From UML to Process Algebra and Back: An Automated Approach to Model-Checking Software Design Artifacts of Concurrent Systems

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Abstract. One of the challenges in 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, so abstract models are necessary for performing formal analysis. 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 refering 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: formal methods, software engineering, UML

1 Introduction

As modern software systems become more complex and distributed, a major challenge is faced in maintaining their quality and functional correctness. Early discovery of design errors which could lead to deadlocks, race-conditions and other flaws, before they can surface, is of a paramount importance. The Unified Modeling Language (UML) [?] has become the lingua franca of software engineering, in particular for the domain of object-oriented systems. Over time, several mature CASE tools have already adopted UML as the industry-standard visual modeling language for describing software systems. However, use of these tools alone does not assure the correctness of the design, nor does it provide direct means to test the software under design, let alone prove certain properties of interest, such as the absence of deadlocks. For safety-critical and complex distributed applications, traditional testing of the resulting software tends to not always expose such problems, so abstract models are necessary for formal analysis. In the last decades, more rigorous methods and tools for modeling and analysis have been proposed. 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 the OO development cycle, for becoming proficient in them. A more substantial problem is the lack of a systematic connection between actual implementation and the semantics of the existing formal languages.

To bridge the gap between industry-adopted methodologies based on UML software designs, and the sophisticated analysis, verification and optimization tools, several approaches have been proposed for automated extraction of the necessary analysis models from the UML artifacts. For instance, Petri Nets [?,?], Layered Queuing Networks [?] and stochastic process algebras [?,?] are used for performance analysis. Model checking for certain properties of the system is often done via translation into process algebra [?,?]. Automatic synthesis of functional test cases from UML models is possible as well [?,?,?]. Model-to-model transformations can also be done within the UML domain itself, for the purpose of model optimization or refactoring [?]. In each of these cases, the translation is mediated by defining graph-transformation rules between the meta models of UML and the target language.

A UML model of a system is typically a combination of multiple views. Devising an automated transformation methodology requires that behavioral views of the system be available. The static views of a system (such as Class and Deployment UML diagrams) are rarely sufficient to extract the necessary information for constructing a target model for meaningful analysis. Activity, Sequence, and State Machines are among the most commonly used behavioral diagrams for this purpose. State Machines (SM) represent the reaction of individual objects on different stimuli; they are suitable for describing specific parts of systems, such as a critical control component, but are very rarely used [?] as the sole paradigm for developing large distributed object-oriented systems. Developers almost never create a fully-formed object a-priori and in isolation, with all the behavior that the object will ever need. On the other hand, Activity Diagrams (AD) describe the system at a higher level of abstraction, where objects and message exchanges are not captured. They represent workflows of activities, with support for choice and concurrency, and are commonly used for business process modeling. Sequence Diagrams (SD) provide the most fine-grained runtime view of the system. They model a set of interacting objects by means of message-exchanges over time. These diagrams contain information about the control flow during the interaction, capturing conditions and iterations. With the introduction of UML 2.x set of rich features such as combined fragments, SDs have become popular for expressing scenarios because of their clear and intuitive visual layout and close correspondence with actual code-like structures. However, most of the proposed transformation approaches up to date target only one particular type of behavioral diagram, mostly AD or SM diagrams [?,?,?,?,?]. When it comes to interactions (SDs) or targeting multiple diagram types, the existing approaches either deal with UML 1.x semantics [?,?,?,?,?], largely limiting the expressiveness by not taking into account all elements which allow designers to describe complex traces in compact manner, or their semantical models suffer from flaws [?,?], as we will show. Furthermore, rarely [?] does an approach give feedback to the software developer on the results of the formal analysis, back into the UML domain.

Our interest in this paper is obtaining a formal model in the Algebra of Communicating Processes (ACP [?]) process algebra mCRL2 [?], taking a UML model as starting point. We chose mCRL2 because it is able to deal with abstract data types as well as user-defined functions for data transformation. Familiarity with the toolset's simulation, debugging, visualization and model-checking capabilities has influenced our decision, although in principle, ACP has many commonalities with other process algebraic formalisms, so the methodology can be easily adapted. The proposed approach in this paper is based on UML 2.x semantics, and makes use of both sequence and activity diagrams to automatically derive the target formal model. We rely on the XMI representation to devise the model transformation procedure. XMI [?] is an XML-based vendor-independent format for metadata exchange between compliant UML tools. Based on the approach, we have developed a prototype tool that can take a UML model in XMI representation as input, and construct the mCRL2 model. Our methodology allows traces from the model checking tool to be conveniently displayed back in any UML tool. We have further applied the tool to the DIRAC [?] Grid framework used to support production activities for one of the LHC experiments.

The paper is structured as follows: Section **??** gives a brief overview of the syntax and semantics of the UML and mCRL2 language notation necessary for understanding the Transformation Methodology (Section **??**). In Section **??** we apply it on a case study from the Grid domain, and we conclude in Section **??**.

