

Property Specification Made Easy: Harnessing the Power of Model Checking in UML designs

Daniela Remenska^{1,3}, Tim A.C. Willemse², Jeff Templon³, Kees Verstoep¹,
and Henri Bal¹

¹ Dept. of Computer Science, VU University Amsterdam, The Netherlands

² Dept. of Computer Science, TU Eindhoven, The Netherlands

³ NIKHEF, Amsterdam, The Netherlands

Abstract. One of the challenges in concurrent software development is early discovery of design errors which could lead to deadlocks or race-conditions. For safety-critical and complex distributed applications, traditional testing does not always expose such problems. Performing more rigorous formal analysis typically requires a model, which is an abstraction of the system. For object-oriented software, UML is the industry-adopted modeling language. UML offers a number of views to present the system from different perspectives. Behavioral views are necessary for the purpose of model checking, as they capture the dynamics of the system. Among them are sequence diagrams, in which the interaction between components is modeled by means of message exchanges. UML 2.x includes rich features that enable modeling code-like structures, such as loops, conditions and referring to existing interactions. We present an automatic procedure for translating UML into mCRL2 process algebra models. Our prototype is able to produce a formal model, and feed model-checking traces back into any UML modeling tool, without the user having to leave the UML domain. We argue why previous approaches of which we are aware have limitations that we overcome. We further apply our methodology on the Grid framework used to support production activities of one of the LHC experiments at CERN.

Keywords: property specification, model checking, UML, sequence diagrams, modal μ -calculus, property patterns

1 Introduction

One of the challenges in concurrent software development is early discovery of design errors which can lead to deadlocks or race-conditions. Traditional testing does not always expose such problems in complex distributed applications. Performing more rigorous formal analysis, like model-checking, typically requires a model which is an abstraction of the system. In the last decades, more rigorous methods and tools for modeling and formal analysis have been developed. Some of the leading model checking tools include SPIN, nuSMV, CADP and mCRL2. Despite the research effort, these methods are still not widely accepted in industry. One problem is the lack of expertise and the necessary time investment in

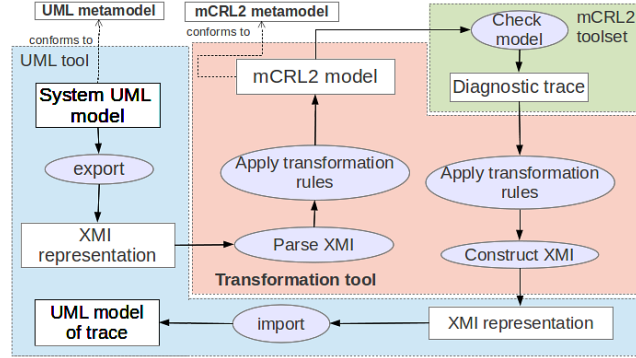


Fig. 1. Automated verification of UML models

the development cycle, for becoming proficient in the underlying mathematical formalisms used for describing the models. To bridge the gap between industry-adopted methodologies based on UML software designs, and model-checking tools and languages, in [1] we devised an automated transformation methodology for verification of UML models, based on sequence and activity diagrams. Our prototype is able to produce a formal model into the mCRL2 process algebra language [2], and feed model-checking traces back into any modeling tool, without the user having to leave the UML domain. We chose mCRL2 because of its strong tool support and rich data types compared to other languages. Figure 1 gives an overview of our approach and implemented toolchain. Although the mCRL2 toolset automatically discovers deadlocks, model checking for application-specific properties requires the use of modal μ -calculus [3]. In principle, regardless of the formal language and tool choice for writing the model, these properties are specified as formulas in some temporal logic formalism, such as Linear Temporal Logic (LTL), Computation Tree Logic (CTL), Quantified Regular Expressions (QRE) or μ -calculus. The level of sophistication and mathematical background required for using such formalisms is yet another obstacle for adopting formal methods. In practice, software requirements are written in natural language, and often contain ambiguities, making it difficult even for experienced practitioners to capture them accurately with temporal logic. There are subtle, but crucial details which are often overlooked and need to be carefully considered in order to distill the right formula.

