JOURNAL OF OBJECT TECHNOLOGY

Online at http://www.jot.fm. Published by ETH Zurich, Chair of Software Engineering ©**JOT, 2008**

Vol. 7, No. 1, January-February 2008

Applying Model Checking to Concurrent UML Models

Patrice Gagnon
Department of Mathematics and Computer Science
University of Québec at Trois-Rivières, Canada

Farid Mokhati
Department of Computer Science
University of Oum-El-Bouaghi, Algeria

Mourad Badri
Department of Mathematics and Computer Science,
University of Québec at Trois-Rivières, Canada

Abstract

We present, in this paper, a framework supporting a formal verification of concurrent UML models using the Maude language. We consider both static and dynamic features of concurrent object-oriented systems. We focus on UML class, state and communication diagrams. The formal and object-oriented language Maude, based on rewriting logic, supports formal specification and programming of concurrent systems, as well as model checking. The major motivations of this work are: (1) translating concurrent UML diagrams into a Maude formal specification and (2) applying model checking to the generated specifications. The approach is illustrated using a concrete case study.

1 INTRODUCTION

UML (*Unified Modeling Language*) is a language for specifying, visualizing and constructing the artifacts of software systems [OMG05]. Nowadays, it is considered as the standard for object-oriented modeling. UML allows modeling various aspects of complex systems. However, UML models can present some ambiguities and inconsistencies as mentionned in several papers [Bruel00, Jean-Pierre05, Barnett04, Taibi03, Gallardo02]. UML suffers, in fact, from a lack of formal semantics [Astesiano98, Reggio04, Taibi03]. This weakness can lead to inconsistencies within the developed models. Using formal methods, particularly in the case of complex systems, presents notable advantages [Bruel00, Gallardo02, Taibi03, Meseguer03, Bowen03], like a simpler design without ambiguities, as well as a more complete documentation [Bowen03, Taibi03].

Concurrent programming is a powerful paradigm where activities can be executed concurrently [Garcia02, Gomaa00]. However, this way of programming has its specific problems. Concurrent threads executing on the same resources can lead to

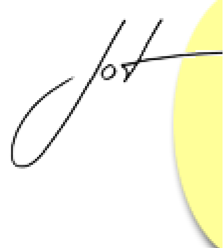
Cite this article as follows: Patrice Gagnon, Farid Mokhati, Mourad Badri: "Applying Model Checking to Concurrent UML Models", in *Journal of Object Technology*, vol. 7, no. 1, January-February 2008, pp. 59-84, http://www.jot.fm/issues/issue_2008_01/article1/

unwanted and unexpected situations. For example, deadlocks, livelocks or data inconsistencies may occur [Garcia02, Gallardo02]. In [Wegner90], Wegner describes the general concept of *active objects*. Contrary to usual objects, which are activated when receiving a message, *active objects* may be already executing when receiving a message. Therefore, these objects have at their disposal a message queue. Wegner also discusses the concepts of internal and external concurrency [Wegner90]. When discussing external concurrency, we mean two active objects executing on the same resource. Those active objects can have a single thread, therefore *sequential*. A *quasi concurrent* active object is an object for which the internal behavior shows concurrent features. Finally, a fully internal concurrent active object has several threads of execution. In this paper, we mainly focus on external concurrency, as two objects attempt to access the same resource.

Furthermore, *Model Checking* is a type of formal methods using a usually abstract model of a system to determine whether a series of properties are satisfied about that system [Chan98a, Chan98b, Cho99, Gallardo02, Merz00, Merz01, Lam04]. According to Gallardo & al. [Gallardo02], Model Checking is one of the most useful results of research in formal methods to increase the quality of software. A model checker is an automatic tool that compares two descriptions of the behavior of a system, one being considered as the requirement and the other the actual design [Gallardo02]. The main usefulness of such a technique is the fact that the automatic tool, upon encountering an error state, returns a counterexample illustrating the path taken to reach that state [Gallardo02, Merz00, Merz01, Lam04]. However, Model Checking suffers from a major problem, known as the *state space explosion problem* [Gallardo02]. Since a model checker confirms the validity of a given property by an exhaustive analysis of all execution paths, the state space can become very big very soon. Several solutions to this were proposed, for example symbolic model checking, abstraction, or on-the-fly analysis [Merz00, Wahl03].

In this paper, we present a formal framework supporting: (1) the translation of UML diagrams into a formal specification based on the Maude language and (2) the verification of some LTL properties using Maude's integrated model checker. We consider both static and dynamic features of concurrent object-oriented systems. We focus, in particular, on UML class, state and communication diagrams jointly. The approach is organized in four major steps. The first step consists of describing both static and dynamic features of an object-oriented system using UML class diagram (static structure), state (individual behavior of objects) and communication diagrams (collective behavior in terms of dynamic interactions between objects). The second step corresponds to an inter-diagrams validation process. The third step consists of automatically generating a Maude description from the considered UML diagrams. The fourth step consists of verifying some LTL properties using Maude's model checker [Eker02, Meseguer03, Clavel05]. We focus, in this paper, on applying Maude model checking techniques to concurrent UML diagrams. The translation process has been addressed in a previous paper [Mokhati06], but was subject of an extension to consider the particularities of concurrent object-oriented systems for both internal and external concurrency.

The remainder of the paper is organized as follows: In Section 2, we give a brief overview of related work. Section 3 briefly presents the UML diagrams we consider. Section 4 gives an overview of rewriting logic and Maude. We present, in Section 5, the main phases of the translation process and illustrate it using a concrete case study



in Section 6. Section 7 presents how Maude's model checker can be used to verify LTL properties. Finally, we give a conclusion and some future work directions in Section 8.

2 RELATED WORK

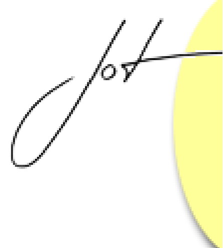
Funes & al. [Funes02] have formalized UML class diagrams using the formal specification language RSL (*RAISE Specification Language*). Using the same language, Meng & al. [Meng04] presented a formalization for state diagrams. Furthermore, Favre [Favre05] has proposed a translation process for class and package diagrams in the *NEREUS* language, based on the MDA (*Model Driven Architecture*) methodology. The obtained *NEREUS* specification is transformed into an object-oriented code (*Eiffel* language). Joao & al. [Araujo00] proposed a generation process to obtain *Object-Z* specifications from UML communication diagrams. In the same context, other UML diagrams have been considered [Dong00, MacColl99]. On the other hand, Paige and Brooke presented in [Paige04] a pragmatic approach integrating the object-oriented methodology BON (an alternative to UML) and the *Object-Z* language. Their approach was implemented using the *BON-CASE* tool [Paige02]. This tool supports formal specifications through pre-conditions, post-conditions and class invariants, whether for reasoning or for formal analysis [Paige02]. The majority of these papers have focused on translating to a formal specification only one feature of object-oriented systems, whether static or dynamic.

In the same context, other approaches have considered jointly class diagrams to describe static aspects of object-oriented systems and state diagrams to describe their dynamic aspects (individual behavior of objects). We can cite, among others, the U2B tool [Snook04]. U2B is a script file for Rational Rose that allows the conversion to the B language the Rational Rose model composed of class and state diagrams. However, the collective behavior of objects, in terms of dynamic interactions between objects, is not considered. Furthermore, H. Ledang & al. have developed the ArgoUML+B tool [Ledang03, Tigris02]. Of course, those proposals have considerably forwarded the domain by integrating static and dynamic features of object-oriented systems and their translation into formal specifications. However, the dynamic features considered in those papers, jointly to the static features, are only related to the individual behavior of objects. The collective behavior is not addressed.