2 Preliminaries

The UML abstract syntax and semantics is described in terms of its *UML metamodel*, which defines the relationships between model elements. To translate a system composed of different diagrams, we chose Sequence Diagrams as a driving behavior description type, and we take the necessary additional information about concurrency from Activity Diagrams. Our choice is motivated by the fact that SDs provide the richest set of constructs for low-level behavior expression, and as such have a close correspondence with actual code. Additional information from ADs is necessary for deriving the actual (OS level) processes, relevant for concurrent and distributed systems.

2.1 Sequence Diagrams

Sequence diagrams model the interaction among a set of participants, with emphasis on the sequence of messages exchanged over time. The participants are class instances (objects) shown as rectangular boxes, with the vertical lines falling from them known as *Lifelines* (See Fig. **??**). Each *Message* sent be-

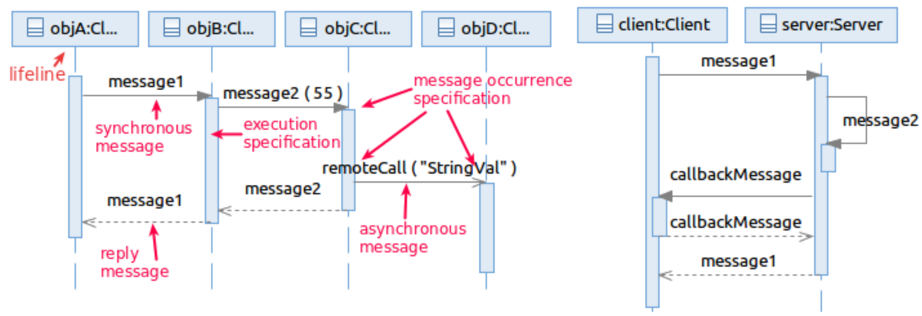


Fig. 1. Sequence Diagrams notation

tween the lifelines defines a specific act of communication, synchronous or asynchronous. The start and end of the directed edge representing a message are called *MessageEnds*, and are marked with a so called *MessageOccurrenceSpecification* element of the UML metamodel, i.e., the occurrence of the send or receive event on the sender's and receiver's lifeline respectively. Synchronous messages are drawn with filled arrow-head, while asynchronous ones have an open arrow-head. Reply messages are drawn as dashed lines. All message types can carry zero or more arguments.

Messages are sent between objects with the aim of invoking specific behavior, known as *ExecutionSpecification*, and visualized as a thin rectangle on the receiver's lifeline. Thus, execution specifications specify when a particular object is busy executing the invoked method. Execution specifications can be nested/overlapping, as a result of a callback message, or an object invoking its own method, an example of both shown in Fig. **??** (right). In this example, the *client* object sends a request for *message1* execution on the *server* side, after which it is blocked until it receives a reply from that method call. However, this does not stop other potential objects from invoking any method of the *client* interface. This possibility of overlapping method executions on the lifeline on a single object plays an important role in our transformation methodology choices, as will become clear later.

Combined Fragments Combined Fragments were introduced to add more expressiveness to SDs by means of constructs capturing complex control flows, thus overcoming many limitations present in UML 1.x. The specification supports different fragment types, such as *alt*, *opt*, *loop*, *break*, *par*. They are visualized as rectangles with a keyword in the top-left corner indicating the type. Combined Fragments consist of one or more *InteractionOperands*. Depending on the type of the fragment, *InteractionConstraints* can guard each of the interaction operands. Combined fragments can be nested with an arbitrary nesting depth, to capture complex workflows. Figure **??** shows how some of them can be used. The guards play a crucial role in deciding which fragment's operand(s) will be executed at runtime. For more information on the semantics of combined fragments, the reader can refer to [**?**].

All fragment types above have equivalent constructs in most object oriented languages. Another useful enhancement is the *InteractionUse* fragment. For ex-

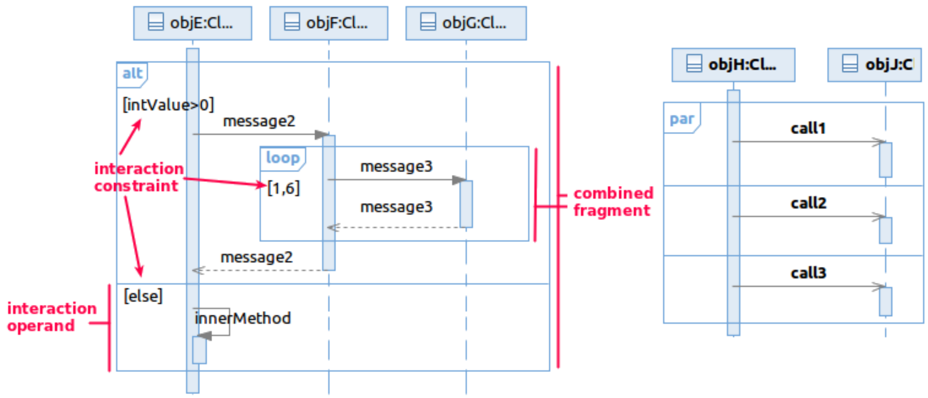


Fig. 2. Combined Fragments example

pressing complex scenarios, one can include a reference to another SD, which is semantically equivalent to including the behavior of the called diagram in the current one. This promotes reuse of already defined sequence diagrams.

