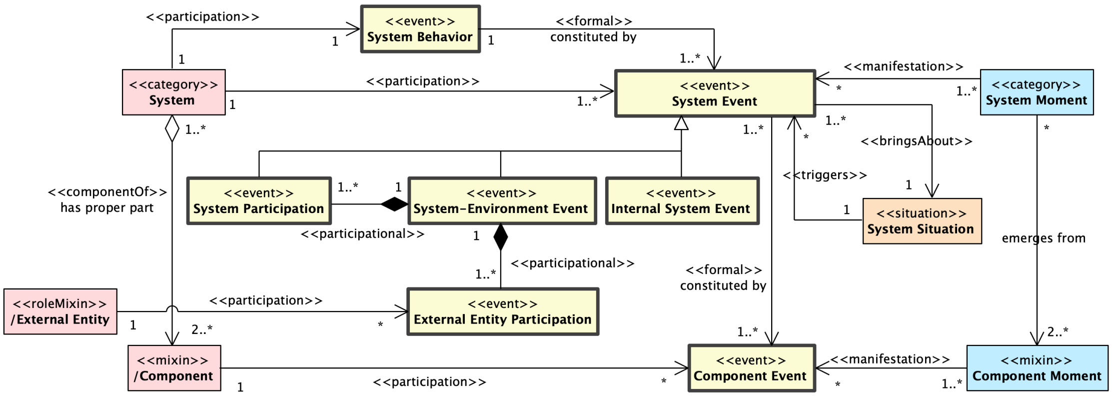

Figure 2: The proposed System Ontology extension (concerning System Behavior)

"chest lockability". As illustrated in the righthand side, these capabilities are manifested in a particular scenario by the "lock *c* at *t*1" event (i.e., *system-environment event*), performed when a user *u* used the key *k* to lock *c* in instant *t*1. As illustrated (in the center of the figure), "chest openability" and "chest lockability" emerge from the "combination" of *component moments*. In this instance, as depicted in Figure 3, "chest lockability" (*system moment*) emerges from the combination of "locking capability" (*component moment* of key *k*) and "locking susceptibility" (*component moment* of lock *lc*); and, "chest openability"' (*system moment*) emerges from "supporting capacity" (*component moment* of the base *b*) and "revolvability" (*component moment* of the lid *ld*) combined.

Complementing the emergence explanations addressed in previous work [16] (based on system structure), here we focus on *disposition theories* and, in particular, the notion of *mutual activation partnership* (MAP) [28], to propose relationships between *component moments* and explain the emergence of properties and, consequently, of behavior. So, based on this, we consider that *component moments* can be "complementary", i.e., reciprocal (mutually activated) [21, 28] or additional (additionally activated) [20]. We also consider which *component moments* can affect each other through relationships of *enabling* (triggering) [20], *disabling* (blocking) [21], and also *changing* (i.e., qualitative modification of other *disposition*). In the chest example, illustrated in Figure 3, all their *component moments* are somehow related: the "supporting capacity" and "revolvability" are reciprocal (MAP), forming the emergent capability "*sub*1 openability" (of the subsystem *sub*1); and, "locking capability" and "locking susceptibility" are also reciprocal (MAP), forming the composed capability "*sub*2 lockability" (of the subsystem *sub*2). In addition, as these subsystems are interconnected, "*sub*2 lockability' disables (prevents) the "*sub*1 openability", as illustrated in Figure 3.

Similarly to the joint manifestations of dispositions, the combination of (interrelated) *component moments* of a system is manifested through (interrelated) *component events*. In the chest case, for example, the "chest lockability" is manifested into the "lock *c* at *t*1" *system event*, as shown on the right side of Figure 3. As depicted, this *system event* is constituted by "lock *lc* at *t*1" (by user *u* with key *k*) and "be locked by *k* at *t*1" (by the lock *lc*), events correspondent to the participation of lock *lc* and key *k* in the "lock *ld* at *t*1" event (interaction) performed