Model checking issues are nowadays a very active research domain. Several tools are offered to assist developers in such a task. Some of those tools also support the formal verification of concurrent systems. SPIN is one of the most renowned model checkers available. It has been used in several works. In [Merz01, Merz00], SPIN has been used to model check state machines and collaborations together, and more particularly concurrent state machines using concurrent regions of a superstate. Their approach consists of verifying that the collective behavior of the objects specified by the collaboration diagram can be satisfied by a set of state-transition diagrams. The authors developed a tool called HUGO which compares the state charts descriptions defined in PROMELA, the input language of SPIN, to textual representations of collaborations. HUGO then uses SPIN to complete its verifications. This approach, however, does not integrate the structural aspects of the system. In [Canals03], the

authors present a tool, called NEPTUNE, which contains a module, called Checker, supporting the verification of UML models including some properties expressed using the OCL language. Furthermore, the tool BON-CASE [Paige02, Paige04] contains a reasoning engine which allows the verification of different properties, which is comparable to NEPTUNE. In [Chan98a, Chan98b], the authors used the RSML language (which is an alternative to UML to represent state charts) to formalize the TCAS II program (avionics anti collision software). They then use the SMV model checker to verify that their system accomplishes its tasks correctly. They also present a number of ways to reduce the state space explosion problem to acceptable levels. Their approach is one of symbolic model checking. Cho & al. [Cho99] propose the use of *APromela*, an extension of the Promela language designed to abstract actors, to apply model checking to concurrent systems using the SPIN model checker. Their approach proposes to translate *APromela* notations to Promela instead of building an entirely new tool. Lam & al. [Lam04, Lam05] propose to use the NuSMV model checker to perform model checking on concurrent systems formalized using π-Calculus. π-Calculus is a process algebra specifically designed to specify concurrent systems in which processes communicate through channels. The authors propose to translate π-Calculus notations, based on the Labelled Transition System (LTS), to Kripke structures notations on which is based the NuSMV input language. However interesting, this approach only focuses on the individual behavior of objects by verifying only formalized state transition diagrams. All these approaches mainly focus on verifying one or two aspects of object-oriented systems using model checking, namely the structural aspects and / or the individual behavior of objects. Only the approach proposed by Merz & al. [Merz01] considered the collective behavior of objects while leaving out the structural aspects.

We present, in this paper, a more global approach that allows the generation of a Maude formal specification integrating both static and dynamic (individual and collective) features of object-oriented systems. We use UML class diagrams to represent static features of an object-oriented system, and state and communication diagrams (respectively individual and collective behavior) to represent its dynamic features. We also focus on some aspects of concurrent object-oriented systems (external concurrency). The formal and object-oriented language Maude, based on rewriting logic, supports the formal specification and programming of concurrent systems [Meseguer92, Clavel99, McCombs03, Eker02, Meseguer03, Clavel05]. It also offers a model checking environment. Maude is a multi paradigm language [Meseguer03, Clavel05] that supports the semantics of concurrency (intra and inter-objects). Furthermore, the Maude language is supported by a tool, which allows validating the generated formal descriptions through simulation, as we will illustrate it in the next sections. Maude also integrates a model checker supporting the verification of Linear Temporal Logic (LTL) properties [Eker02, Meseguer03, Clavel05]. The Maude environment is still not very used. We wished to explore its possibilities in both formal specification and model checking aspects of concurrent UML diagrams.



3 UML DIAGRAMS

Class Diagram

UML class diagrams express the static structure of a system in terms of classes and relationships between classes. Classes are essentially organized through aggregation, inheritance or association relationships [Muller00, OMG05].

State Diagram

UML state diagrams [Muller00, OMG05] describe, using finite state machines, the life cycle of objects. Different types of event are defined by UML. We will focus only on the events of the "Call" type. State Diagrams can also be concurrent in nature [Börger00, Börger03, Schmidt99]. In fact, a composite state can have several orthogonal regions, each active at the same time that the composite state is active. This form of State Diagram models the internal concurrency of a class and models how several subtasks can be executed concurrently in the execution of a more global task accomplished by a class. Each orthogonal region of a composite state is seperated by a dashed line. Entry in each of these regions is done through the use of an initial state or through a fork structure (which then in turn requires a join structure when leaving the composite state).

Communication Diagram

UML Communication diagrams [OMG05], known as Collaboration diagrams in previous versions of UML [Booch98, Muller00] describe how a set of objects collaborate to accomplish a specific task. They emphasize the dynamic interactions between those objects (message exchanges) as well as their synchronization. A message sent can be so in two different manners: synchronous or asynchronous. The messages sent between two classes can be sequential (with messages of the same level having a sequence number incremented, for example 1, 2, 3, …), concurrent (two concurrent messages will have the same sequence number, differentiated only by an added name, for example 1a and 1b), or they can be both at the same time. The concept of synchronization between messages is accomplished using the "/" symbol. A synchronization point is used to note the necessity of the completion of a particular message before the execution of another can begin, for example.

4 REWRITING LOGIC AND MAUDE

Rewriting Logic

Rewriting logic, having a sound and complete semantics, was introduced by Meseguer [Meseguer92]. It allows describing concurrent systems [Meseguer03, McCombs03, Eker02, Clavel05]. This logic unifies all the formal models that express concurrency [Meseguer90]. The rewriting rules are of the form $R : [t] \rightarrow [t'] \ if \ C$, which indicates

that, according to rule *R*, term *t* becomes *t'* if a certain condition *C* is verified. Condition *C* is optional, so rules can be of the unconditional form.

Maude

Maude is a specification and programming language based on rewriting logic [Meseguer92, Clavel99, Clavel05, McCombs03]. Three types of modules are defined in Maude. *Functional* modules allow defining data types and their functions. *System* modules allow defining the dynamic behavior of a system. This type of module augments the functional modules by introducing rewriting rules. Finally, *object-oriented* modules, which can be reduced to system modules, offer a more appropriate syntax to describe the basic entities of the object paradigm. Subsection *Model checking and Maude* of Section 7 will deal more specifically on how Maude can be used for model checking. Fig. 1 shows a small Maude program.

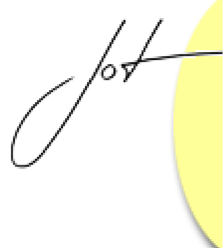
```
1.  sort Configuration .
2.  sort Object .
3.  sort Msg .
4.  subsort Object < Configuration .
5.  subsort Msg < Configuration .
6.  op null : -> Configuration .
7.  op_ _ : Configuration Configuration -> Configuration
    [assoc comm id : null] .
```

Fig. 1. Short program in Maude

The example shown in Fig. 1 gives the definition of three types: Configuration, Object and Msg (those two last being subtypes of Configuration). In the case where there is no floating messages or live objects, the global configuration of the system is empty. The construction of a new configuration, in terms of other configurations, is done with the operation given on line 7. This operation satisfies the structural laws of associability and commutability and possesses a neutral element called *null*.

5 TRANSLATING UML DIAGRAMS INTO MAUDE

The adopted translation process consists of systematically deriving a Maude formal specification from an analysis of the UML class, state and communication diagrams. Fig. 2 presents the steps of the translation process we elaborated in [Mokhati06]. The diagrams go through a first verification step to make sure, for example, that each message sent to a destination object in the communication diagram exists in the state diagram and that it is accessible. During the translation process of the considered UML diagrams, several Maude modules are generated. Fig. 3 shows those modules. Please note that modules in bold are object-oriented modules, while all others are system modules. As for programming purposes, all object-oriented notations will be reduced to its system form.



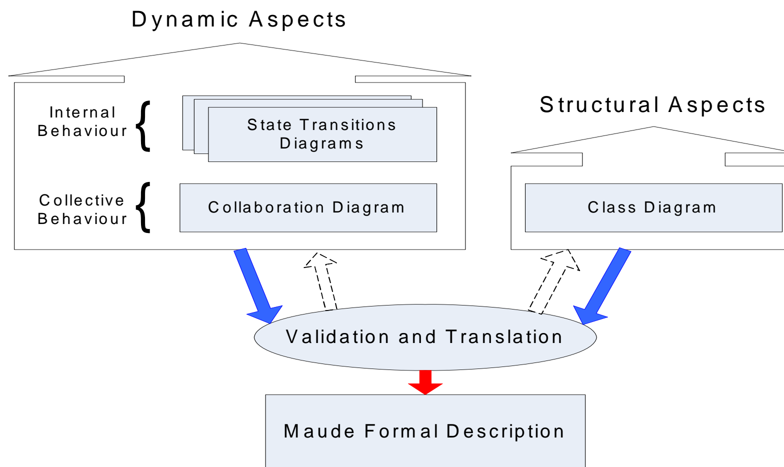


Fig. 2. Overview of the Translation Process

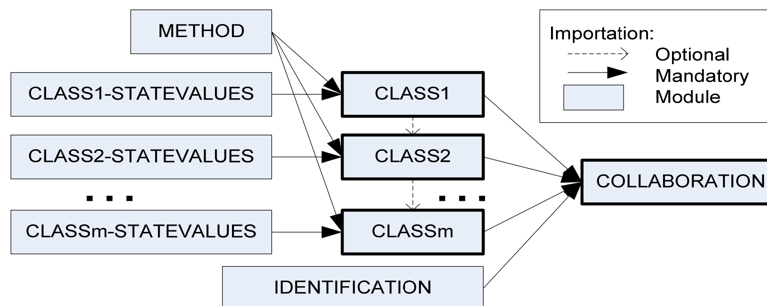


Fig. 3. Generated modules

The functional module *METHOD* (see Fig. 4) contains all the types used to describe a method. Types *Parameter* and *ParameterList* are generic. They describe the type of parameters a method uses. Furthermore, *ResultType* and *Void* describe the type of the result returned by the method. *ResultType* is generic, and *Void* is a particular case of *ResultType*. The operation (_,_) is a constructor for the parameter list of a function.

```
fmod METHOD is
  sorts  ParamaterList ResultType Paramater Void .
  subsort Paramater < ParamaterList .
  subsort Void < ResultType .
  op EmptyParamaterList : -> ParamaterList .
  op _,_  : Paramater ParamaterList -> ParamaterList .
endfm
```

