An Extension of OCL with Temporal Logic

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Abstract. UML class diagrams are widely used to model the static structure of object-oriented software systems. As a supplement, OCL becomes more and more popular for formulating constraints that can not be modeled by the diagrams. In this paper, we extend OCL with elements of temporal logic. With this extension, constraints on the temporal development of the system structure as well as on the system behavior can be stated in terms of temporal invariants and pre- and postconditions.

1 Introduction

UML class diagrams are popular for modeling the static structure of object-oriented software systems. However, not all structural details can be expressed in a class diagram. Some of these details can be stated in the Object Constraint Language (OCL), a textual language for specifying additional constraints on the objects of the system. Syntax and semantics of UML diagrams are semi-formally defined in [11, 12]; OCL, which is a part of UML, is defined in [9] in the same semi-formal way. A formal semantics for UML class diagrams and OCL, which is also included in the current OCL 2.0 OMG submission [2], was given in [17, 15].

OCL is quite similar to first order predicate calculus: Boolean expressions can be built and combined by logical connectives; universal and existential quantifiers are also available. As expressions of the predicate calculus, OCL expressions used in invariants are evaluated in a single system state. In addition to such OCL invariants considering single states, OCL pre- and postconditions characterize operations by considering state transitions, i.e., state pairs.

Temporal logic, as an extension of predicate logic, has been used successfully in the field of software development (see [13, 8, 7], among other approaches). The basic idea of (linear) temporal logic is to consider not only single states or state pairs, but to care about arbitrary finite state sequences. By doing so, it is possible to characterize system behavior and system development by specifying the allowed system state sequences as life cycles. Critical systems often incorporate situations where desired state sequences characterize the allowed behavior or undesired state sequences describe the forbidden behavior. Both kinds of constraints can be formulated as OCL constraints with temporal quantifiers. We demonstrate these ideas with a classical example from critical system development, the steam boiler example [1].

There is already work to extend OCL with temporal logic in various directions. [14] extends OCL with operators of a linear temporal logic. However, the paper does not give a formal foundation of the extension. [4] proposes an extension of OCL with temporal operators in a similar way also without formal semantics. In [5], the object-based temporal logic BOTL is defined, which is based on the branching temporal logic CTL and a subset of OCL. But inheritance and subtyping are not considered in this approach. [6] presents an OCL extension, equally based on CTL, for specification of state-oriented constraints. This extension concerns system behavior modeled by statechart diagrams; but the development of attributes is not considered there. In [3], OCL is extended with temporal constructs based on the observational mu-calculus. The authors concede that using the resulting logic $\mathcal{O}\mu$(OCL) directly requires the developer to have a profound understanding of the mathematical background, so they suggest using "templates" with user-friendly syntax which then have to be translated to $\mathcal{O}\mu$(OCL). However, there is no way out for developers of OCL tools implementing the proposed semantics: they still must have this background knowledge, which we think can not be expected in general. Therefore, we think our direct semantics in term of set theory is useful as well.

In this paper, we present an extension of OCL with important elements of a finite linear temporal logic. Past and future temporal operators are introduced. Our extended version of OCL, which we call *TOCL* (*Temporal OCL*), is capable of specifying constraints on the temporal development of a system's structure. For example, the temporal development of attributes and the existence of objects and links can be described in our approach. Constraints on system behavior can be specified with temporal invariants and pre- and postconditions. We define the extension by building upon the formal definition of OCL presented in [17, 15].

The paper is organized as follows. In Sect. 2, we motivate the temporal extension of OCL by giving examples. In Sect. 3, object models, system states, and state sequences are introduced as a context for TOCL. Section 4 gives a brief overview of the type system of TOCL. In the central Sect. 5, TOCL expressions and invariants are formally defined. We give an idea how pre- and postconditions can be formalized. Section 6 concludes with a summary and an outline of future work.

2 Basic Idea

To give an idea of the usefulness of a temporal OCL, we demonstrate how parts of the "Steam-boiler control specification problem" [1] can be specified using TOCL. The underlying object model is shown in Fig. 1. It is beyond the scope of this section to elaborate on all of its elements; they are explained as they are used in the following example constraints.