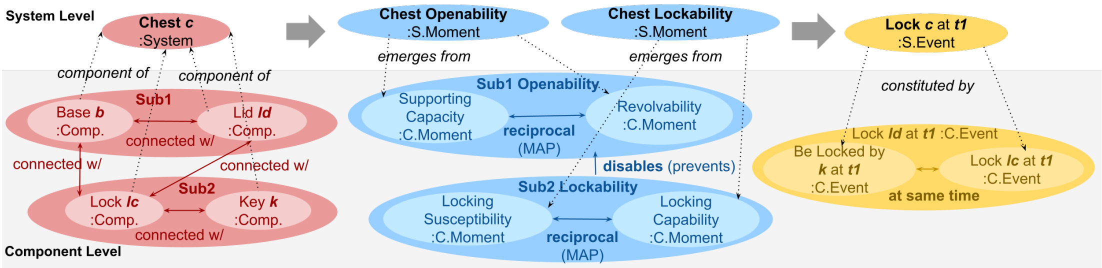

Figure 3: Illustration of System Behavior from System Moments and System Structure

by subsystem *sub*2. The way the capabilities are related, in this case, influences the way they manifest themselves. For example, as depicted in Figure 3, “lock *lc* at *t*1” and “be locked by *k* at *t*1”*component events* must occur at the same time (*Allen's equal* relation [22]), which is compatible with the corresponding component moments “locking capability” and “locking susceptibility” being reciprocal (MAP). Besides this, in this instance, with the manifestation of the “*sub*2 lockability”, by subsystem *sub*2, the “*sub*1 openability” (of subsystem *sub*1) is blocked and it is not manifested.

System events in general are activated by a specific *system situation*, as represented by the “triggers” relationship in Figure 2 [22]. As depicted, after the manifestation of *system events*, they bring about a new *system situation* concerning the *system*. For example, to (intentionally) unlock the chest *c*, the following *system situation* is required: the chest *c* must be *closed* and *locked*; the user *u* must have the intention to unlock (and has the “unlocking ability”); and, finally, (iii) the user *u* must have the key *k*. In the same way, to (intentionally) open the chest *c*, the chest *c* must be *closed* but *unlocked*; and, the user *u* must have the intention to open it (and have the “opening ability” as well). In this case, after the *system event* “open *c* at *t*1” is performed, a new situation is brought about: the chest *c* changes its state to “opened”; and, *u*'s intention is satisfied.

5. Concluding remarks

Most of the ontologies proposed in related work focus on defining basic concepts, such as systems, components (subsystems), and their parthood relations. A part of these models also considers system characteristics, such as attributes, properties, and capabilities [9, 11, 13]. Regarding the representation of *emergent properties*, almost none of the ontologies consider this. Exceptions are [8, 7] that define the notion of *emergent property*, also based on Bunge's work [14]. Despite that, they do not relate the *emergent properties* to the basic properties (those inherent in system parts) to account for emergence and do not consider the behavior emergence phenomenon. System behavior is generally considered indirectly, through related concepts such as “function”, “event”, or “process”, as in the case of the Industrial Ontologies Foundry (IOF) core ontology [29]. Other ontologies, such as OntoCape [13], Naudet et al.'s [10], and Yilma et al.'s [30], address explicitly the *system behavior* concept, representing “actions” or “events” in specific contexts, as chemical process engineering, interoperability, and cyber-physical systems.

These ontologies do not consider *dispositions theories* (and the relationships between *component moments*) to account for behavior emergence. We believe these are important to explain how the various parts contribute jointly to system behavior.

Ontologies can contribute to a better understanding of systems and of the behavior emergence phenomenon. Here, we have extended a *system ontology* [16] based on UFO and GST principles, incorporating behavioral notions. This led to an initial exploration of system behavior, and the relation between a behavior and its constituent events. This system ontology may be used as reference to improve conceptual modeling notations, concerning the representation of emergent system behavior, the relations between properties at different levels, and between properties and events. It may also serve to integrate distinct perspectives of systems diagrams, unifying structural and behavioral perspectives. As future work, we intend to extend (or propose language patterns to) OntoUML, concerning behavioral aspects to create perspectives such as system composition, functional decomposition, system structure, system mechanism, and system characterization [6]. We also intend to fully axiomatize, formally verify and validate, as well as empirically evaluate the proposed ontology. Finally, we also intend to publish an operational version of the ontology in OWL and use this work to improve the behavior emergence modeling of domain ontologies, such as [31].

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