Fig. 4. The *METHOD* module

We associate to each state diagram a functional module for which the name is the concatenation of the class' name and the string '*STATEVALUES*'. The functional module *IDENTIFICATION* is generated to describe the identification mechanism of the objects of the communication diagram. For each class of the class diagram, we associate an object-oriented module bearing the same name as the class, while adopting a generic form for the classes (Fig. 5). In the case where one of such a class is in relation to other classes in the class diagram, the module associated to it must

import all the other modules associated to those classes. The class is declared in a module with an attribute called *State* and for which its type is declared in the corresponding functional module. This attribute is automatically added to all classes to model its objects' state. It has for objective to explicitely note the objects' state. In the case of an aggregation class, an identification list of all the aggregated classes must also be present as attribute to the class. The generic form of classes also shows an open attribute list and a regional states list, which is explained further on.

```
class ClassName | State : ClassNameStateValues [, RegSubstateAtt]
[, ComponentList] [, AttributeList] .
```

Fig. 5. Generic form adopted for the classes, with optional regional substates for concurrent composite states, an optional component list and an opened list of attributes

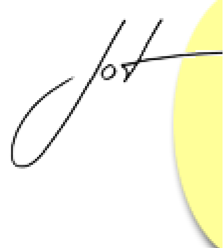
The modules in which are declared the classes also contain the declaration of the class' methods. Each of the functions are declared using the generic form shown in Fig. 6. *ParameterList* and *ResultType* were introduced in the *METHOD* module (Fig. 4).

```
op FunctionName : ParamaterList -> ResultType .
```

Fig. 6. Form adopted for the methods

The translation process was mainly developed for traditional sequential programs. However, concurrent systems require slight modifications to the adopted process. Since Concurrent Object-Oriented Systems (COOS) are based on objects, the basic structure remains the same and so does the general translation process. The main element in which more attention is required when translating external concurrency is the fact that two (ore more) objects are active (executing) at the same time. Therefore, rewriting rules must be produced accordingly in the COMMUNICATION module. See below for further details on this module. As for internal concurrency, the best option is to model the class with more State attributes, one for each of the orthogonal regions of its concurrent composite state. For example, a class that has a concurrent composite state with 2 orthogonal regions, aside from the main State attribute described above, there will be two more. This also means that the 'STATEVALUES' module for that class will also define two new sorts with their respective values, in the same manner defined earlier. We also introduce an Inactive value for those "regional" substates for when the object is not in its concurrent composite state. All the while an orthogonal region is active within a concurrent composite state, the object remains in this composite state, and only the "regional" states' values vary. When all the orthogonal regions have completed their execution, the object can now leave its concurrent composite state. Then, all "regional" states are put in their Inactive state.

The object-oriented module *COMMUNICATION* is the principal one generated by our approach. It imports all the other modules. In it, we extend all the other object-oriented modules by describing the behavior of the different objects involved in the communication diagram using rewriting rules. Each message exchanged between two objects of the communication diagram is translated in the form of a *ComingMsg* (Fig. 7).



```
op ComingMsg :  ResultType Receiver -> Msg  .
```

Fig. 7. Form adopted for the messages

With this message, we specify two things. On the first hand, we identify the destination object (*Receiver*) and, on the other hand, the result type of the operation to be executed. In fact, each sending of a message in the communication diagram corresponds to a Call Event, launching a transition in the state diagram of the destination object. This transition is described in this module whether by an unconditional rewriting rule in the case where the sending of the message is not linked to a condition or by a conditional rewriting rule otherwise. To implement the concept of *Synchronization Point* of the messages sent within a communication diagram, we introduce a new message called *IsAccomplished* (see Fig. 8). The rewriting rule that implements a transition corresponding to the sending of a message on which depends other messages must generate a number of *IsAccomplished* messages equal to the number of messages to be sent. To better illustrate the use of the *IsAccomplished* synchronization message, consider the *ProducerSleep* message of Fig. 11, where it is required that message *Put* be completed for it to be executed.

```
op IsAccomplished : ResultType Receiver -> Msg
```

Fig. 8. Form of the synchronisation message

The *IsAccomplished* message does not represent a message sent between two objects in the communication diagram. It must be interpreted as an indication that the sending of the message is terminated. As mentionned previously, we focused in this paper on external concurrecy. The considered example will not show any internal concurrency. However, internal concurrency has been considered in our work in others case studies (not adressed in this paper).

6 CASE STUDY

Presentation

To illustrate our approach, we present a simple, yet concrete case study. In the present section, only the translation of the example's UML models to Maude formal specifications is introduced. The formal verification of the models using Model Checking techniques is addressed in the next section.

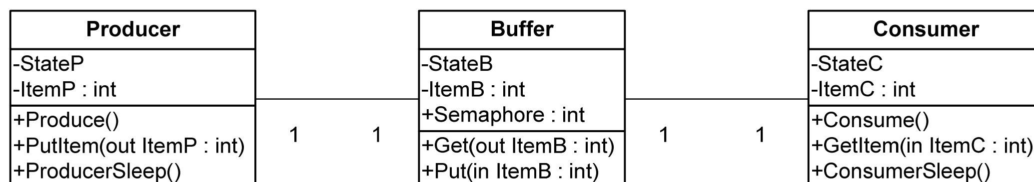


Fig. 9. Class Diagram of the system

The example we chose to illustrate our approach is a simple concurrent object-oriented system. It is based on the classic *Producer – Consumer* problem. Our example is an adaptation between the examples presented in [Gomaa00] and [Meseguer03]. Fig. 9 presents the UML Class Diagram associated to this system. Our system is then composed of 3 classes. The first class, called *Producer*, is designed to have objects generating integer elements (the *Produce* function) as information to transmit (through the *PutItem* function). The class has also a *ProducerSleep* method that puts an object into a suspended state while the memory buffer is unavailable to receive new information. The *Consumer* class is designed to have objects that will be getting information from a memory buffer through its *GetItem* function and use that information in some manner with the *Consume* function. This class also possesses a *ConsumerSleep* function that, similarly to class *Producer*, puts the objects of that class into a suspended mode while the buffer has no new information to transmit. The last class, *Buffer*, is the memory buffer of the system. It has an *ItemB* attribute, which is the memory buffer in itself, and is of size 1.

Therefore, the *Buffer* can contain only one integer information at a given time. Functions *Put* and *Get* are used respectively to collect information coming from a *Producer* object, and transmit that information to a *Consumer* object. The public attribute *Semaphore* will be used for coordination purposes between the *Consumer* and the *Producer* of the system. It will take only values 0 or 1, interpreted as follows: when *Semaphore == 1*, the memory buffer is free and can be used by either a *Producer* object to put a new element, or by a *Consumer* object to get an existing element. When *Semaphore == 0*, the memory buffer is already used by an object and is locked, preventing any other object the possibility of using the shared resource. Figure 10 presents the corresponding State-Transition Diagrams. Diagram (10.a) is associated to the *Producer* class, where the transition associated to a procedure call of the *PutItem* function is guarded by a condition on the *Buffer* object's *Semaphore* attribute. The *GetItem* procedure call transition of Diagram (10.b) associated to a *Consumer* object is similar. Finally, diagram (10.c) is associated to a *Buffer* object.