The first invariant simply states that the value of attribute failureDetected is the disjunction of the values of the attributes that indicate a more concrete failure (i.e., it is true if and only if a failure of the water level measurement device or the steam measurement device or the pump or the controller is detected). The

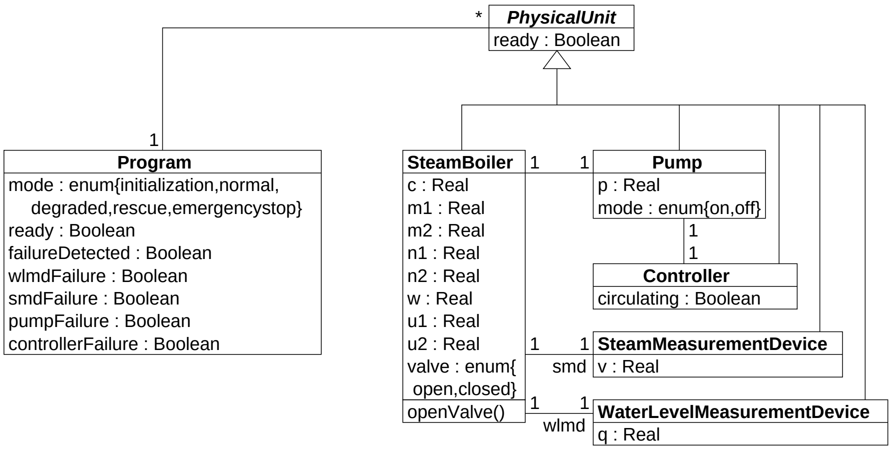

Fig. 1: Object model for the steam-boiler problem

newly introduced operator 'always' makes explicit that this has to be the case in all system states. You can think of the 'always' operator as being used implicitly in standard OCL invariants.

```
context Program inv:
  always failureDetected = (wlmdFailure or smdFailure or
    or pumpFailure or controllerFailure)
```

The next invariant requires that the program starts in the mode 'initialization'. The expression 'previous e' is true if and only if e is true in the previous state or there is no previous state. The expression 'previous false' is therefore true only in the first state.

```
context Program inv:
  (previous false) implies mode = 'initialization'
```

The following invariant applies the operator 'next' to specify that the mode changes from 'initialization' to 'emergencystop' if a failure of the water level measurement device is detected.

```
context Program inv:
  (mode = 'initialization' and wlmdFailure)
  implies next mode = 'emergencystop'
```

When the program is ready, it waits for the physical units being ready. The next invariant says that the program has to be ready before the physical units are. Here, the operator 'sometime-before' is applied.

```
context PhysicalUnit inv:
  sometime program.ready before ready
```

Of course, TOCL can be used in pre- and postconditions as well. The operation openValve() causes the valve of the steam-boiler to be open until the water level (attribute q) sinks under the normal upper boundary n2. The operator 'always-until' is used in the postcondition.

```
context SteamBoiler::openValve()
  post: always valve = #open until wlmd.q <= n2
```

3 Object Models

In our context, an object model uses all those UML concepts that are essential for modeling structural aspects of a problem domain. An object model can be visualized by a UML class diagram. Instances of an object model (i.e., states of the modeled system) can be visualized by a UML object diagram. Object models are referred to by TOCL constraints and are therefore a prerequisite for the TOCL definition. We adopt the object model definition presented in [17, 15, 2] but extend it with *state sequences*.

An *object model*

$$\mathcal{M} = (\textsc{Class}, \textsc{Att}_c, \textsc{Op}_c, \textsc{Assoc}, \mathrm{associates}, \mathrm{roles}, \mathrm{multiplicities}, \prec)$$

consists of a set of classes ($\textsc{Class}$) with each class c having attributes ($\textsc{Att}_c$) and operations ($\textsc{Op}_c$) assigned to it. Associations ($\textsc{Assoc}$) connect classes with each other. The function 'associates' maps each association name to a finite list of participating classes. The function 'roles' assigns a role name to each participating class. Objects of associated classes can be connected with links. The number of links an object can be associated with is specified by the function 'multiplicities'. $\prec$ is an irreflexive partial order on the set of classes, representing a generalization hierarchy.