Runtime Semantics Unlike the syntax, the SD semantics is scattered through the UML specification, and defined by the means of natural language. The most important points can be summarized as follows: the sending of a message is caused by previous message receptions, and is the object's reaction to these receptions. In that sense, an object does not control the reception of a message. Message and execution completion are considered local concepts. For a message m sent from object *o1* to object *o2*, the sender's view of that message completion is the sending, the receiver's view of the message completion is its reception, while other objects have no knowledge of m. Thus, the only synchronization points between the objects are the message exchanges. *This semantics does not impose a total ordering of the messages in a given SD.*

2.2 Activity Diagrams

As already stated, we use ADs to extract concurrency information necessary for deriving OS-level processes in a distributed system setup. Although the notion of concurrency is present in some form in SDs, the *par* fragment only indicates that the implementation can execute any interleaving of the operands' behaviors, without mandating that the implementation be concurrent or distributed. In a concurrent or distributed setup, each of the SDs could be parts of multiple processes that must be initialized by the system environment at some point, and this is where elements of ADs help. We defer the explanation of the limited subset of used elements to the section where we explain the transformation methodology, illustrating it on an example.

2.3 The mCRL2 Language

mCRL2 is a process algebra language for specification and analysis of concurrent systems. Our choice of mCRL2 as a formal language is motivated by its rich set of abstract data types as first-class citizens, as well as its powerful toolset for analysis, simulation, and visualization of specifications. The syntax of mCRL2 is given by the following BNF grammar:

$$p ::= a(d_1, \ldots, d_n) \mid \tau \mid \delta \mid p + p \mid p.p \mid p||p \mid \sum_{d:D} p \mid c \rightarrow p \diamond p$$

A basic action a of a process may have a number of data arguments $d_1, ..., d_n$. The action τ denotes an internal step, which cannot be observed from the external world. Non-deterministic choice between two processes is denoted by the $+$ operator. Processes can be composed sequentially and in parallel by means of "." and "||". The sum operator $\sum_{d:D} p$ denotes (possibly infinite) choice among processes parameterized by d. $c \rightarrow p \diamond p$ is a conditional process, and depending on the value of the boolean expression c, the first or second operand is selected.

To enforce synchronization, the allow operator $\Delta_H(p)$ specifies the set of actions H that are allowed to occur. To show possible communications in a system and the resulting actions, the communication operator $\Gamma_C(p)$ is used. The elements of set C are so-called multi-actions of the form $a_1 \mid a_2 \mid \ldots \mid a_n \rightarrow c$, which intuitively means that action c is the result of the multi-party synchronization of actions $a_1, a_2, \ldots$ and a_n. There are a number of built-in data types in mCRL2, such as (unbounded) integers, (uncountable) reals, booleans, lists, and sets. Furthermore, by a **sort** definition one can define a new data type. A new process is declared by **proc**.

The semantics associated with the mCRL2 syntax is a Labeled Transition System system that has multi-action labeled transitions. A more elaborate description of mCRL2 and its features can be found in [**?**].

3 Transformation Methodology

3.1 The Rationale

Before describing the transformation methodology, we outline the rationale behind the choices we made, and why they differ from previous approaches that deal with SDs as behavioral description diagrams of a system. The approaches of which we are aware, and which use a process algebra formalism for a target model, translate each lifeline (hence, each object) into a sequential process[5]. However, this implies that an object behaves intrinsically sequentially, which is not the case. The object's individual processing capabilities are exposed via its methods. In a concurrent setting, multiple threads of a process (or even multiple processes sharing an object, if the implementation language permits this) could be invoking methods of the same object, thus, that object could be executing multiple behaviors at the same time.

Consider the simple SD in Fig. **??**. Even if we assume that the scenario is executed by a single OS process, treating each object as a sequential process is problematic. In the example, after invocation of *message1*, object a needs to know the choice that object b has made (modeled with the *alt* fragment), while this choice is based on local conditions that only b is aware of. Therefore, a

[5] The only exception made to this rule is when dealing with the *par* fragment.

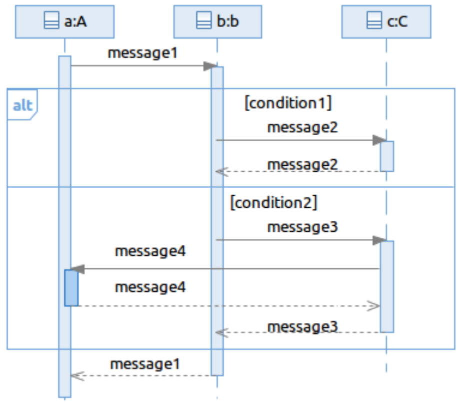


Fig. 3. Sequence Diagram example

cannot know whether its method *message4* will be invoked by object *c*, before a return from *message1* is received on the same lifeline. Consequently, a single process representation of the lifeline *a* should not control the reception of *message4* and execution of the associated behavior. Some approaches attempt to deal with this by making all involved processes aware of each others' local decisions, but this quickly becomes cumbersome and prone to errors, given how complex UML 2.x SDs can be made by nesting combined fragments.