Based on investigation of more than 500 properties coming from different domains, and specified in several formalisms, a pattern-based classification was developed in [4]. The authors observed that almost all the surveyed properties can be mapped into one of several property patterns. Each pattern is a high-level, formalism-independent abstraction that captures a commonly occurring requirement. These patterns can be instantiated with specific events or states and then mapped to several different formalisms for model checking tools. Their hierarchical taxonomy is based on the idea that each pattern has a *scope*, which defines the extent of program execution over which the pattern must hold, and a *behavior*, which describes the intent of the pattern. The pattern system identifies 5 scopes and 8 behavior variations that can be combined to create 40 different

properties. Examples of scopes are: globally, before an event or state occurs, after an event or state occurs. Examples of behavior classification are: absence (an event or state should never occur during an execution), precedence (which requires that a given event or state always occurs before another one), or response (the occurrence of a given event or state must be followed by designated event or state), capturing a cause-effect relation. Although the patterns website [5] contains a collection of mappings for different target formalisms, such as LTL, CTL, Graphical Interval Logic, and Quantified Regular Expressions, which can be considered helpful, practitioners have to fully understand the provided solutions before they can select and apply the appropriate ones in practice.

To mitigate the problem, several approaches [6–8] propose conversational tools for elucidating properties, based on the property patterns. These approaches guide users in selecting the appropriate pattern for the property in mind, and optionally produce a formula in some target temporal logic. Another category of approaches [9–11] deal with temporal extensions of the Object Constraint Language (OCL), as means to specify system properties. OCL is a declarative textual language for describing invariants for classes and pre- and postconditions of operations. Although it forms an integral part of UML, it lacks means to specify constraints over the dynamic behavior of a model. Finally, a third class of approaches [12–18] tackle the property specification problem by proposing graphical notations.

The objective of this work is to simplify the process of correctly eliciting functional requirements, without the need of expertise in temporal logic. - stay within the same UML IDE environment (does not work with any of the approaches, be it wizards or LSC or other graphical formalisms) - sequence diagrams used - already the notation familiar to designers mention why not state machines for example - event-based formalism, most are state-based (LTL,FSA)

- patterns extended, all existing patterns can be expressed - questionnaire for easier elucidation of properties, automatic generation of formulas for 100 property types which questionnaires distill what? and you have to manually provide states/events in the placeholders. If your design is changed later on, you must re-do it

This automation will increase the accessibility of our approach by allowing software engineers to remain focused in the realm of Sequence Diagrams.

- case study revisited, we were wrong in specifying the property - monitor for "runtime verification" for more efficient bug hunting, fighting state space - quantification for dealing with data; possible to work with state-based formulas, states of objects, quantify forall! '*' LTL, CTL are not that powerful to allow this Finally, we introduce the possibility to define quantifiers for temporal properties to express complex properties in a more concise manner, e.g., every element of a certain type has to fulfill a certain property. μ -calculus is reach enough to be able to achieve this

This paper is structured as follows: in Section 2 we survey the most relevant related approaches, and outline their advantages and shortcomings. Section 3 briefly introduces the syntax and semantics of mCRL2, μ -calculus and UML

Sequence diagrams. We describe our approach in Section 4. In Section 5 we apply it on a case study from the Grid domain, and we conclude in Section 6.

2 Related Work

In [6] the authors developed PROPEL, a tool for guiding users in selecting the appropriate template. Recognizing that there are subtle aspects not covered by the original patterns, such as what happens in a response property if the cause occurs multiple times before the effect takes place, they extended them with variants. The resulting templates are represented using disciplined natural language and finite state automata. PROPEL does not support the universality, bounded existence, and the chain patterns. It also does not produce a formula in any temporal logic formalism. In a similar manner, SPIDER [7] and Prospec [8] offer assistance in the specification process, and extend the original patterns with compositional patterns that are built up from combinations of more basic patterns. Unfortunately, we could not find SPIDER online, and the version of Prospec that we found (Fig. 2a) produces only formulas in Future Interval Logic, not LTL as stated in the work. Of the approaches that deal with temporal extensions of OCL, [9] introduces the @next and @pre temporal modifiers for specification of past and future state-oriented constraints. By means of UML Profiles, [10] proposes another OCL extension for real-time constraints. They claim to be able to describe all the existing patterns in these OCL expressions. Their starting point for model descriptions are UML state machines. To simplify constraint definition with OCL, in [11] the authors propose to use specification patterns for which OCL constraints can be generated automatically. The behavioral specification of software components refers to interface specifications, which are not really dynamic views. This work does not yet introduce means to specify temporal properties. Resembling an OO programming language, OCL constraints can become quite complex and cryptic, and editing them manually is error-prone. Another problem is the extent to which designers are familiar