An object model specifies the possible states of a system. A *system state*

$$\sigma(\mathcal{M}) = (\sigma_{\textsc{Class}}, \sigma_{\textsc{Att}}, \sigma_{\textsc{Assoc}}),$$

also called a snapshot of a running system, consists of the existing objects ($\sigma_{\textsc{Class}}$) with its current attribute values ($\sigma_{\textsc{Att}}$) and links ($\sigma_{\textsc{Assoc}}$) connecting them.

We write σ instead of $\sigma(\mathcal{M})$ if the model is clear from the context.

An OCL constraint is evaluated in a single system state. Since TOCL is intended for formulating constraints on the temporal development of a system, a single system state is not sufficient here. We therefore introduce *state sequences* for a model $\mathcal{M}$, denoted as

$$\hat{\sigma}(\mathcal{M}) = \langle \sigma_0, \ldots, \sigma_n \rangle.$$

The order of the states reflects a temporal relationship; that is, the system is in state σ_0 at the beginning, later in state σ_1, and so on. The length of a sequence is denoted as $|\hat{\sigma}(\mathcal{M})|$. Again, we write $\hat{\sigma}$ instead of $\hat{\sigma}(\mathcal{M})$ if the model is clear from the context. For example, $\sigma_{0_{\textsc{Class}}}(c)$ is the set of objects of class c existing in the first state of the sequence. One state of the state sequence is the "current state", also called the "reference state".

4 TOCL Types

TOCL is a strongly typed language. We adopt the type system of OCL defined in [17, 15, 2], extending it with one additional and one modified operation on object types: allInstancesInTime and oclIsNew.

The types of (T)OCL can by divided into several groups. The set T_B of basic types includes *Integer*, *Real*, *Boolean* and *String* with the expected domains. Enumeration types (T_E) are user-defined; that is, the user specifies the name and a list of possible values for the type. Object types (T_C) are derived from the object model. There is an object type for each class, having the same name as the corresponding class. The domain of an object type is an infinite set of objects of the class.

Collections of values can be described by the complex types $\mathit{Set}(t)$, $\mathit{Sequence}(t)$, $\mathit{Bag}(t)$, and $\mathit{Collection}(t)$. The parameter t denotes the type of the elements of the set, sequence, or bag (multi-set), respectively. Each type has a special undefined value $\perp$ contained in its domain.

Each type has a set of associated operations. The operations $\mathrm{allInstances}_t : \rightarrow \mathit{Set}(t)$, $\mathrm{allInstancesInTime}_t : \rightarrow \mathit{Set}(t)$ and $\mathrm{oclIsNew}_t : t \rightarrow \mathit{Boolean}$ are defined for all object types $t \in T_C$. While allInstances is already present in OCL, allInstancesInTime is newly introduced in TOCL. oclIsNew is present in OCL but only applicable in postconditions. In TOCL it can be applied in invariants and preconditions as well. With c being the class corresponding to type t and $\preceq$ being the reflexive closure of $\prec$, the semantics function I, which depends on a state sequence and a reference index, maps the operation signatures to functions as follows:

$$
\begin{aligned}
&I(\hat{\sigma}, i)(\mathrm{allInstances}_t : \rightarrow \mathit{Set}(t)) = \cup_{c' \preceq c} \sigma_{i\,\mathrm{CLASS}}(c'),\\
&I(\hat{\sigma}, i)(\mathrm{allInstancesInTime}_t : \rightarrow \mathit{Set}(t)) = \cup_{0 \le j \le |\hat{\sigma}|} (\cup_{c' \preceq c} \sigma_{j\,\mathrm{CLASS}}(c')),\\
&I(\hat{\sigma}, i)(\mathrm{oclIsNew}_t : t \rightarrow \mathit{Boolean})(\underline{c}) =\\
&\quad\begin{cases}
\text{true} & \text{if } i > 0 \text{ and } \underline{c} \in I(\hat{\sigma}, i)(\mathrm{allInstances}_t)\\
 & \text{and } \underline{c} \notin I(\hat{\sigma}, i-1)(\mathrm{allInstances}_t),\\
\text{true} & \text{if } i = 0 \text{ and } \underline{c} \in I(\hat{\sigma}, i)(\mathrm{allInstances}_t),\\
\text{false} & \text{otherwise.}
\end{cases}
\end{aligned}
$$