The system we consider in our example present concurrent aspects since objects of classes *Producer* and *Consumer* can attempt to access the *Buffer* object at the same time. Each object of those two classes will then have its own process within the system and are considered as *Active Objects*.

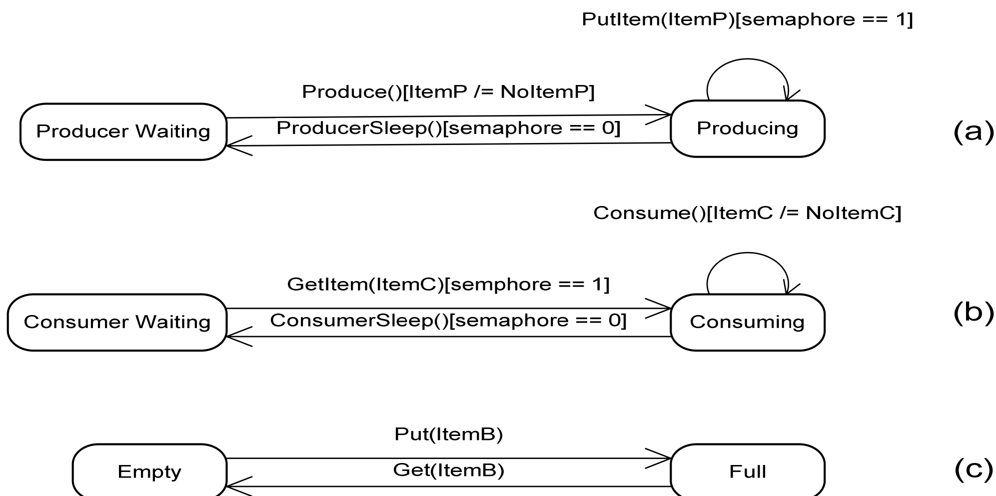
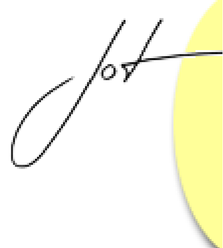


Fig. 10. State-Transition Diagrams for classes (a) *Producer*, (b) *Consumer* and (c) *Buffer*



In the communication diagram of Fig. 11, we observe a *Producer* object attempting to write information in a *Buffer* object's memory and at the same time a *Consumer* object attempts to read the information contained in the *Buffer* object. Since the *PutItem* and *GetItem* functions of classes *Producer* and *Consumer* respectively are guarded with the use of *Buffer*'s *Semaphore* attribute, simultaneous reading and writing on the shared resource *Buffer* is not allowed.

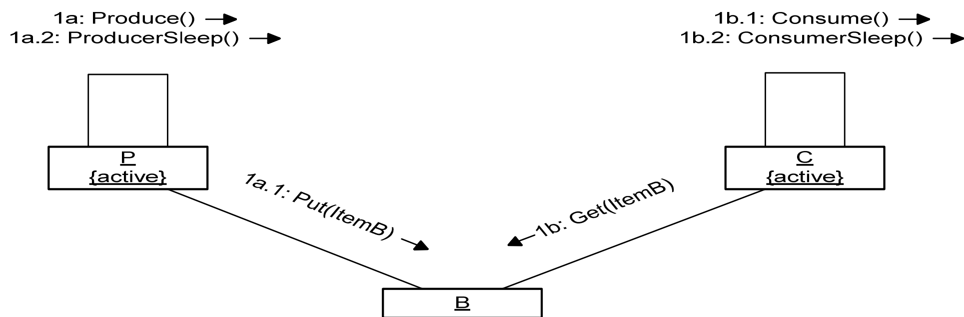


Fig. 11. Communication Diagram of the System

Application of the Translation Process

In this section, we illustrate the application of the translation process (Section 5) to the example described above. We focus here on the translation to Maude notations. Three Maude functional modules are introduced to describe the state values of each class present in the system. Those three modules are named *PRODUCER-STATEVALUES*, *CONSUMER-STATEVALUES* and *BUFFER-STATEVALUES*, respectively for classes *Producer*, *Consumer* and *Buffer*. For space limitation reasons, only one of those modules is shown here, namely *PRODUCER-STATEVALUES* (Fig. 12).

```
fmod PRODUCER-STATEVALUES is
  sort ProducerStateValues .
  ops Producing ProducerWaiting : -> ProducerStateValues .
endfm
```

Fig. 12. Module PRODUCER-STATEVALUES

A module *IDENTIFICATION* (Fig. 13) imports the predefined *CONFIGURATION* module. This module contains the definition of types *Poid*, *Coid* and *Boid* which describe the identification mechanism of the objects *P*, *C* and *B*, instance of classes *Producer*, *Consumer* and *Buffer* respectively.

```
fmod  IDENTIFICATION  is
  including CONFIGURATION .
  sorts Poid Coid Boid Receiver .
  subsort Poid Coid Boid < Oid .
  subsort Receiver  < Poid Coid Boid .
endfm
```

Fig. 13. Module *IDENTIFICATION*

Knowing that the system we study has 3 classes (Producer, Consumer and Buffer), three object-oriented modules are generated by our approach, respectively named PRODUCER, CONSUMER and BUFFER, which will introduce each of the classes and their respective methods. For space limitation reasons, only one of those modules is given, namely the object-oriented module PRODUCER in Fig. 14. The Producer class is defined with 2 attributes, StateP will contain information about the current state of the object (for which the possible values are given in module PRODUCER-STATEVALUES of Fig. 12), and an attribute ItemP that will contain the produced item that the Producer object will transmit to the Buffer. The class has 3 methods. The first is named Produce and is the method that will create an item of information destined to be transmitted to the Buffer. The second method is called PutItem and is the actual method that will transmit the information to the Buffer object by a method call. The last method is called ProducerSleep, and has for objective to put the Producer object into a suspended mode when the transmission to the Buffer object is completed. Finally, the NoItemP operator is actually a new possible value for integer variables, and will represent the fact that the ItemP attribute of a Producer object contains no value.

```
mod PRODUCER is
  protecting METHOD PRODUCER-STATEVALUES INT .
  sort Producer .
  subsort Producer < Cid .
  *** Class and Attributes
  op Producer : -> Producer .
  op StateP :_ : ProducerStateValues -> Attribute .
  op ItemP :_ : Int -> Attribute .
  *** Methods
  op Produce : ParameterList -> Void .
  op PutItem : ParameterList -> Void .
  op ProducerSleep : ParameterList -> Void .
  op NoItemP : -> Int .
endm
```

Fig. 14. Module *PRODUCER*

Module *COMMUNICATION* is the primary module generated. It contains rewriting rules modeling the behavior of the system concerning the realization of a specific task given in the communication diagram of Fig. 11. Specifically, the task consists on a concurrent get and put access to a memory *Buffer* by two active objects. Fig. 15 shows part of the *COMMUNICATION* module. As specified earlier, the module imports all the other modules defined namely *IDENTIFICATION*, *PRODUCER*, *CONSUMER* and *BUFFER*.

```
mod COMMUNICATION is
  protecting IDENTIFICATION PRODUCER CONSUMER BUFFER .
  subsort Int < Parameter .
  *** Utility Messages *********************************
  op ComingMsg : Event Receiver -> Msg .
  op IsAccomplished : Event Receiver -> Msg .
  *** Variables ****************************************
  var P : Poid .   var sema : Nat .
  var C : Coid .   var item : Int .      var B : Boid .
  *** Producer's behavior ******************************
  crl [ProduceItem]:  ComingMsg(Produce( EmptyParameterList), P)
        < P : Producer | StateP : ProducerWaiting, ItemP : item >
```

```
      < B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : sema >
      =>
      < P : Producer | StateP : Producing, ItemP : 5 >
      < B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : sema >
      IsAccomplished( Produce( EmptyParameterList), P)
      ComingMsg( Put( 5 ), B) if item == NoItemP .
     crl [PutItem]: ComingMsg( Put( 5 ), B)
      IsAccomplished( Produce( EmptyParameterList), P)
      < P : Producer | StateP : Producing, ItemP : 5 >
      < B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : sema >
      =>
       < P : Producer | StateP : Producing, ItemP : NoItemP >
       < B : Buffer | StateB : Full, ItemB : 5, Semaphore : 0 >
       ComingMsg( ProducerSleep( EmptyParameterList ), P)
       IsAccomplished( Put( 5 ), B) if sema == 1 .
 ... emdm
```