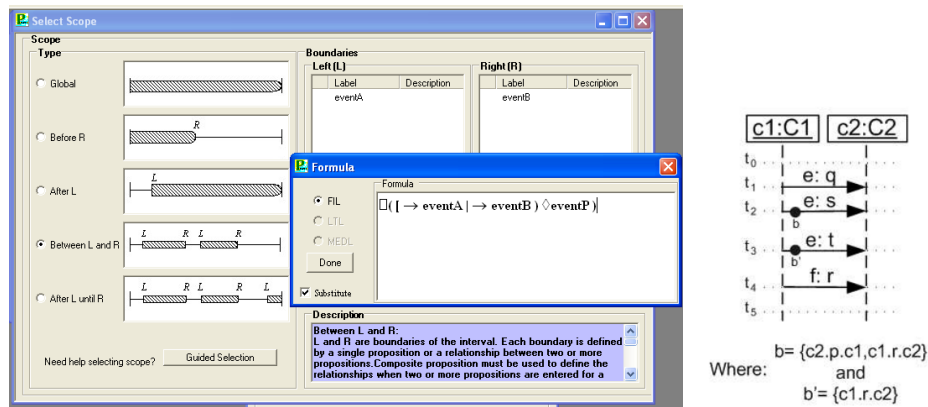


Fig. 2. Left: Prospec tool; Right: CHARMY PSC graphical notation

with this language. Graphical notation approaches come closest to the realm of modeling the system behavior. The CHARMY approach [12] presents a scenario-based visual language called Property Sequence Charts, where a property is seen as a relation on a set of exchanged system messages. The language borrows concepts from UML 2.0 Sequence Diagrams, and its expressiveness is measured with the property patterns. SPIN is used as a backend for model checking of the Buchi automata [19], which are an operational representation for LTL formulas generated automatically with this approach. The PSC notation uses textual restrictions for past and future events, placed as circles directly on the message arrows (Fig. 2b). Such a mix of textual and visual representation of message communication within a diagram is tedious and error-prone. Additionally, asynchronous communication is not supported. Furthermore, even though concepts from UML are borrowed, CHARMY is a stand-alone framework for architectural descriptions, not inter-operable with UML tools, and as such has limited usefulness in industrial context. Another graphical language is proposed in [13], where formulas are represented as acyclic graphs of states and temporal operators as nodes. While they manage to hide the formal notation from the user by generating LTL formulas, their notation is still very close to an actual temporal logic formula. The TimeLine Editor [14] also attempts to simplify the formalization of certain kinds of requirements. Response formulas are depicted in timeline diagrams by specifying temporal relations among events and constraints. The timeline specification is automatically converted into a Buchi automaton, amenable to model checking with SPIN. Unfortunately the tool is no longer available. HUGO/RT [15] is a tool for model checking UML 2.0 interactions against a model composed of message-exchanging state machines. The interactions represent the desired properties, and are translated together with the system model into Buchi automata for model checking with SPIN. The approach uses some inner format for textual representation of UML interactions (rather than the standard XMI), and the version we tested does not support asynchronous messages, or combined fragments. vUML [16] is a tool for automatic verification of UML models comprising state machines. However, properties must be specified in terms of undesired events, which is not always convenient. This is because the verification is based on checking whether it is possible to reach error states, specified by the user. Live Sequence Charts (LSC) are also used [17, 18] as a graphical formalism for expressing behavioral properties. Their elements allow to distinguish between possible (cold) and mandatory (hot) behavior. In both approaches, Buchi automata and a LTL formulas are generated automatically from the diagrams. However, UML 2.0 sequence diagrams already borrow many concepts from LSC, by introducing the assert and negate fragments to capture mandatory and forbidden behavior. On the other hand, being an older graphical notation, LSC lack many UML features.

