Modeling Context-aware Systems: A Conceptualized Framework

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Abstract: Context-aware systems keep on emerging in all of our daily activities. Context, which can be a location, a user, an actual activity, or physical conditions, plays a major role in such systems. Actually, everything we refer to in our systems can be considered as context. To cope with this new situation, mechanisms for managing context were devised, including frameworks and programming languages. However, modeling languages that address the notion of context are rare. In this paper, we aim at framing and further defining the requirements for context modeling languages. Such a conceptualized framework sets the ground for designing and evaluating modeling languages for context-aware systems. We demonstrate a possible use of the proposed framework through the evaluation of CO-LSC, a context-oriented modeling language.

1 INTRODUCTION

Context-aware systems are all around us and are actually involved in every domain of our daily socio-technological life, for example, in health care (Bricon-Souf and Newman, 2007), in education (Ireri et al., 2018), and in ambient intelligent systems (Ramos et al., 2011). Such systems sense their environment and their internal state and adapt their behavior accordingly. Thus, both the environment and the internal state can be considered as context. Environmental context can be location, temperature, or user attributes, and internal context, i.e., the system state, can be a combination of objects' properties or sequences of operations. Thus, a context is an abstraction of certain circumstances that are of interest to the system and plays a major role in designing such systems, as it facilitates situational information (Dey et al., 2000).

As it appears that everything can be considered as a context, various context-oriented, context-based, and context-aware techniques have emerged, including Context-Oriented Programming (COP) (Hirschfeld et al., 2008), context-oriented behavioral programming (Elyasaf, 2021; Elyasaf et al., 2019), and modeling facilities (Sindico and Grassi, 2009). Nevertheless, these studies address context to a limited extent and only focus on certain aspects of it. One prominent reason for this gap is that the context definition, and the requirements from it, are still quite vague and there is no consensus of what a context is. Is it external or internal? Is it a set of information or processes? Is it static or dynamic?

With the vast knowledge of context-aware systems and context-oriented techniques that emerged during the last two decades, we believe it is time to clarify the requirement for context modeling and further conceptualize the notion of a context along with its many facets. Specifically, we wish to describe the relationships between the context of the system and its behavior, and how the data aspects and the behavioral aspects of the system interact and influence one another.

Various attempts to conceptualize context have been suggested (Cabrera et al., 2017; Bettini et al., 2010).Yet, these refer mainly to the structure and context types neglecting the relationship to the system behavior.

The contribution of this paper is two-folded. First, we provide a concise and clear view of a context for the purpose of modeling context-aware systems. Second, we define a framework that can be used for analyzing and developing context-oriented modeling languages (and techniques).

The paper is organized as follows. In Section 2 we revisited the requirements for context modeling language, review studies that aim at similar goals as ours, i.e., framing the notion of context, and refer to existing context modeling languages. In Section 3 we present a case study that serves us for demonstrat-

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ing the context conceptual framework we suggest in Section 4. In Section 5 we demonstrate potential use of the framework, i.e., use it as a benchmark to examine a specific context-oriented modeling language. Finally, in Section 6 we conclude and refer to further framework utilization.

2 RELATED WORK

To set a conceptualized framework for context modeling we begin with setting the requirements. In doing so, we refer to existing studies, such as (Bettini et al., 2010) and to the experience we gained in context-aware systems. In the following, we list the requirements we gathered. A context-oriented modeling language should:

- Handle the heterogeneity of context information sources.
- Capture the relationships between contexts and system behaviors.
- Refer to past states of the system.
- Deal with the uncertainty of both data and behavior.
- Facilitate reasoning in detecting problems in the model and during execution.
- Manage the complexity of context.

In light of these requirements, we start with reviewing studies related to context conceptualization and then refer to specific modeling languages.

2.1 Conceptualizing Context

When referring to context conceptualization there are two major directions. One refers to metamodels and the other to ontology specification. We first begin with analyzing metamodels followed by ontology studies.

Referring to service-oriented computing, a metamodel that emphasizes the structure of contextual entities and also refers to the system behaviors that are determined by the context is presented (Vieira et al., 2011). It refers to both static and dynamic aspects of context-sensitive systems. The approach taken addresses the handling of many information sources and captures the relationships between context and behavior via contextual graph. Nevertheless, it neglects past states, uncertainty, the management of contexts, and reasoning.