Fig. 15. Part of the *COMMUNICATION* module

The part of the module shown in Fig. 15 concerns more closely the behavior of objects of the *Producer* class. Maude being particularly developed for the modeling of concurrent systems (as stated in Section 4), it is therefore appropriate for the modeling of active objects like we have in the system we consider. Two rewriting rules are shown in Fig. 15. Rule '*ProduceItem*' shows the behavior of such an object when it receives a '*Produce*' message to start producing integer element to transmit to the *Buffer* object. This method then generates an integer element and places it in the *ItemP* attribute. For the execution to take place, the *ItemP* attribute must not already contain an element (condition of the translation rule). A *IsAccomplished* message is generated to allow the execution of the second rewriting rule. The second rule, '*PutItem*' is actually intended to model the execution of the *PutItem* method. This method uses the *Put* function of a *Buffer* object to transmit the integer element to the shared memory, while insuring this resource is not already used by another object (guard condition). A *IsAccomplished* message is also generated so that the third rule can be executed ('*ProducerSleep*'), effectively putting the *Producer* object into its *ProducerWaiting* state. The *Producer* object then waits until the shared memory of *Buffer* is once again available to receive new information. See Fig. 11 for further information.

Validation of the Generated Description

Concerning the verification of the developed models, rewriting logic and Maude are very versatile with simulations, since it allows the selection of a personalized initial configuration from which to start the simulation. It is very useful when attempting to verify part of a system while not compromising the rest of it. The first verification we attempt is started from the initial configuration shown in Fig. 16. This configuration is composed of two objects, *P* and *B* of classes *Producer* and *Buffer* respectively, both containing no item. We also have a *Produce* message sent to *P*. The results of this verification are given in Fig. 17.

```
< P : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
< B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : 1 >
ComingMsg( Produce( EmptyParameterList ), P )
```

Fig. 16. Initial configuration

The results (Fig. 17) can be interpreted as follows. Following the execution of message *Produce*, object *P* has produced an integer element, here 5, and transmitted it to the shared memory of a *Buffer* object. *P* is then in its *ProducerWaiting* state and awaits the next time *B* is available and in its *Empty* state. Finding a new *ComingMsg* to produce a new item is correct knowing that the classic *Producer – Consumer* problem is a perpetual process that goes on until stopped.

```
ComingMsg( Produce( EmptyParameterList ), P )
< P : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
< B : Buffer | StateB : Full, ItemB : 5, Semaphore : 1 >
```

Fig. 17. Result of the unlimited rewriting of the initial configuration of Fig. 16

We will now attempt to verify the behavior of a *Consumer* object. To perform this verificaiton, the initial configuration of Fig. 18 is used, and the results are given in Fig. 19. This initial configuration is composed of a *C* object and a *ComingMsg* to try and get an element available from the *Buffer*. The initial configuration also shows a *B* object of the *Buffer* class, already contaniting an element (here, 5). Its *StateB* attribute is set to *Full*, and *Semaphore* to 1 to signify *B* is not currently used by another thread.

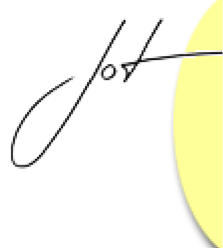
```
ComingMsg( Get( 5 ), B )
< C : Consumer | StateC : ConsumerWaiting, ItemC : NoItemC >
< B : Buffer | StateB : Full, ItemB : 5, Semaphore : 1 > .
```

Fig. 18. An initial configuration

The results of the rewriting of Fig. 18's initial configuration can be interjpreted as follows. *C*, after getting and consuming an element of information from *Buffer* is in its *ConsumerWaiting* state, awaiting a new integer information available in the *Buffer*. *B* is now *Empty*, since the information it contained was taken by *C*, and the system generates a new *ComingMsg* destined to *C* to try and get new information from the *Buffer*, conforming to the perpetual execution untill stopped idea. Having verified the behavior of objects of the *Producer* and *Consumer* classes respectively, we can now proceed on to the verificaiton of the behavior of the entire system altogether.

```
ComingMsg( Get( 5 ), B )
< B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : 1 >
< C : Consumer | StateC : ConsumerWaiting, ItemC : NoItemC >
```

Fig. 19. Result of the unlimited rewriting of the initial configuration of Fig. 18



```
code PC - Notepad
File  Edit  Format  View  Help
crl [PutItem]:
        ComingMsg( Put( 5 ), B)
        IsAccomplished( Produce( EmptyParameterList), P)
        < P : Producer | StateP : Producing, ItemP : 5 >
        < B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : sema >
        =>
        < P : Producer | StateP : Producing, ItemP : NoItemP >
        < B : Buffer | StateB : Full, ItemB : 5, Semaphore : 0 >
        IsAccomplished( Put( 5 ), B) ComingMsg( ProducerSleep( EmptyParameterList ), P)
        if sema == 1 .

crl [ProducerSleep]:
        IsAccomplished( Put( 5 ), B)  ComingMsg( ProducerSleep( EmptyParameterList ), P)
        < P : Producer | StateP : Producing, ItemP : NoItemP >
        < B : Buffer | StateB : Full, ItemB : 5, Semaphore : sema >
        =>
        < P : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
        < B : Buffer | StateB : Full, ItemB : 5, Semaphore : 1 >
        ComingMsg(Produce( EmptyParameterList), P)
        if sema == 0 .

endm

rew [6] ComingMsg(Produce( EmptyParameterList), P) ComingMsg( Get(5), B)
        < P : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
        < C : Consumer | StateC : ConsumerWaiting, ItemC : NoItemC >
        < B : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : 1 > .
Ln 21, Col 1
```

Fig. 20. Part of the developed code

Fig. 20 shows part of the Maude code we developed. It shows, on the first hand, rewriting rules '*PutItem*' and '*ProducerSleep*' that model part of the behavior of the *Producer* objects and, on the second hand, one rewriting command issued to the Maude environment. This simulation is started from an initial configuration where we have three different objects, *P*, *C* and *B*, respectively of classes *Producer*, *Consumer* and *Buffer*, in their initial states, as well as incoming messages *Produce* and *Get* as shown in the communication diagram of Fig. 11. The number of rewriting steps is limited to 6 since the system is modelled as an infinite loop, and is therefore not terminating.

```
C:\Program Files\MaudeFW\maude.exe
==========================================
rewrite [6] in COMMUNICATION : <<<< B : Buffer | StateB : Empty,ItemB :
    NoItemB,Semaphore : 1 > < C : Consumer | StateC : ConsumerWaiting,ItemC :
    NoItemC >> < P : Producer | StateP : ProducerWaiting,ItemP : NoItemP >>
    ComingMsg(Get(5), B)> ComingMsg(Produce(EmptyParameterList), P)> .
rewrites: 12 in 50116ms cpu (1ms real) (0 rewrites/second)
result [Configuration]: ComingMsg(Produce(EmptyParameterList), P) ComingMsg(
    Get(5), B) < P : Producer | StateP : ProducerWaiting,ItemP : NoItemP > < B
    : Buffer | StateB : Empty,ItemB : NoItemB,Semaphore : 1 > < C : Consumer |
    StateC : ConsumerWaiting,ItemC : NoItemC >
Maude> _
```

Fig. 21. Results of the rewriting of Fig. 20

Fig. 21 shows the results of this rewriting command. The limited rewriting grants us the possibility of visualizing that the system behaves properly. As we can see, the system eventually returns to its actual initial state, which is exactly what it should do according to the classic *Producer – Consumer* problem.

7 APPLYING MODEL CHECKING

In our opinion, the verification of the collective behavior of a group of objects that are collaborating to accomplish a specific task begins with the verification of the individual behavior of the objects. We propose, in what follows, an incremental process for the definition and verification of properties to be verified within our system. The properties we propose are defined in LTL. The next subsection exposes the generic process to use Maude's model checker. We then propose 4 properties relevant to the individual behavior of objects *P*, *C* and *B*, instances of classes *Producer*, *Consumer* and *Buffer* respectively. The following subsection proposes 3 properties related to the collective behavior of those same objects. The final subsection describes the adopted process to verify the proposed properties.

