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Refereed Article

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The Complexity of Model Checking in Modal Event Calculi with Quantifiers

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Abstract: *Kowalski and Sergot's Event Calculus (*EC*) is a simple temporal formalism that, given a set of event occurrences, derives the maximal validity intervals (MVIs) over which properties initiated or terminated by these events hold. It does so in polynomial time with respect to the number of events. Extensions of its query language with Boolean connectives and operators from modal logical have been shown to improve substantially its scarce expressiveness, although at the cost of an increase computational complexity. However, significant sublanguages are still tractable. In this paper, we further extend* EC *queries by admitting arbitrary event quantification. We demonstrate the added expressive power by encoding a hardware diagnosis problem in the resulting calculus. We conduct a detailed complexity analysis of this formalism and several sublanguages that restrict the way modalities, connectives, and quantifiers can be interleaved. We also describe an implementation in the higher-order logic programming language λProlog.*

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The Event Calculus

The *Event Calculus*, abbreviated *EC*, is a simple temporal formalism designed to model and reason about scenarios characterized by a set of *events*, whose occurrences have the effect of starting or terminating the validity of determined properties. Given a *possibly incomplete* description of when these events take place and of the properties they affect, *EC* is able to determine the *maximal validity intervals*, or *MVIs*, over which a property holds uninterruptedly.

State-of-the-art

A systematic analysis of *EC* has recently been undertaken in order to gain a better understanding of this calculus and determine ways of augmenting its expressive power. The keystone of this endeavor has been the definition of an extendible formal specification of the functionalities of this formalism. This has had the effects of establishing a semantic reference against which to verify the correctness of implementations, of casting *EC* as a model checking problem, and of setting the ground for studying the complexity of this problem, which was proved polynomial. Extensions of this model have been designed to accommodate constructs intended to enhance the expressiveness of *EC*. In particular, modal versions of *EC*, the interaction between modalities and connectives, and preconditions have all been investigated in this context.

Contributions

The main contributions of the present paper are the following:

- *The extension of a family of modal event calculi with quantifiers.*

  We enhance the expressive power of *EC* by considering the possibility of quantifying over events in queries, in conjunction with boolean connectives and modal operators. We also admit requests to check the relative order of two events. We thoroughly analyze the representational and computational features of the resulting formalism, that we call *QCMEC*. We also consider two proper sublanguages of it, *EQCMEC*, in which modalities are applied to atomic formulas only, and *CMEC*, which is quantifier-free.

- *The use of the proposed formalisms to encode diagnosis problems.*

  We consider a case study taken from the domain of hardware fault diagnosis. We model it using *EC* and use the various extensions of *EC* to draw conclusions about it.

- *The use of the higher-order features of modern logic programming languages in temporal reasoning.*

  > We provide an elegant implementation in the higher-order logic programming language λ*Prolog* and prove its soundness and completeness.

- *Analyzing the complexity of model checking in the proposed extensions of* EC.

  > We prove that model checking in *CMEC*, *EQCMEC*, and *QCMEC* is **PSPACE**-complete. However, while solving an *EQCMEC* problem is exponential in the size of the query, it has only polynomial cost in the number of events, thus making *EQCMEC* a viable formalism for *MVI* verification or computation. Since in most realistic applications the size of databases dominates by several orders of magnitude the size of the query, the former is asymptotically the parameter of interest.