In the case of service adaptation, a metamodel is proposed for conceptualizing context-aware systems (Peinado et al., 2015). While the metamodel includes the notion of context, its abstraction is limited and mainly refers to the system architecture rather than modeling contexts and their binding to the system behaviors. Past states, uncertainty, and reasoning are also neglected.

Domain-specific languages are also means for addressing context modeling, for example via a UML profile for context modeling (Simons, 2007). Such a profile includes a static view of a system and refers to contexts as classes. It addresses the notion of different information sources, yet the other requirements set above are mostly neglected. The metamodel of the language is centered around the notion of an entity that is assigned with a context. It further elaborates on various types of contexts including physical (e.g., time, speed), environmental (e.g., distance, location), computational (e.g., network traffic, hardware status), personal (e.g., age, gender, preferences), social (e.g., law, rules, roles, friends), and task (e.g., activities that need to be performed or are already being executed) that set the context landscape. It refers to information sources and to various properties of a context. However, the relationship to the system behavior, uncertainty, past states, and reasoning features are not explicated.

A model–based approach for context-aware systems is suggested in (López-Jaquero et al., 2016). It is centered around a goal-oriented approach and thus the main entity that considers the context for its operation is a task. A task in that metamodel consists of contexts that comprise context elements which are actually data information in the form of attributes, that are monitored to identify a context. The metamodel also includes resources that support awareness. In addition, the paper presents a context metamodel that further elaborates the context components that correspond to either the static or dynamic aspects of a context. Here again, the operation of a context, i.e., its activation and execution implications are ignored (including references to past states, reasoning, and uncertainty).

A comprehensive framework for model-driven development of context as a service is presented in (Moradi et al., 2020). The authors introduce various viewpoints on context and its related aspects. In particular, they refer to modeling context-aware objects, high-level contexts, situations, context elements, context sources, and changes in context. In addition to the above, the resulting metamodel also consists of derivation rules according to which contexts are created. However, the framework focuses on context execution and provides little evidence for its specification (including reference to past states, reasoning, and uncertainty).

Following two surveys (Bettini et al., 2010; Cabrera et al., 2017) dealing with ontology with respect to context modeling, the authors emphasize two issues: context information model and reasoning techniques, see for example, (Brings. et al., 2018; Ejigu et al., 2007; Aguilar et al., 2018). In that sense, ontology-based approaches focus on the system/context structure and facilitate reasoning capabilities, yet these neglect the behavioral aspect. The context information is classified following a pre-defined ontology, thus, sometimes it limits the flexibility of the context information model.

2.2 Context-Oriented Modeling Techniques

Various context-oriented modeling techniques were devised. For example, Context-Oriented Domain Analysis (CODA) adds the notion of context on top of feature diagrams to model software requirements (Desmet et al., 2007). The approach mainly refers to the system structure and functionality, yet the actual behaviors are not elaborated. As it utilizes feature models reasoning is also applicable.

Context modeling can also be modeled using states (Yue et al., 2017). In that case, each state represents a context instance with values of several attributes. The transitions between the contexts describe the system behavior. Nevertheless, it seems that describing context instances using that approach may result in states explosion.

Context Modeling Language (CML) was also devised for the purpose of developing context-aware systems (Henricksen and Indulska, 2006). The language focuses on the context information and the relationships among that information. It neglects the binding to the system behavior, yet it facilitates reasoning.

The search we performed for context-oriented modeling reveals that the modeling needs for context-aware systems are addressed only to a limited extent. It seems that no comprehensive language that takes into account the overall needs exist and there is also a need to define such requirements. In this paper, we aim at addressing the latter.

Summary. Back to the requirements, we set before, it seems that the majority of the approaches address the context information (static) model to a large extent. In some cases, reasoning capabilities are also provided. However, most approaches neglect the binding of the context to behavior, the past system state, the uncertainty, and the management of the context complexity. We believe that a major reason for that is the lack of conceptualizing these aspects. Thus, in this paper, we aim at framing the notion of context, its components, and the semantics that need to be taken care of.