We wish to preserve the OO paradigm in the transformation to a formal model. In this paradigm, unless an object is active, it does not control the invocation of its methods; it only responds by executing the associated behavior. An OS process is then essentially a chain of method invocations on objects. To achieve this, we associate an mCRL2 process *description* with each class method. A description (be it actual program code or a UML model) of a class method should not differ across objects that are instances of that class. Of course, at runtime objects execute only one of the multiple possible traces captured by that description, based on variable values. In our methodology, each such mCRL2 process *instance* carries data parameters that encode the class, object, and OS process instance to which the exhibited method behavior belongs at runtime. As an important consequence of this choice, *we preserve information on objects, classes and method calls in the mCRL2 model*, which makes it easy to reverse model-checking traces back into the UML domain.

3.2 The Approach

Figure **??** gives a general overview of our approach and implemented toolset. Both the source (UML) and the target (mCRL2) models adhere to their respective metamodels. Although any mature UML modeling tool with XMI export/import capabilities can be used, we chose IBM's Rational environment because of the excellent support for SDs and consistency preservation across multiple views of the same model. For parsing and manipulation of the XMI representations we use Eclipse's MDT-UML2 plugin, which implements the UML

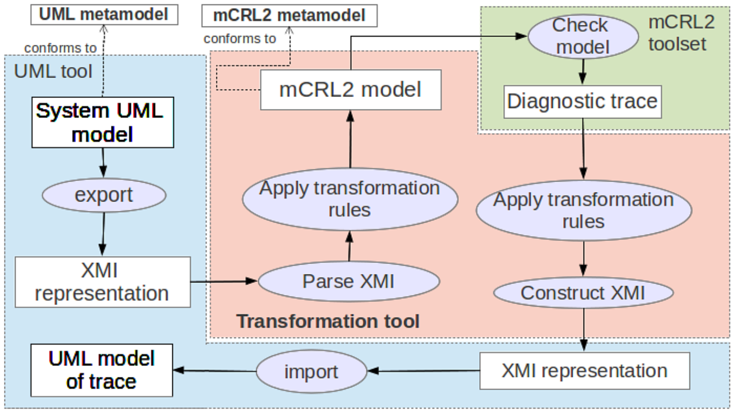


Fig. 4. Automated verification of UML models

2.x metamodel. The transformation rules define how to incrementally generate a model that conforms to a particular metamodel, from a model that conforms to another metamodel.

To achieve the basic idea of mapping each method along a lifeline into an mCRL2 process description, we process the ordered events along every lifeline individually, thus decomposing the lifeline into individual *ExecutionSpecifications*. We take into account both synchronous and asynchronous messages, so there are essentially 6 different types of message events (shown in Fig. **??**) that we consider: (1) *SendEvent_synchCall*; (2) *SendEvent_reply*; (3) *ReceiveEvent_synchCall*; (4) *ReceiveEvent_reply*; (5) *ReceiveEvent_asynchCall*; and (6) *SendEvent_asynchCall*. In UML metamodel terms, each of these events correspond to *MessageOccur-*

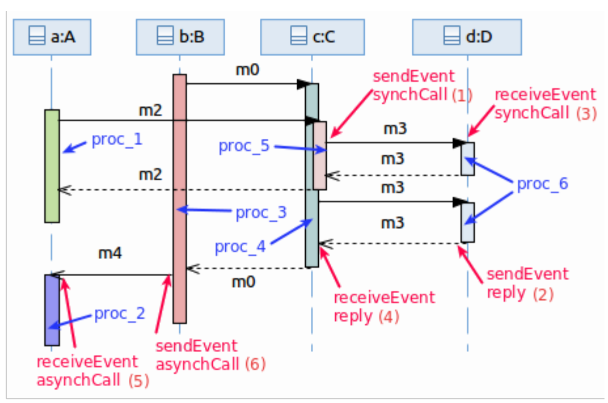


Fig. 5. Identifying event types along lifelines

renceSpecifications, and refer to the ends of each *Message*. Readers familiar with the UML metamodel are referred to Fig. **??** for a simplified class diagram of the Interactions metamodel, though the transformation process in the sequel can be understood without it. An *Interaction* (a Sequence Diagram) essentially encloses *Messages*, *Lifelines* and an ordered list of *InteractionFragments*. Each *Message* is accompanied by a pair of *MessageOccurrenceSpecifications*, and has a reference to the lifeline from which the message is sent and to which that message is received. Both *MessageOccurrenceSpecifications* and *CombinedFragments* (omitted from the figure for clarity) are specializations of *InteractionFragment*. We exploit these relationships in our algorithm for matching and transforming into an mCRL2 model.