Model Checking and Maude

As was illustrated in Section 6, an object-oriented system can be described with relative ease using the Maude language. With the help of a single rewriting rule, we can express many things: the consumption of floating messages, the sending of new messages, the destruction of objects, the creation of new objects, as well as state changes. However, Maude offers another important tool in the verification of a system: it has an integrated model checker that verifies LTL properties in the system under development [Clavel05, Eker02, MacColl99, Meseguer90, Meseguer92, Meseguer03]. However, using that model checker implies the use of a technique, which we introduce briefly in this subsection. We then use it to perform more advanced verifications on our example. Maude supports model checking with LTL properties mainly for its simplicity and the well defined decision procedures it offers [Clavel05, McCombs03]. Fig. 22 illustrates the defined LTL operators. Other operators exist, but can be derived from those primary operators.

```
fmod LTL is ...  *** defined LTL operators
 op _->_ : Formula Formula -> Formula .        *** implication
 op _<->_ : Formula Formula -> Formula .       *** equivalence
 op <>_ : Formula -> Formula .                 *** eventually
 op []_ : Formula -> Formula .                 *** always
 op _W_ : Formula Formula -> Formula .         *** unless
 op _|->_ : Formula Formula -> Formula .       *** leads-to
 op _=>_ : Formula Formula -> Formula .              *** strong
implication
 op _<=>_ : Formula Formula -> Formula .             *** strong
equivalence
... endfm
```

Fig. 22. A module in Maude implementing the operators of LTL logic

For the definition of LTL properties, we need an operator to determine the result, *True* or *False*, of a property in a certain system state. For that, the |= operator is introduced in the predefined *SATISFACTION* module (Fig. 23).

```
fmod SATISFACTION is
 protecting LTL .
 sort State .
 op _|=_ : State Formula ~> Bool .
endfm
```

Fig. 23. The *SATISFACTION* module

It is then possible to define diverse system properties in a new module that imports both the *SATISFACTION* module and the module or modules defining the system to be studied. Fig. 24 shows the *M-PREDS* module, in which predicates about the system are defined. Those predicates will be used to later define LTL properties about the system. Also note that *M* symbolizes a module in which the studied system is modelled.

```
mod M-PREDS is
  protecting M .
  including SATISFACTION .
  subsort Configuration < State .
  ... endm
```

Fig. 24. The *M-PREDS* module

The next step in the model checking process of Maude consists on the definition of a final module called *M-CHECK* in which all the elements are bound together for the verification. We also introduce all the initial configurations used in the verification process in this module. Figure 25 shows the *M-CHECK* module.

```
mod M-CHECK is
  including M-PREDS .
  including MODEL-CHECKER .
  including LTL-SIMPLIFIER .
  ... endm
```

Fig. 25. The *M-CHECK* module

The final step consists on launching the verification calls into the Maude system using the *modelCheck* function of module *MODEL-CHECKER*. (Fig. 26).

```
fmod MODEL-CHECKER is
  including SATISFACTION .  ...
  op counterexample : TransitionList TransitionList ->
     ModelCheckResult [ctor] .
  op modelCheck : State Formula ~> ModelCheckResult .
  ... endfm
```

Fig. 26. The *MODEL-CHECKER* module

To give a small overview of a typical model checking call using Maude, Fig. 27 shows the generic form used to launch a verification. In this call, *initial_state* represents an initial configuration of the system where the verification should start, and *LTL_property* expresses a desirable or non desirable requirement that the system should verify. This LTL property is the one that is getting verified with this call.

```
modelCheck( initial_state, LTL_property) .
```

Fig. 27. A typical model checking call

Properties Related to the Individual Behavior of Objects

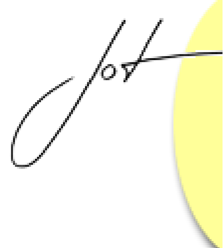
In this section, we propose 4 properties related to the individual behavior of objects *P* and *C*. Properties 1 and 2 concern the behavior of *P*, and properties 3 and 4 are relevant to the behavior of *C*.

- **Property 1:** *[] PutingItem("P")*
  Starting the verification from initial configuration *initial1* (see Fig. 28), this property expresses that the *Producer* is always in its critical section, namely transmitting its information to the *Buffer*. *[]* is the *Always* temporal operator. This property specifies that *P* is always in its critical section and not leaving it and represents a non desirable characteristic.
- **Property 2:** *~ [] ProducerSleeping("P")*
  Starting the verification from initial configuration *initial1* (see Fig. 28), this property verifies that the *Producer* object is not always in its *ProducerWaiting* state. ~ is the *Not* temporal operator. The *Producer* not always in its waiting state is a desirable characteristics since it insures that it eventually does accomplish the task it was assigned.
- **Property 3 :** *[] GetingItem("C")*
  Starting the verification from initial configuration *initial1* (see Fig. 28), this property expresses that the *Consumer* is always in its critical section, namely getting information from the *Buffer*. This property specifies that *C* is always in its critical section and not leaving it and represents a non desirable characteristic.
- **Property 4:** *~ [] ConsumerSleeping("C")*
  Starting the verification from initial configuration *initial1* (see Fig. 28), this property verifies that the *Consumer* object is not always in its *ConsumerWaiting* state. The *Consumer* not always in its waiting state is a desirable characteristics since it insures that it eventually does accomplish the task it was assigned.

Properties Related to the Collective Behavior

In the previous section, we introduced properties of the individual behavior of objects *P and C*. We now introduce 3 other properties to verify the collective behavior of those same objects.

- **Property 5:** *[] ~(PutingItem("P") /\ GetingItem("C"))*
  Starting the verification from the initial configuration *initial1* (see Fig. 28), this property verifies that mutual exclusion is satisfied. Namely, this means that it is not possible to find both the *Producer* and *Consumer* in their critical section (respectively transmitting and getting information) at the same time.
- **Property 6:** *[] <> (PutingItem("P") -> ConsumerSleeping("C"))*
  Starting the verification from the initial configuration *initial1* (see Fig. 28), this property is infinitely often true: when the *Producer* is transmitting information to the *Buffer*, the *Consumer* is in its *ConsumerWaiting* state. <> is the *Eventually* temporal operator. This property insures the correct behavior of objects when transmitting information to the *Buffer*.



- **Property 7:** *[] <> (GetingItem("C") -> ProducerSleeping("P"))*
  This property is the counterpart of Property 6. Starting the verification from the initial configuration *initial1* (see Fig. 28), this property is infinitely often true: when the *Consumer* is getting information from the *Buffer*, the *Producer* is in its *ProducerWaiting* state. This property insures the correct behavior of objects when transmitting information to the *Buffer*.

Fig. 27 presents a part of the *COMMUNICATION-PREDICATES* module, in which we define the predicates relative to the *Producer - Consumer* system we are studying. We define, in this module, the necessary operators that we used in the definition of the properties that we wish to verify. We limit the shown predicates to the ones relative to the class *Producer*. Lines 1 and 2 show respectively the predicate associated to the *Producing* state of class *Producer* and the one associated to the *ProducerSleep* state. The predicates relevant to the other class are omitted since they are very similar to the ones presented here.

```
mod COMMUNICATION-PREDICATES is
  protecting COMMUNICATION .  including SATISFACTION .
  subsort Configuration < State .      var Cf : Configuration .
  ops PutingItem ProducerSleeping : Poid -> Prop .
  ops GetingItem ConsumerSleeping : Coid -> Prop .
    eq  < "P" : Producer | StateP : Producing, ItemP : 5 >
    < "B" : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : 1 >
    Cf |= PutingItem ("P") = true .                           *** 1
  eq < "P" : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
    Cf |= ProducerSleeping("P") = true .                      *** 2
... endm
```