3 THE TRAINING SYSTEM

As mentioned before, in this paper, we propose a framework for conceptualizing context. To clarify the definitions and the concepts of this framework, we demonstrate them via a training-system case study that we now describe. The system allows trainers to plan the training for their trainees and adapt the plans to various situations and circumstances. A simplified (class) model of such a system is depicted in Figure 1 and the basic training behavior is depicted in Figure 2. A trainer selects a training type for the trainee and executes it, where each training is composed of one or more activities. Note that we deliberately omit the many details of the models (such as relationship types and multiplicities, as well as exact navigation across objects) as these are of limited importance for this paper.

Naturally, this basic training behavior might require some adjustments, depending on the context. For example, the actual training has to be adjusted for senior trainees or be rescheduled upon bad weather (Figure 3).

4 CONCEPTUALIZING CONTEXT

A context according to Dey is “any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application themselves” (Dey et al., 2000). Such a definition which is adopted in many studies is too vague and refers only to some facets of a context.

In this paper, we propose to further refine the definition of context and refer to its components, operations, and states. To do that, we devise a metamodel and a life cycle of a context, based on related studies and experience we gained in context-oriented systems.

4.1 Preliminaries

The Word ‘Context’. Generally, when describing systems, the term “context” is used in two different

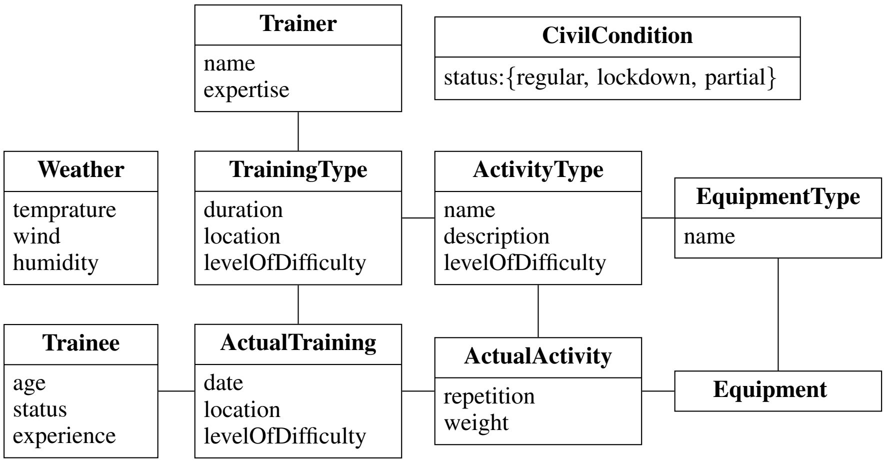


Figure 1: The class diagram of the training system.

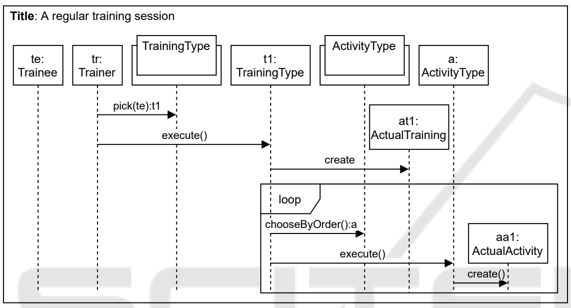


Figure 2: The default training behavior.

ways:

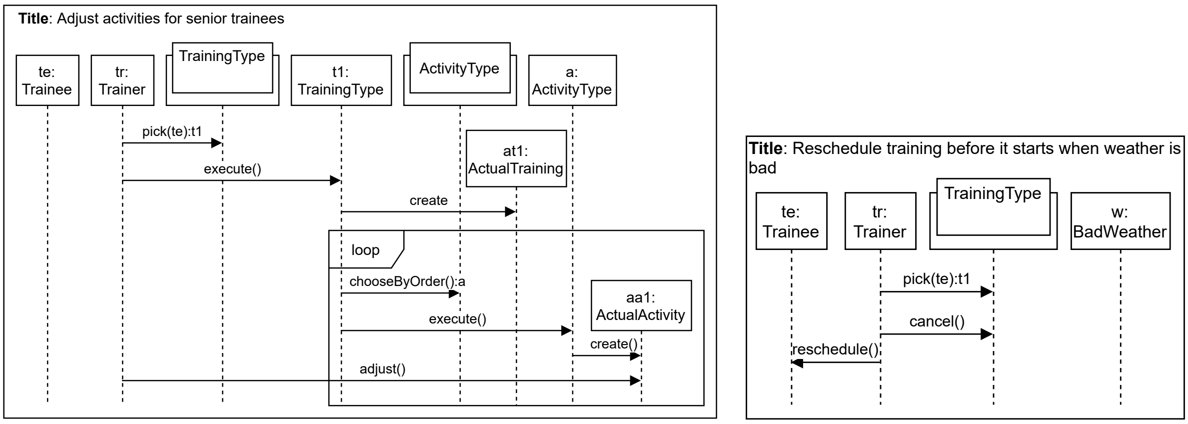
- *System Context* — the internal and environmental state of the system. For example, the system context in the training system includes the state of all system objects (that also represent the environment) and the state of the executing behaviors.
- *Behavior Context* — the context of each of the system's behaviors. Such a context is a projection of the system context in view of the specific behavior. For example, "During a lockdown, all training sessions must be held virtually, i.e., via Zoom. Thus, only indoor activities are permitted and these should require only equipment that is available at the trainee location." In such a case the "during lockdown" is the context that matters for the training behavior. It is important to stress that contexts only affect the system behaviors.