The result of allInstances is the set of objects of the given type existing in the reference state (denoted by the reference index). This includes instances of child classes of the corresponding class. allInstancesInTime is the temporal extension of allInstances and results in the set of objects of the given type existing in any state of the state sequence. The operation oclIsNew can be used to check whether an object is new, that is, whether it exists in the reference state and not in the preceding state. In the first state of a sequence, all existing objects are new.

We describe the type system of TOCL in a model signature $\Sigma_{\mathcal{M}} = (T_{\mathcal{M}}, \le, \Omega_{\mathcal{M}})$. $T_{\mathcal{M}}$ is the union of all types for a model $\mathcal{M}$, $\Omega_{\mathcal{M}}$ is the union of associated operations, and $\le$ is a type hierarchy. The type hierarchy is a reflexive partial order on the set of types, defining a subtype relationship. The subtype relationship between object types is derived from the class hierarchy, *Integer* is a subtype of *Real* (denoted as $Integer \leq Real$) and *oclAny* is the supertype of all other simple types. Set, sequence and bag types are subtypes of collection types. And finally, a set/sequence/bag type is a subtype of another set/sequence/bag type if the parameter type of the first is a subtype of the second.

5 TOCL Expressions and Constraints

In this section we define syntax and semantics of expressions and constraints. Expressions are used to construct constraints on a model.

5.1 Expressions

We now extent the syntax of OCL expressions to include temporal expressions. The syntax of OCL expressions is defined in [17, 15, 2] by giving six rules. We do not repeat them here but add another seven rules for expressions of a future-directed temporal logic. For each expression the set of free occurrences of variables is also defined.

Definition 1 (Syntax of future expressions)
Let $\Sigma_\mathcal{M} = (T_\mathcal{M}, \leq, \Omega_\mathcal{M})$ be a model signature over an object model $\mathcal{M}$. Let $\mathrm{Var} = \{\mathrm{Var}_t\}_{t \in T_\mathcal{M}}$ be a family of variable sets where each variable set is indexed by a type t. The syntax of future expressions over the signature $\Sigma_\mathcal{M}$ is given by a set $\mathrm{Expr} = \{\mathrm{Expr}_t\}_{t \in T_\mathcal{M}}$ and a function $\mathrm{free} : \mathrm{Expr} \to \mathcal{F}(\mathrm{Var})$ that are defined as follows.[1]

vii. If $e \in \mathrm{Expr}_{Boolean}$ then **next** $\boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{next}\ e) := \mathrm{free}(e)$.
viii. If $e \in \mathrm{Expr}_{Boolean}$ then **existsNext** $\boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{existsNext}\ e) := \mathrm{free}(e)$.
ix. If $e \in \mathrm{Expr}_{Boolean}$ then **always** $\boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{always}\ e) := \mathrm{free}(e)$.
x. If $e \in \mathrm{Expr}_{Boolean}$ then **sometime** $\boldsymbol{e} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{sometime}\ e) := \mathrm{free}(e)$.
xi. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then **always** $\boldsymbol{e_1}$ **until** $\boldsymbol{e_2} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{always}\ e_1\ \mathrm{until}\ e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.
xii. If $e_1, e_2 \in \mathrm{Expr}_{Boolean}$ then **sometime** $\boldsymbol{e_1}$ **before** $\boldsymbol{e_2} \in \mathrm{Expr}_{Boolean}$ and $\mathrm{free}(\mathrm{sometime}\ e_1\ \mathrm{before}\ e_2) := \mathrm{free}(e_1) \cup \mathrm{free}(e_2)$.
xiii. If $\omega : t_1 \times \cdots \times t_n \to t \in \Omega_\mathcal{M}$ and $e_i \in \mathrm{Expr}_{t_i}$ for all $i = 1, \ldots, n$ then $\boldsymbol{\omega@\mathbf{next}(e_1, \ldots, e_n)} \in \mathrm{Expr}_t$ and $\mathrm{free}(\omega@\mathrm{next}(e_1, \ldots, e_n)) := \mathrm{free}(e_1) \cup \cdots \cup \mathrm{free}(e_n)$.