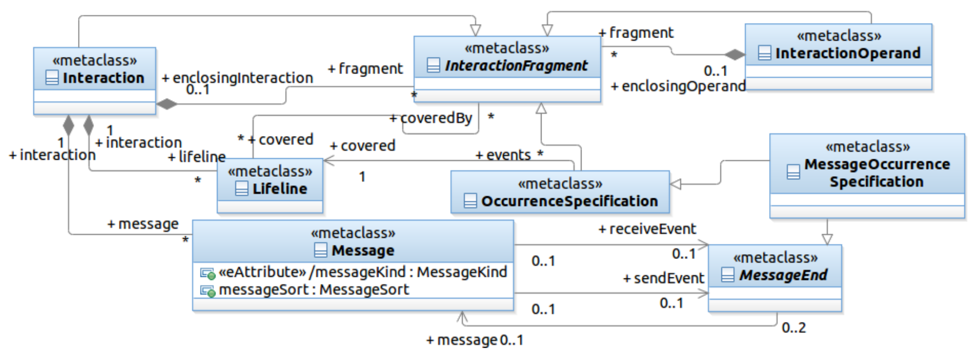


Fig. 6. Selected elements of the Interactions metamodel

All fragments of an *Interaction* are processed sequentially, and depending on their type, different mapping rules are applied. In case of *MessageOccurrence-Specifications*, each event type is treated separately. In case of a *CombinedFragment*, each *InteractionOperand*'s nested fragments are treated by applying the same procedure recursively.

procedure PROCESSFRAGMENTS($fragments \leftarrow interaction.getFragments()$)
  for each $fragment$ in $fragments$ **do**
    if $fragment.type = MessageOccurrenceSpecification$ **then**
      $message \leftarrow fragment.getMessage()$
      $arguments \leftarrow message.getArguments()$
      $event \leftarrow fragment.getEvent()$
      $objName, className \leftarrow fragment.getCovered.getObjectAndClass()$
      $theReadyStack \leftarrow readyProcessesPerLifeline.get(objName)$
      $theBusyStack \leftarrow busyProcessesPerLifeline.get(objName)$

Two in-memory stacks are kept for the currently "ready" and the "busy" methods on each lifeline, for cases of overlapping invocations. Busy methods are waiting (blocked) for a reply from another method execution that they have invoked, while ready processes are active, but not blocked. The message, arguments, class, and object corresponding to the handling event are retrieved.

      switch $event$ **do**

```
11:     case SendEvent_synchCall :                                    ▷ Case (1)
12:       mcrl2Process ← theReadyStack.pop()
13:       if insideInteractionOperand & firstEvent then
14:         operator ← getCombinedFragmentOperand()
15:         guard ← getCombinedFragmentOperandGuard()
16:         if operator = "alt" then
17:           mcrl2Process.addAltFragment(guard)
18:           [...]
19:         else if operator = "par" then
20:           mcrl2Process.addParFragment(guard)
21:         else if operator = "loop" then
22:           loopProcess ← newLoopProcess()
23:           mcrl2Process.addCallToLoopProcess(loopProcess)
24:           theReadyStack.push(mcrl2Process)
25:           loopProcess.addCondition(guard)
26:         end if
27:       end if
28:       mcrl2Process.addInvocation(
29:       "synch_call_send(id, className, objName, message, arguments)")
30:       theBusyStack.push(theProcess)
```

The above pseudocode handles the case of *SendEvent_synchCall* observed on a lifeline. For invocation to be possible, the object representing that lifeline must already be active in some method, at the same time **not** being blocked and awaiting for a return from a method call. We obtain that "ready" method (or mCRL2 *process*) from a stack, on line 12. In addition, this is the only valid UML case where it is possible for a *SendEvent_synchCall* to be the first event inside a *CombinedFragment*. The different fragment types are handled by associating a corresponding mCRL2 structure in the mCRL2 process (lines 14-27). The details of how each type of fragment is mapped to an mCRL2 structure will be explained after the algorithm walk-through, where also invocations (line 28) added to each process will be discussed.

```
31:     case SendEvent_reply :                                        ▷ Case (2)
32:       mcrl2Process ← theReadyStack.pop()
33:       mcrl2Process.setProcessed()
34:       mcrl2Process.addInvocation("
35:       synch_reply_send(id, className, objName, message, arguments)")
```

Once a method sends a reply (*SendEvent_reply*), that mCRL2 process description is finished. The process is removed from the appropriate "ready" stack, as it no longer exhibits behavior after this point.

```
36:     case ReceiveEvent_synchCall :                                 ▷ Case (3)
37:       findProcess ← findProcess(className, message)
38:       if findProcess = null then
39:         findProcess ← newProcess(className, message)
40:       end if
41:       if ¬findProcess.isProcessed then
42:         theReadyStack.push(findProcess)
```

$findProcess.addInvocation($
$"synch\_call\_receive(id, className, objName, message, arguments)")$
end if

Reception of a synchronous call on a lifeline indicates method invocation. Unless the mCRL2 process corresponding to this method has already been fully constructed, a new one is created, and pushed to the "ready" stack.