As the two meanings of context may confuse, some paradigms use different terms for each meaning. In context-oriented programming, for example, the term context refers to the system context, while the term layer refers to the context of a behavioral aspect (Hirschfeld et al., 2008). We believe that there is no difference between the two, and artificially separating them may be confusing even more. Thus, in the proposed meta-model we refer to the system context as a composition of other contexts that combine many simple and complex elements, where each context corresponds to a different behavioral aspect of the system.

Separation of Concerns. Many times, several behaviors are bound to the same context, as in the case of the "bad weather" context, where both the following behaviors are bound to it — "Suspend active training when the weather gets bad" and "Reschedule training before it starts when weather is bad" (Figure 3b). Similarly, multiple conditions can lead us to determine that we are in the context of bad weather, such as weather forecast; sensors data; or even a sequence of events, like three sequential sensor readings. The proposed metamodel and life cycle support this separation of concerns between "*what* to do in context *x*", i.e., the system behavior, and "*when* is context *x* active", i.e., the context information model.

Context Data. Furthermore, when describing context-dependent behaviors, we encapsulate the relevant data for specific behavior in the context. For example in Figure 3a, given the context "a training session with a senior trainee", the actual adjustment may rely on the age of the trainee. Such data is encapsulated within the context.

Inter-context Relationship. Different contexts may relate to other contexts in different ways. The relations can be structural, temporal, and dependency. Another type of relation is priority, which defines the priority of context-dependent behaviors, based on the priority of the context that they are bound to. The use of priorities is one of the approaches for handling contradicting behaviors.



(a) Adjust activities in the context of a senior trainee.

(b) Reschedule training in the context of bad weather.

Figure 3: Context-dependent behavioral variations of Figure 2.

4.2 The Context Metamodel

To cope with the above definitions we devise the metamodel presented in Figure 4. In the following, we explain the various components of a context, explicate their rationale, and demonstrate these via the training system.

Generally, each behavior in a system is bound to a context, meaning that the behavior is relevant only when the context preconditions are met. Of course, a context-independent behavior is a special case of the general behavior, where the context is always active (e.g., the context "the system is running").

Context. An information that refers to elements and their activities. A context is defined by its preconditions and the data that it encapsulates. For example, the context "a training session with a senior trainee" (Figure 3a) is active whenever a session with a senior trainee is started. The *preconditions* in this example are both behavioral (something happens) and structural (constraints on the Trainee element). The *data* of this context is a specific training session with a senior trainee, meaning that it encapsulates structural elements that are relevant for this context, such as Trainee, Trainer, Training Type, and ActualTraining. Each system behavior (behavioral element) is bound to a specific context, recall that unbound behavior is a private case of general behavior, and whenever the context's preconditions are met, the system behavior starts running, with the relevant context data given as a parameter for the behavior. For example, as mentioned before, the actual age of a trainee might affect the required adjustment.

Context Type. Context has a type. It can be static, i.e., predefined and constant, such as a specific location, like a training studio. It can also be dynamic, that is, the structure of the context is defined, yet it is populated during run time, such as the Weather. It can also be behavioral, that is, refers to a sequence of operations, such as three Actual Training in a Week. The context type is not explicated in the metamodel, yet, it is derived from the elements that define it.