Fig. 27. The COMMUNICATION-PREDICATES module

Properties Verification

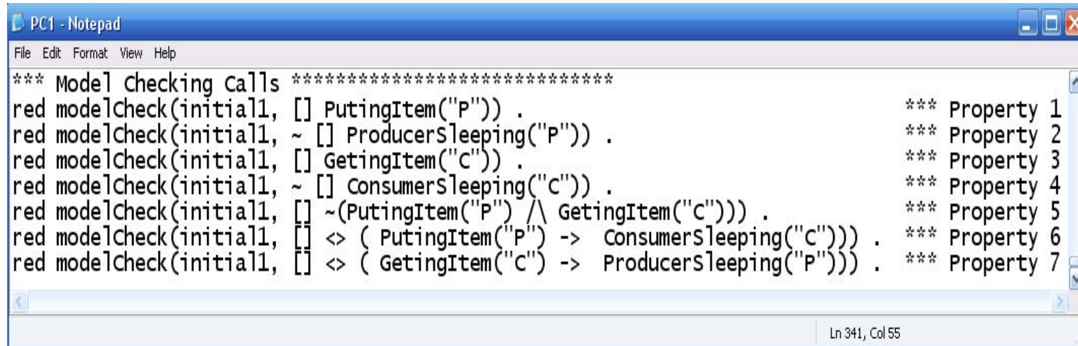
As mentioned previously, the Maude environment has an integrated model checker, in the form of the *modelCheck* function of module *MODEL-CHECKER*. Fig. 28 shows the module *COMMUNICATION-CHECK* in which is defined the initial configuration used: *initial1*. It is the same initial configuration used for the simulation of the entire system in Subsection *Validation of the Generated Descriptions* of Section 6.

```
mod COMMUNICATION-CHECK is
 including COMMUNICATION-PREDICATES MODEL-CHECKER LTL-SIMPLIFIER .
 op initial1 : -> Configuration .
 eq initial1 = ComingMsg(Produce( EmptyParameterList), "P")
               ComingMsg( Get(5), "B")
  < "P" : Producer | StateP : ProducerWaiting, ItemP : NoItemP >
  < "C" : Consumer | StateC : ConsumerWaiting, ItemC : NoItemC >
  < "B" : Buffer | StateB : Empty, ItemB : NoItemB, Semaphore : 1
> .
endm
```

Fig. 28. The *COMMUNICATION-CHECK* module describing the initial state used

All the necessary elements to proceed to the verification are now defined. Fig. 29 shows the calls to the *modelCheck* function of Maude, seven in all, one for each of the properties that were defined previously. Fig. 30 shows part of the results obtained with Maude. Maude evaluated all the properties in less than a second. Table 1 shows a summary of the results of the evaluation of the 7 properties. They are as follows: on

the 7 properties evaluated, 5 have a positive result (*True*) meaning that those properties are verified within our system. Two of the properties, however, show a *Counterexample* result, meaning that they were not verified, and the *Counterexample* shows the exact path the Maude *modelCheck* algorithm took to reach the error state. The two properties showing a negative result are relevant to the individual behavior of objects, one for *Producer* and one for *Consumer*.



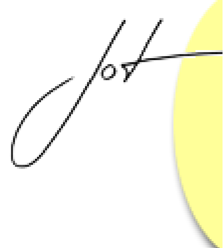
```
*** Model Checking Calls ******************************
red modelCheck(initial1, [] PutingItem("P")) .                              *** Property 1
red modelCheck(initial1, ~ [] ProducerSleeping("P")) .                      *** Property 2
red modelCheck(initial1, [] GetingItem("C")) .                              *** Property 3
red modelCheck(initial1, ~ [] ConsumerSleeping("C")) .                      *** Property 4
red modelCheck(initial1, [] ~(PutingItem("P") /\ GetingItem("C"))) .        *** Property 5
red modelCheck(initial1, [] <> ( PutingItem("P") -> ConsumerSleeping("C"))) . *** Property 6
red modelCheck(initial1, [] <> ( GetingItem("C") -> ProducerSleeping("P"))) . *** Property 7
```

Fig. 29. Model Checking calls

Property	Result
1	*Counterexample*
2	*True*
3	*Counterexample*
4	*True*
5	*True*
6	*True*
7	*True*

Table 1: Results of the evaluation of the properties

The results can be interpreted as follows. Let us firstly consider the results relevant to the individual behavior of objects. For object *P* of the *Producer* class, for which 2 properties were defined to verify its behavior (properties 1 and 2), the results confirm that the object behaves correctly. In fact, Property 1, aimed at verifying if the object was always in its critical section of transmitting information to the *Buffer*, the result obtained is a *Counterexample*. However, obtaining a negative result actually means the system does not allow the *Producer* to eternally be in its critical section, which is the intended behavior. The second property, defined to verify the possibility of the *Producer* not being in its *ProducerSleeping* state forever returned a positive result (*True*). This property being verified means the system does not allow this situation. The properties concerning the behavior of the *Consumer* are very similar in nature to the ones relevant to the *Producer*. Properties 3 and 4 are then analogous to Properties 1 and 2. Property 3 attempted to verify if the system allowed the *Consumer* to be in its critical section (getting information from the *Buffer*) forever. The result was a *Counterexample*, meaning that such a situation was not possible. Property 4, on its part, attempted to verify that the system did not allow the *Consumer* to be locked in its *ConsumerWaiting* state. Because this property was defined using the combination ~ *[]* combination of temporal operators and that the result was *True*, this characteristic is not allowed by the system.



Finally, the three last properties, relevant to the collective behavior of objects *P*, *C* and *B*, were all evaluated to *True*, meaning they all have been verified. Property 5 was intended to verify if the system allowed for *P* and *C* to be in their respective critical section at the same time. The positive result knowing that the ~ temporal operator was used proves that this situation is impossible within our system (mutual exclusion is then satisfied). Properties 6 and 7 were used to insure that it is infinitely often true that while one thread is in its critical section, the other is not. Property 6 verified that if a *Producer* object is in active mode, the *Consumer* object is sleeping, while Property 7 verified the counterpart (namely if a *Consumer* object is in active mode, the *Producer* object is sleeping). Those two properties were both evaluated to *True*.

```
C:\Program Files\MaudeFW\maude.exe
==========================================
reduce in COMMUNICATION-CHECK : modelCheck(initial1, []GetingItem("C")) .
rewrites: 23 in -2265875647ms cpu (2ms real) (~ rewrites/second)
result [ModelCheckResult]: counterexample({ComingMsg(Produce(
    EmptyParameterList), "P") ComingMsg(Get(5), "B") < "B" : Buffer | StateB :
    Empty,ItemB : NoItemB,Semaphore : 1 > < "C" : Consumer | StateC :
    ConsumerWaiting,ItemC : NoItemC > < "P" : Producer | StateP :
    ProducerWaiting,ItemP : NoItemP >,'ProduceItem}, {ComingMsg(Get(5), "B")
    ComingMsg(Put(5), "B") IsAccomplished(Produce(EmptyParameterList), "P") <
    "B" : Buffer | StateB : Empty,ItemB : NoItemB,Semaphore : 1 > < "C" :
    Consumer | StateC : ConsumerWaiting,ItemC : NoItemC > < "P" : Producer |
    StateP : Producing,ItemP : 5 >,'PutItem} {ComingMsg(ProducerSleep(
    EmptyParameterList), "P") ComingMsg(Get(5), "B") IsAccomplished(Put(5),
    "B") < "B" : Buffer | StateB : Full,ItemB : 5,Semaphore : 0 > < "C" :
    Consumer | StateC : ConsumerWaiting,ItemC : NoItemC > < "P" : Producer |
    StateP : Producing,ItemP : NoItemP >,'ProducerSleep} {ComingMsg(Produce(
    EmptyParameterList), "P") ComingMsg(Get(5), "B") < "B" : Buffer | StateB :
    Full,ItemB : 5,Semaphore : 1 > < "C" : Consumer | StateC : ConsumerWaiting,
    ItemC : NoItemC > < "P" : Producer | StateP : ProducerWaiting,ItemP :
    NoItemP >,'GetItem} {ComingMsg(Produce(EmptyParameterList), "P") ComingMsg(
    Consume(5), "C") IsAccomplished(Get(5), "B") < "B" : Buffer | StateB :
    Empty,ItemB : NoItemB,Semaphore : 0 > < "C" : Consumer | StateC :
    Consuming,ItemC : 5 > < "P" : Producer | StateP : ProducerWaiting,ItemP :
    NoItemP >,'ProduceItem} {ComingMsg(Consume(5), "C") ComingMsg(Put(5), "B")
    IsAccomplished(Produce(EmptyParameterList), "P") IsAccomplished(Get(5),
    "B") < "B" : Buffer | StateB : Empty,ItemB : NoItemB,Semaphore : 0 > < "C"
    : Consumer | StateC : Consuming,ItemC : 5 > < "P" : Producer | StateP :
    Producing,ItemP : 5 >,'ConsumeItem} {ComingMsg(ConsumerSleep(
    EmptyParameterList), "C") ComingMsg(Put(5), "B") IsAccomplished(Produce(
    EmptyParameterList), "P") IsAccomplished(Consume(5), "C") < "B" : Buffer |
    StateB : Empty,ItemB : NoItemB,Semaphore : 0 > < "C" : Consumer | StateC :
    Consuming,ItemC : NoItemC > < "P" : Producer | StateP : Producing,ItemP : 5
    >,'ConsumerSleep})
==========================================
reduce in COMMUNICATION-CHECK : modelCheck(initial1, ~ []ConsumerSleeping("C"))
    .
rewrites: 11 in 7649095001ms cpu (1ms real) (0 rewrites/second)
result Bool: true
==========================================
reduce in COMMUNICATION-CHECK : modelCheck(initial1, []~ (PutingItem("P") /\
    GetingItem("C"))) .
rewrites: 36 in 7649102001ms cpu (3ms real) (0 rewrites/second)
result Bool: true
==========================================
reduce in COMMUNICATION-CHECK : modelCheck(initial1, []<> (PutingItem("P") ->
    ConsumerSleeping("C"))) .
rewrites: 40 in 7649102001ms cpu (3ms real) (0 rewrites/second)
result Bool: true
Maude> _
```