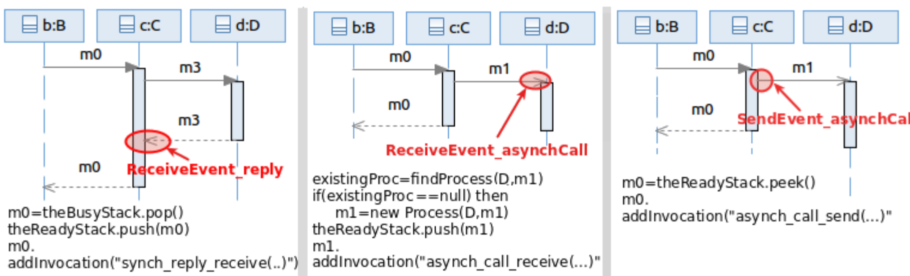


Fig. 7. Handling Case 4(left), Case 5(middle) and Case 6(right)

To get an intuition on how the algorithm proceeds, we treat Cases 4, 5, and 6 along with a graphical notation (Fig. **??**), rather than an algorithmic exposition. Upon reception of a reply from a method (Case (4)), the one initiating it is no longer blocked, so the corresponding mCRL2 process is removed from the "busy" stack and added to the "ready" one. Handling of Case (5) is analogous to Case (3), except that a different kind of invocation is added to the mCRL2 process. Finally, handling Case (6) is also analogous to Case (1), with the important difference being that the active method invoking this asynchronous call on another object will not be blocked after the call. This is why the process is not removed from the "ready" stack nor pushed to the busy one.

else if $fragment.type = CombinedFragment$ **then**
getOperandsForCombinedFragment($fragment$)
end if
end for
end procedure

procedure GETOPERANDSFORCOMBINEDFRAGMENT($fragment$)
$operands \leftarrow fragment.getOperands()$
for each $operand$ in $operands$ **do**
$processFragments(operand.getFragments())$ ▷ handle recursively
end for
end procedure

All operands that belong to a *CombinedFragment* are processed in turn, recursively handling all fragments (possibly also nested *CombinedFragments*) contained in them, by calling *processFragments* again. This concludes the basic algorithm for transformation of SDs of arbitrary complexity into mCRL2 process descriptions. When the algorithm is applied to the example in Fig. **??** it should result in 6 different process definitions. The data that messages convey, and which takes part in decisions, are owned by the objects representing the lifelines. This data is maintained by introducing a recursive "memory" process for each object within the mCRL2 specification, which carries all data values as parameters [**?**]. Most of the primitive data types used have a direct mapping into mCRL2 types. Strings are handled using mCRL2's abstract data type capabilities. Due to space limitations we will not explain the transformation rules for activity diagrams, although they are rather simple. We will demonstrate them on an example instead.

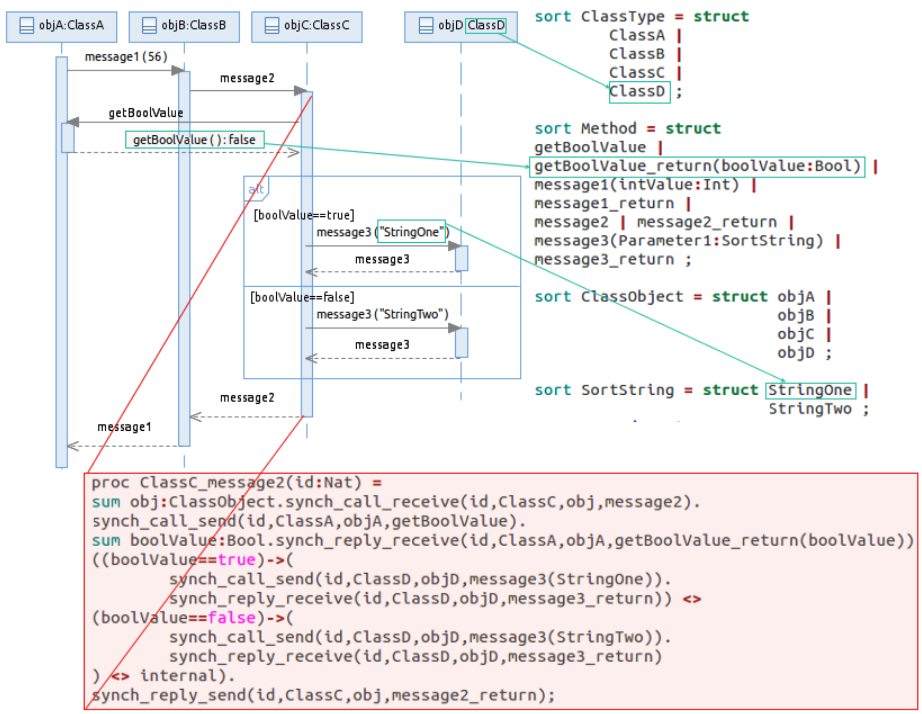
The different invocation types added to the mCRL2 processes in the course of the transformation are mCRL2 actions. They carry all parameters necessary for exchange of data between processes, and are used for synchronizing the processes on the corresponding send/receive events. The actions *synch_call_send* and *synch_call_receive* represent two ends of a synchronous message exchanged between two processes. Similarly, *synch_reply_send* and *synch_reply_receive* correspond to a reply message, while *asynch_call_send* and *asynch_call_receive* represent an asynchronous call. By applying the mCRL2 communication (Γ) and allow (Δ) operator in the following manner:

$$\begin{gathered}\Delta_{\{synch\_call,\ synch\_reply,\ asynch\_call\}} \\ \Gamma_{\{synch\_call\_send|synch\_call\_receive\ \rightarrow synch\_call,} \\ {}_{synch\_reply\_send|synch\_reply\_receive\ \rightarrow synch\_reply,} \\ {}_{asynch\_call\_send|asynch\_call\_receive\ \rightarrow asynch\_call\}}\end{gathered}$$

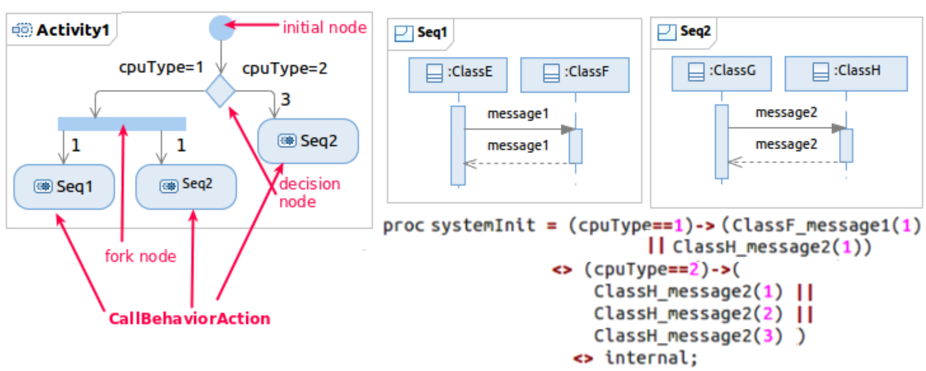
communication is enforced between processes as a result of the multi-action synchronization at the corresponding events.

Figure **??** demonstrates the transformation rules on a simple example. Classes, objects, method names and string values are represented by enumerated data types (**struct**). Replies are distinguished from their respective method calls, as they may also carry parameters. The mCRL2 summation (**sum**) operator is used for binding parameter identifiers to actual values when two processes communicate. This example illustrates how the *alt* fragment is translated into the mCRL2 conditional operator. To avoid deadlocks, and permit the process to continue in case none of the guards evaluates to true, the **internal** (τ) step is added as a last choice. The translation of the *opt* and *break* fragments uses the conditional operator in a very similar manner. In a *par* fragment, all communication inside each operand is set to run in parallel with the "||" mCRL2 operator. The *loop* fragment has a special treatment. It is translated into a recursive process referenced by the mCRL2 process representing the method active at the moment of entering the loop.

Finally, Fig. **??** shows how a simple system-level concurrency can be expressed in an AD, and how it is translated into an mCRL2 specification. ADs consist of *Actions* and *Control Nodes* connected by *Activity Edges*, with each diagram having one *Initial Node*. The control nodes have their intuitive meaning as in traditional flow charts, namely to depict concurrent flows (*Fork*), and decision points (*Decision*). While there are various action types, we are primar-



(a) Application of the SD transformation rules



(b) Application of AD transformation rules for system-level concurrency setup

Fig. 8. Transformation methodology by example

ily interested in the *CallBehaviorAction*, which invokes a referenced behavior directly. Since SDs are classified as behavior, we use this action type to provide the link between SDs and the concurrent system setup described in an AD. In the given example, depending on the condition, three concurrent OS process instances are started with the *Seq2* SD, or alternatively one instance of *Seq1* and *Seq2* in parallel. The *id:Nat* parameter that each mCRL2 process carries is used to bind it to an OS process in the system setup. It is also possible to add *Activity Final Node* for systems where execution terminates, by design.

4 Case Study:DIRACs Executor Framework

DIRAC [?] is the grid framework used to support production activities of the LHCb experiment at CERN. Jobs submitted via its interface undergo several processing steps between the moment they are submitted to the grid, to the point when their execution on the grid actualizes. The crucial Workload Man-