Simple Context. A simple context is an atomic piece of information or an action. For example, the location of the training, a trainee at a certain age/age range, and the weather, when referring to information. When referring to an action or a behavior, a context can be, for example, running, swimming, functional exercise, or on the way (for training).

Complex Context. A complex context consists of multiple other contexts. For example, the "training session" context consists of the following simple contexts: Trainee, Trainer, Training Type, and ActualTraining. The "training session with a senior trainee" consists of the complex context "training session" and the simple context "a senior trainee". This is, of course, only one way to model such contexts.

Inter-context Relationship. Different contexts may have various types of relationships among them. In the following we elaborate on common relationships we identified:

- **Structural**, including *Association* and *Generalization*. Association refers to cases in which a context in associated with another context. For example, an ActualTraining is associated with an

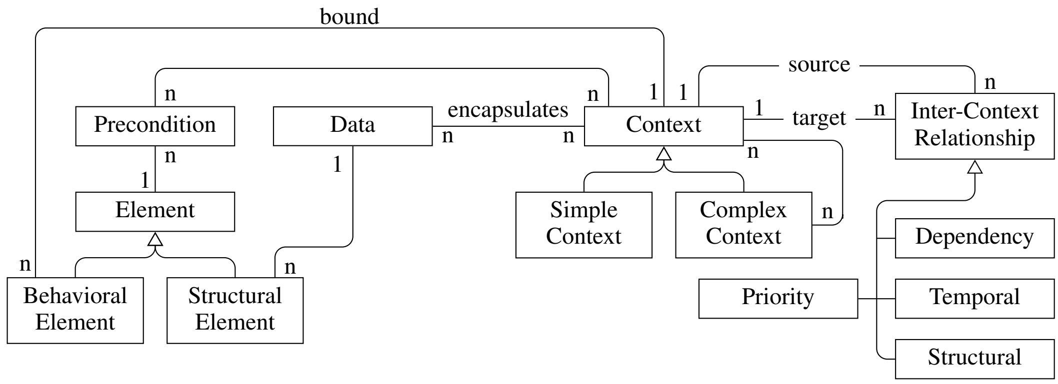


Figure 4: A context metamodel.

ActualTrainee. *Generalization* refers to cases in which a context may be refined. For example, the VirtualTraining context and PhysicalTraining context are both refinements of the Training context. In that case, it means that all properties, constraints, dependencies, and relationships that refer to the Training context are applied to the other two unless specified otherwise.

- **Context Dependency**. Context dependency refers to cases when one context relies on another one. For example, every actual training depends on the Weather context, though not necessarily vice versa.

- **Context Temporal**. The context temporal relationship refers to temporal relationships between contexts. For example, the period between two Actual Trainings should be at least 24 hours.

- **Context Priority**. In some cases, several contexts are simultaneously active, which may result in several active context-dependent behaviors. This may be problematic if two contradicting behaviors are active at the same time. For example, the context of a specific activity within a training requires X repetitions, yet in another context in which the Trainee fails in accomplishing the goal, the number of repetitions should be reduced by 30%. There are many ways to overcome such contradictions, for example, by defining the priority of each context of behavior. While priorities may be dangerous, as they require a cross-aspect perspective on the system, it is still a popular option, as in the case of rule-based systems, which is why we include this type of relation. Yet, other solutions may be more robust to constant changes, such as explicitly defining the behavior when the two contexts are simultaneously active.

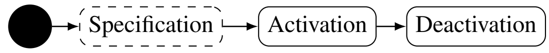


Figure 5: The context life cycle.

4.3 The Context Life Cycle

Another important observation we had is that context has both a type (its specification) and occurrences (instances). Thus, the life cycle of a context can be summarized as appears in Figure 5.

Context Specification: refers to its definition. The activity is dashed since it is usually done before the system runs, though it can also be done during run time, in cases of self-adaptive systems.

Context Activation: refers to the instantiation of a context, based on its preconditions. Meaning that the system tracks the elements' state (i.e., the state of the system) and the set of context preconditions. At the moment that some elements become to a state that resembles the elements' state of context preconditions – then the context is instantiated. In the case of the training system, the identification of the bad-weather context occurs when the temperature actually drops below zero.

Once a new context instance is generated, the behaviors that are bound to this context take place. In the case of the training system, the behavior in Figure 3b takes place whenever the bad-weather context is active.