An expression of type t' is also an expression of a more general type t. For all $t' \leq t$: if $e \in \mathrm{Expr}_{t'}$ then $e \in \mathrm{Expr}_t$. □

[1] $\mathcal{F}(\mathrm{Var})$ denotes the set of all finite subsets of Var.

The following definition gives semantics to the TOCL expressions above. Expressions are evaluated in an environment $\tau = (\hat{\sigma}, i, \beta)$ consisting of a state sequence $\hat{\sigma}$, a reference index i, and variable assignment β.

Definition 2 (Semantics of future expressions)
The semantics of a future expression $e \in \mathrm{Expr}_t$ is a function $I[\![\, e \,]\!] : \mathrm{Env} \to I(t)$ that is defined as follows.

vii. $I[\![\, \text{next } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } i = |\hat{\sigma}| - 1 \text{ or } I[\![\, e \,]\!](\hat{\sigma}, i+1, \beta) = \text{ true,} \\ \text{false} & \text{otherwise.} \end{cases}$

viii. $I[\![\, \text{existsNext } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } i < |\hat{\sigma}| - 1 \text{ and } I[\![\, e \,]\!](\hat{\sigma}, i+1, \beta) = \text{true,} \\ \text{false} & \text{otherwise.} \end{cases}$

ix. $I[\![\, \text{always } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{ true for all } i \leq j < |\hat{\sigma}|, \\ \text{false} & \text{otherwise.} \end{cases}$

x. $I[\![\, \text{sometime } e \,]\!](\tau) = \begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } i \leq j < |\hat{\sigma}|, \\ \text{false} & \text{otherwise.} \end{cases}$

xi. $I[\![\, \text{always } e_1 \text{ until } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{true for all } i \leq j < l \\ & \text{with } l = \min\left\{\{k \geq i \mid I[\![\, e_2 \,]\!](\hat{\sigma}, k, \beta) = \text{true}\} \cup \{|\hat{\sigma}|\}\right\}, \\ \text{false} & \text{otherwise.} \end{cases}$$

xii. $I[\![\, \text{sometime } e_1 \text{ before } e_2 \,]\!](\tau) =$
$$\begin{cases} \text{true} & \text{if } I[\![\, e \,]\!](\hat{\sigma}, j, \beta) = \text{true for some } i \leq j < l \\ & \text{with } l \text{ defined as in xi,} \\ \text{false} & \text{otherwise.} \end{cases}$$

xiii. $I[\![\, \omega@\text{next}(e_1, \ldots, e_n) \,]\!](\tau) =$
$$\begin{cases} I(\hat{\sigma}, i+1)(\omega)(I[\![\, e_1 \,]\!](\tau), \ldots, I[\![\, e_n \,]\!](\tau)) & \text{if } |\hat{\sigma}| > i+1, \\ \perp & \text{otherwise.} \end{cases}$$

□

An expression 'next e' is true if e is true "in the next state"; that is, if e is true with a reference index incremented by one. It is also true if there is no next state. In all other cases the evaluation results in false. An expression 'existsNext e' differs from 'next e' in that it becomes false if there is no next state.

An expression 'always e' is true if e is true in the reference state and in all future states of the sequence, otherwise false. An expression 'sometime e' is true if e is true in the reference state or in one of the future states. Otherwise it is false.

An expression 'always e_1 until e_2' is true if e_1 is true "from now on" (including the reference state) until e_2 is true for the first time in future. Otherwise it is false. If e_2 is true in the reference state then the whole expression is true regardless of e_1. For an expression 'sometime e_1 before e_2' to be true, e_1 just has to be true in at least one of these states mentioned above.