3 Preliminaries

3.1 Brief Introduction to mCRL2 and μ -calculus

3.2 UML Sequence Diagrams

4 The Approach

4.1 The Rationale

4.2 Transforming a μ -calculus Formula Into a Monitor Process

We translate a fragment of the μ -calculus to mCRL2 processes which can subsequently serve as monitor processes.

We restrict to the following grammar:

$$\begin{aligned}\phi_1 & ::= b \mid \forall d : D. \phi_1 \mid [R]\phi_1 \mid \phi_1 \wedge \phi_2 \\ R_1, R_2 & ::= \alpha \mid nil \mid R_1 \cdot R_2 \mid R_1 + R_2 \mid R_1^* \mid R_1^+ \\ \alpha_1, \alpha_2 & ::= b \mid a(e) \mid \neg\alpha_1 \mid \alpha_1 \wedge \alpha_2 \mid \exists d : D. \alpha_1\end{aligned}$$

Before we present the translation, we convert the formulas in guarded form. That is, we remove every occurrence of R^* and nil using the following rules:

$$\begin{aligned}[nil]\phi &= \phi \\ [R^*]\phi &= [nil]\phi \wedge [R^+]\phi\end{aligned}$$

The function TrS takes two arguments (a formula and a list of typed variables) and produces a process. It is defined inductively as follows:

$$\begin{aligned}\text{TrS}_l(b) &= (\neg b \rightarrow \text{error}) \\ \text{TrS}_l(\forall d : D. \phi_1) &= \sum d : D. \text{TrS}_l \text{ ++ } [d:D](\phi_1) \\ \text{TrS}_l(\phi_1 \wedge \phi_2) &= \text{TrS}_l(\phi_1) + \text{TrS}_l(\phi_2) \\ \text{TrS}_l([R]\phi_1) &= \text{TrR}_l(R) \cdot \text{TrS}_l(\phi)\end{aligned}$$

where TrR takes a regular expression (and a list of typed variables) and produces a process or a condition:

$$\begin{aligned}\text{TrR}_l(\alpha) &= \bigoplus_{a \in \text{Act}} (\sum d_a : D_a. \text{Cond}_l(a(d_a), \alpha) \rightarrow a(d_a)) \\ \text{TrR}_l(R_1 \cdot R_2) &= \text{TrR}_l(R_1) \cdot \text{TrR}_l(R_2) \\ \text{TrR}_l(R_1 + R_2) &= \text{TrR}_l(R_1) + \text{TrR}_l(R_2) \\ \text{TrR}_l(R_1^+) &= X(l) \quad \text{where } X(l) = \text{TrR}_l(R_1) \cdot X(l) \text{ is a recursive process}\end{aligned}$$

where \bigoplus is a finite summation over all action names $a \in \text{Act}$ and where Cond takes an action and an action formula and produces a condition that describes when the action is among the set of actions described by the action formula:

$$\begin{aligned}\text{Cond}_l(a(d_a), b) &= b \\ \text{Cond}_l(a(d_a), a'(e)) &= \begin{cases} d_a = e & \text{if } a = a' \\ \text{false} & \text{otherwise} \end{cases} \\ \text{Cond}_l(a(d_a), \neg\alpha_1) &= \neg\text{Cond}_l(a(d_a), \alpha_1) \\ \text{Cond}_l(a(d_a), \alpha_1 \wedge \alpha_2) &= \text{Cond}_l(a(d_a), \alpha_1) \wedge \text{Cond}_l(a(d_a), \alpha_2) \\ \text{Cond}_l(a(d_a), \exists d : D. \alpha_1) &= \exists d : D. \text{Cond}_l(a(d_a), \alpha_1)\end{aligned}$$

4.3 The Wizard

5 Case Study: DIRAC's Executor Framework revisited

6 Conclusions and future work

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