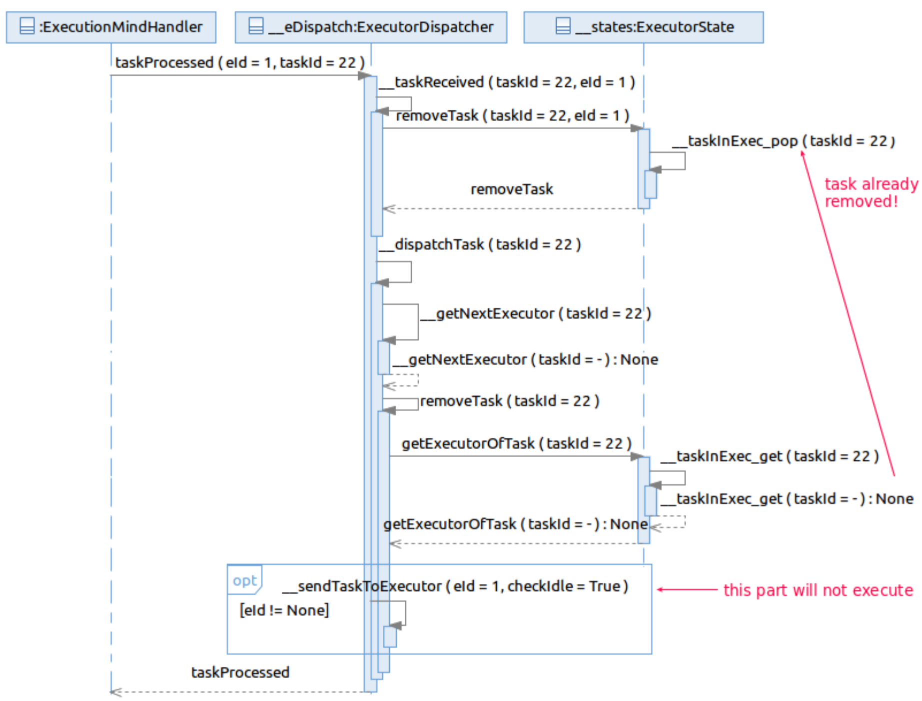


Fig. 9. SD trace showing a case of no-progress of tasks scheduling

agement components responsible for orchestrating this process are the *ExecutorDispatcher* and the *Executors*. Executors process any task sent to them by the ExecutorDispatcher, each one being responsible for a different step in the handling of tasks (such as resolving the input data for a job). The ExecutorDispatcher takes care of persisting the state of the tasks and distributing them amongst all the Executors, based on the requirements of each task. It maintains a queue of tasks waiting to be processed, and other internal data structures to keep track of the distribution of tasks among the Executors.

We used our toolset to generate an mCRL2 model based on the provided sequence diagrams of the Executor Framework. Using the mCRL2 toolset, we discovered a problematic behavior in the ExecutorDispatcher component, which results in no further progress of submitted tasks. Such behavior is shown in Fig. **??**, obtained by transforming the mCRL2 trace into an SD, using our toolset. The original trace is much longer (and available along with the model at [**?**]), here we only present the most important part for understanding the cause. Whenever a task has been processed by some of the Executors, the ExecutorDispatcher is notified (*taskProcessed(eId,taskId)*), and this removes it from its internal list of processing tasks. To further dispatch the task to another Executor, this task is removed from the ExecutorDispatcher's memory of processing tasks, followed by retrieval of the next responsible Executor. In case it was actually processed by the last Executor in the chain, the dispatcher attempts to retrieve its last Executor (*getExecutorOfTask(taskId))*, so that more tasks can be dispatched by this (now free) Executor. However, this information is already removed, as can be seen from the figure. As a result, the *opt* fragment (shown only for clarity, not generated by the toolset) will not be executed, and no further tasks waiting for this Executor will be dispatched. This was confirmed to occur in the real system, but the cause could not be identified by testing.

5 Conclusions and Future Work

We have presented an automated transformation methodology for verification of UML models, based on sequence and activity diagrams, preserving the object-oriented view of the system in the transformation. Both the input and the output of our implemented toolchain are expressed in UML, so engineers do not have to leave the UML environment, nor have a background in process algebra and model checking. We have further applied our toolset to a use case from the domain of distributed object-oriented software, in particular to a component of the DIRAC grid system used by the LHCb experiment at CERN, and discovered a logical flaw leading to no-progress.

Although the mCRL2 toolset automatically discovers deadlocks, model checking for application-specific properties requires the use of temporal logic on the generated model. Part of the future work is expressing modal μ-calculus formulas as sequence diagrams of accept/reject scenarios: behaviors that the designer wants to either confirm or avoid in the model. This can be easily achieved, given that μ-calculus formulas are action-based, and actions correspond to message exchanges in our transformation methodology. Furthermore, we plan to explore the limitations of this approach, given that process proliferation is likely to happen in larger systems. In our case study, we have as many as 50 processes, and already generating the entire state space can be problematic at this scale, given that the generated model is over 2000 lines of model code.

Besides discovering behavioral problems, automating performance analysis is on our road-map as well. UML provides extension mechanisms called *Profiles* which allow annotating models with quantitative information, such as expected execution time, resource usage, number of requests, etc. These quantities permit assessing the systems efficiency and reliability. Our approach can be easily extended in this direction, by taking into account not only message occurrences, but also annotated execution specifications within SDs. We can use the same target formalism for enhancing the models with such quantitative information. The CADP toolset [**?**] for analysis of stochastic models is well integrated with mCRL2 for this purpose.