Context Deactivation: refers to the point in which a context is not relevant anymore. So, in the case of the above example, due to heating devices, the temperature crosses zero and the training should get back to normal. This should also affect the system's operation.

In this case, the active behaviors that are bound to the bad-weather context, are either immediately terminated, or they may perform a "cleanup" action before terminating, such as: gracefully ending the current activity before returning to normal.

4.4 Reflection over the Metamodel

Here again, we review the devised metamodel in light of the requirements set in Section 2. In the metamodel, we did not elaborate on the context information. To cope with heterogeneous information sources, such information can be associated with the context element. Relationships are explicitly defined in the metamodel. References to past states can be accomplished by the behavioral aspect specified in the metamodel. The complexity is dealt with through the context hierarchy and its relationships. Applying reasoning capabilities depends on the implementation approach and uncertainty can be handled by the binding and priority mechanisms.

5 UTILIZING THE PROPOSED FRAMEWORK

In this section, we aim at demonstrating the usage of the framework we suggested. For that purpose, using the framework, we examine an existing context-aware modeling technique based on live-sequence charts (LSC) (Harel and Marelly, 2003), an extension of message-sequence charts (MSC) with the ability to specify possible and mandatory behaviors of reactive systems (Harel and Pnueli, 1985), as well as forbidden behavior. LSC has execution semantics that allows for synthesizing the model and verifying its correctness (Harel et al., 2010; Harel and Marelly, 2003).

Elyasaf et al. proposed an extension to LSC (CO-LSC) that allows for subjecting charts to context and demonstrated it on a case study of a smart-home system (Elyasaf et al., 2018). Specifically, they proposed to handle contextual data in terms of a relational data model, where preconditions are specified as 'select' queries, and any change to the contextual data is done using 'update' queries. The charts can be bound to one or more contexts, represented as the queries' names. They also presented translational semantics to the LSC semantics and implemented them in a tool that enables the execution and verification of the charts. According to these semantics, whenever the context preconditions are met (i.e., there is a new answer to the query), a new live copy of the chart is created, with the context's data encapsulated as a parameter for the chart.

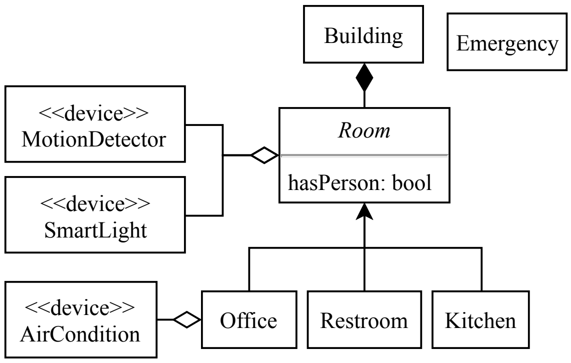


Figure 6: The contextual-data schema of (Elyasaf et al., 2018).

Figure 6 depicts the schema of the contextual data of the smart home application and Table 1 presents the definition of contexts, i.e., the names of the contexts, their preconditions, and the definition of the context encapsulated data. We note that the queries' elements are all structural, and while it may seem that the preconditions are using structural elements only, it is not the case, as depicted in Figure 7. The chart on the left is bound to the context of "Nonempty-Room", specifying that whenever a room becomes nonempty, then the lights should be turned on, and when the context ends (deactivated) – they should be turned off (allowing for performing "cleanup" actions when the context becomes deactivated). The chart on the right demonstrates how the NonemptyRoom is activated/deactivated based on the detection of a motion. While the NonemptyRoom precondition is defined by a structural element, the state of this element is controlled by a behavioral element – the chart in Figure 7b.

The charts in Figure 7 demonstrate the separation of concerns between the specification of what to do in a nonempty room, and the specification of how we know that a room is nonempty using the update queries appear in Table 2.

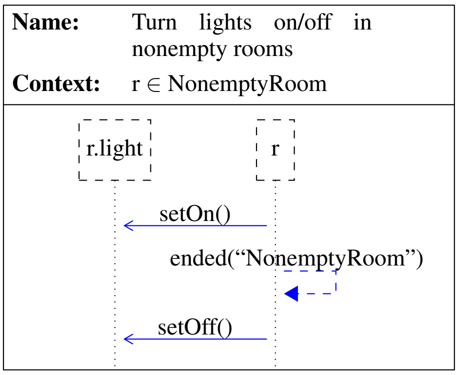
Finally, Figure 8 depicts the use of a complex context. In CO-LSC there is no explicit composition of contexts, but rather implicit composition within a query.