The @next modifier applied to an operation has the effect of evaluating the operation in the next state. If there is no such state the result is the undefined value.

The past expressions 'previous e', 'existsPrevious e', 'alwaysPast e', 'sometimePast e', 'always e_1 since e_2', 'sometime e_1 since e_2, and the modifier @pre can be defined analogously. They behave like the future expressions flipped (with respect to to the temporal ordering) across the reference state.

5.2 Constraints

A TOCL constraint can either be an invariant or an operation specification. We formally define the slightly modified semantics of invariants. In addition, semantics of pre- and postconditions are informally described.

Invariants. In OCL an invariant is a condition that must be satisfied in all system states. In TOCL an invariant is a condition that must be satisfied in all state sequences, with the first state as reference state. Thus an OCL invariant is just a special TOCL invariant with an (implicit) 'always' operator at the out-most level.

Definition 3 (Semantics of invariants)
An invariant $\phi = \mathbf{context}\ v_1 : t_1, \ldots, v_n : t_n\ \mathbf{inv}$: e is *valid in a state sequence* $\hat{\sigma}$, denoted as $\hat{\sigma} \models \phi$, if $I[\![e']\!](\hat{\sigma}, 0, \beta) = \text{true}$ with e' being the following expression:

```
t1.allInstancesInTime->forAll(v1:t1 |
    ...
    tn.allInstancesInTime->forAll(vn:tn |
      e
    )
    ...
)
```

An invariant that is not valid is denoted as $\hat{\sigma} \not\models \phi$. □

The expression e is extended to an expression e' that quantifies the declared variables over the set of objects of the respective type existing in the state sequence. e has to be a boolean future expression. If e is an expression of the form 'always e''', then the always operator can be omitted. In this way it is ensured that every OCL invariant is also a TOCL invariant with semantics as expected.

In this case, the assignment β is irrelevant for the result since there are no free variables in e'.

Pre- and Postconditions. Pre- and postconditions are part of operation specifications. They are used to specify conditions to be satisfied before and after the execution of a user-defined operation, respectively.

For an operation specification to be valid in a state sequence, the postcondition must be satisfied in the poststate of all executions of the given operation if the precondition is satisfied in the corresponding prestate. In TOCL, the conditions can either be standard OCL expressions, or boolean past expressions (in preconditions), or boolean future expressions (in postconditions).

This definition could probably formalized using *message types* as introduced in [2]. In this way, operation specifications could be reduced to invariants making use of messages to get the pre- and poststates. However, the semantics of these types is not so clear yet in [2].

6 Summary and Conclusions

In this paper we presented TOCL, an extension of OCL with elements of a finite linear temporal logic. We have started with a description of object models, modeling the static structure of a system. System states have been introduced as snapshots of a running system. Multiple states, which are ordered in time, form state sequences that constitute part of the environment for evaluating TOCL expressions.

We have proceeded with an outline of the TOCL type system, where we have added/modified some operations to object types.

In the central part of the paper, TOCL expressions and constraints have been defined. Temporal operators have been introduced to combine boolean expressions to new ones. Expressions have been used to form constraints, i.e., invariants and operation specifications (with pre- and postconditions). The semantics of invariants has been formally defined.

There are some issues that are topics of further research. It could be examined to which extent TOCL is capable of describing properties of the various UML diagram types. While TOCL needs a class diagram providing the context, other diagram types (like certain statechart diagrams) could be explained by appropriate TOCL constraints, maybe in part or even completely.

Furthermore, operation specifications (with pre- and postconditions) could possibly be defined formally using message types that are introduced in [2]. In this way, operation specifications could be reduced to invariants making use of messages to get the pre- and poststates.

Finally, a tool could be developed for validation of TOCL constraints with respect to state sequences. The USE tool [16] allows validation of OCL constraints by testing the validity of constraints with respect to example states. For TOCL, example state sequences would be necessary. These could be recorded by a tool like USE; however, long sequences can hardly be produced manually. The automatic production of appropriate state sequences would be a welcome feature.

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