In the following we discuss the inter-context relationships support in CO-LSC:

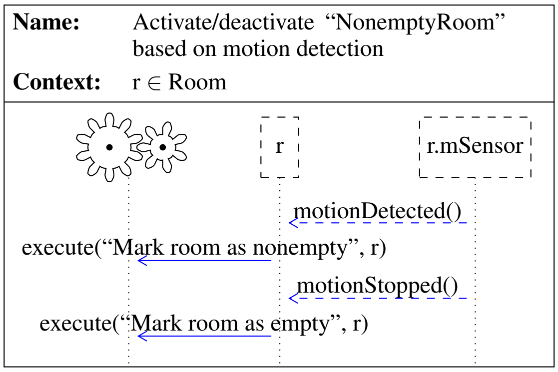
1. **Structural —** In CO-LSC there are no explicit relationships among contexts. Nevertheless, such relationships can be expressed via the query operators. For example, an association can be specified using additional phrases of a query. Generalization can be specified by adding conditions to further refine the query results.
2. **Dependency and Temporal —** since CO-LSC is

Table 1: Context Definition of (Elyasaf et al., 2018).

ID	Context Name	Pre-Conditions	Encapsulated Data
1	Room	r ∈ Room	Room
2	Emergency	e ∈ Emergency	Emergency
3	NonemptyRoom	r ∈ Room: r.hasPerson	Room & Person



(a) Binding charts to dynamically created context.



(b) Execute ‘update’ queries to activate/deactivate context(s). The gears lifeline denotes a contextual data controller that allows for querying and updating the system context.

Figure 7: The smart-home system of (Elyasaf et al., 2018). Charts are bound to contexts Room and NonemptyRoom.

Table 2: Context Initiation of (Elyasaf et al., 2018).

ID	Context Name	Operation
1	Mark room as nonempty	r.hasPerson = true
2	Mark room as empty	r.hasPerson = false

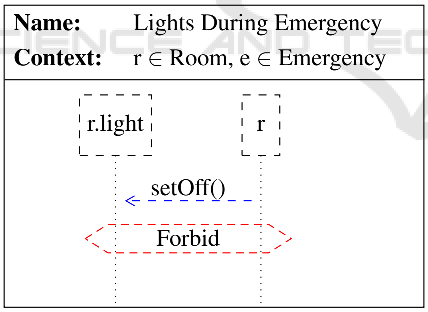


Figure 8: A Complex context, binding to more than one simple context.

provided with execution semantics, these relationships exist during execution and verification. For example, the contexts EmptyRoom and NonemptyRoom are temporally related, as they cannot be simultaneously active. Thus dependency and temporal relations are specified in the behavioral charts. Furthermore, reasoning techniques can be applied to the model for extracting the implicit temporal and dependency relationships.

3. **Priority —** CO-LSC supports priorities for events through the mechanism of smart play-out (execution) (Harel et al., 2010; Harel et al., 2002). If a certain behavior in a specific context requires a higher priority than another, then it is possible to prioritize the events of the first. Yet, CO-LSC does not provide an idiom for prioritizing all the behaviors that are bound to a specific context. While it is technically possible to create such an idiom, it might not be safe to prioritize a context with all the current and future behaviors that are bound to it. In addition, CO-LSC does not support the prioritization of contexts.

4. **Life Cycle Support —** CO-LSC supports the entire context life cycle. Contexts are specified using queries and are activated and deactivated based on the system behavior and the update queries.

To conclude, it seems that CO-LSC provides comprehensive support for context-aware systems. However, it can benefit from explicit references to the context core elements.

6 SUMMARY

This paper proposes a framework for supporting the evaluation of context-oriented development methods (i.e., modeling techniques and programming languages). It conceptualizes and explicates the building blocks of context-aware systems. Such a framework can be used for evaluating existing development methods (as we demonstrated in this paper) and for the development of new ones.

We do not claim that the framework is complete, yet it certainly can serve as a starting point for benchmarking of context-oriented development methods. For that reason, we suggest adopting the framework with caution as more refinements may emerge. In future work, we wish to continue to examine the proposed framework and further examine context-oriented/aware programming/modeling approaches.

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