Fig. 30. Part of the results of the Model Checking calls of Fig. 29

8 CONCLUSIONS AND FUTURE WORK

The translation of UML diagrams in formal languages has been addressed in numerous papers. Several tools helping the translation process have been developed. However, the majority of those approaches did not consider the collective behavior of objects. In this paper, we proposed a generic approach that allows the translation of static aspects (described by UML class diagram) and dynamic aspects (described by UML state and communication diagrams) of object-oriented systems into a Maude formal specification. More particularly, we applied the translation process we developed in [Mokhati06] to a concurrent object-oriented system. Such a specification integrates both static and dynamic features of the described system. However, our approach is limited to basic state and communication diagrams, modelling the most common features. The Maude language is supported by a tool, which allowed us to validate the generated code by simulation. Moreover, Maude offers a model checker in its environment, which uses Linear Temporal Logic (LTL) to verify properties among the models developed [Eker02, Meseguer03, Clavel05]. We defined some LTL properties about our system and used Maude's model checker to verify them. It is to be noted that the example used is small and simple and is aimded to test the notations we developed. The properties we defined included inherent problems known to concurrent systems, such as deadlocks. Among future directions to this work, we plan on testing the approach on larger scale examples and integrating other UML diagrams.

REFERENCES

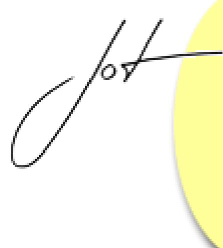
[Araujo00] J. Araujo and A. Moreira. "Specifying the Behavior of UML Collaborations Using Object-Z". Departamento de Infomatica, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Portugal, 2000.

[Astesiano98] E. Astesiano. "UML as Heterogeneous Multiview Notation. Strategie for a Formal Foundation". In *Proceedings of OOPSLA'98 – Workshop on Formalizing UML. Why? How?*, L. Andrade, A. Moreira, A. deshpande, and S. Kent, editors, , Canada, 1998.

[Barnett04] M. Barnett, R. DeLine, M. Fahndrich, K. Rustan, M. Leino, and W. Schulte. "Verification of object-oriented programs with invariants", In Journal of Object Technology, vol. 3, no. 6, June 2004, Special issue: ECOOP 2003 workshop on FTfJP, pp. 27–56, http://www.jot.fm/issues/issue_2004_06/article2

[Booch98] G. Booch, J. Rumbaugh et I. Jacobson. *The Unified Modeling Language User Guide*, Addition-Wesley, Object Technology Series, 1998.

[Börger00] E. Börger, A. Cavarra, and E. Riccobene. "Modeling the Dynamics of UML State Machines". In *ASM '00 : Proceedings of the International Workshop on Abstract State Machines, Theory and Applications*, pages 223–241, London, UK, 2000. Springer-Verlag.



[Börger03] E. Börger, A. Cavarra, and E. Riccobene. "The Meaning of Concurrent States in UML State Diagrams". Presentation Slides for *SAC 2003*.

[Bowen03] J. Bowen. Formal Specification and Documentation Using Z: A Case Study Approach, 2003.

[Bruel00] J.M. Bruel, J. Lilius, A. Moreira, and B. Robert. "Defining Precise Semantics for UML". In *ECOOP'2000 Workshop Reader*, Cannes, France, number 1964 in *Lecture Notes in Computer Science*. Springer-Verlag, November 2000.

[Canals03] Canals et al. "How You Could Use NEPTUNE in the Modelling Process". In Journal of Object Technology, vol. 2 num. 1, pages 69–83, 2003, http://www.jot.fm/issues/issue_2003_01/article1

[Chan98a] W. Chan, et al. "Model checking large software specifications". In *IEEE TSE*, vol. 24, num. 7, pp 498–520, July 1998.

[Chan98b] W. Chan et al. "Improving efficiency of symbolic model checking for state-based system Requirements". In *ISSTA 98 : Proceedings of the ACM SIGSOFT International Symposium on Software Testing and Analysis*. Michal Young, editor, , pp 102–112, Clearwater Beach, USA, March 1998.

[Cho99] S. M. Cho, D. Hwan Bae, S. Deok Cha, Y. Gon Kim, B. Kyu Yoo, and S. Taek Kim. "Applying model checking to concurrent object-oriented software". In *ISADS '99: Proceedings of the The Fourth International Symposium on Autonomous Decentralized Systems*, page 380, Washington, DC, USA, 1999. IEEE Computer Society.

[Clavel99] M. Clavel and al. "Maude: Specification and Programming in Rewriting Logic". Internal report, SRI International, 1999.

[Clavel05] M. Clavel, F. Durán, S. Eker, P. Lincoln, N. Martí-Oliet, J. Mesenguer, and C. Talcott. *Maude Manual (Version 2.1.1)*, April 2005.

[Dong00] Dong J. S. "Formal Specification and Design Techniques". Lecture Notes, 2000.

[Eker02] S. Eker, J. Meseguer, A. Sridharanarayanan. "The Maude LTL Model Checker". Elsevier Science B. V., 2002, 27 pages. URL: http://www.elsevier.nl/locate/entcs /volume71.html

[Favre05] L. Favre: "Foundations for MDA-based Forward Engineering", in *Journal of Object Technology*, vol. 4, no. 1, January-February 2005, pp. 129-153. http://www.jot.fm/issues/issue_2005_01/article4/

[Funes02] A. Funes and C. George. "Formal Foundations in RSL for UML Class Diagrams". Technical Report 253, UNU/IIST, May 2002.

[Gallardo02] M. del Mar Gallardo, P. Merino, and E. Pimentel. "Debugging UML designs with model checking". In Journal of Object Technology, Vol. 1(No. 2): pages 101–117, 2002. http://www.jot.fm/issues/issue_2002_07/article1/

[Garcia02] E. García-Roselló et al: "Design Principles for Highly Reusable Concurrent Object-Oriented Systems", in *Journal of Object Technology*, vol. 1, no. 1, May -June 2002, pages 107-123, http://www.jot.fm/issues/issue_2002_05/article3/

[Gomaa00] H. Gomaa. *Designing Concurrent, Distributed, and Real-Time Applications with UML*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 2000.

[Jean-Pierre05] S.V. Jean-Pierre, H. Malgouyres et G. Motet. "Identification de règles de cohérence d'UML 2.0", *Journée SEE "Systèmes Informatiques de Confiance"* on the theme of "*Vérification de la cohérence de modèles UML*", France (Mars 2005).

[Ledang03] H. Ledang. J. Souquières et S. Charles. "ArgoUML+B : un Outil de Transformation Systématique de Spécifications UML en B". In *Actes de la conférence AFADL'03*, INRIA, pages 15-17, Rennes, France, Janvier 2003.

[MacColl99] I. MacColl and D. Carrington. "Specifying Interactive Systems in Object-Z and CSP". Software Verification Center, Department of Computer Science & Electrical Engineering, University of Queensland, Australia, 1999.

[McCombs03] T. McCombs. "Maude 2.0 Primer, Version 1.0". Internal report, SRI International, 2003.

[Meng04] S. Meng, Z. Naixiao and B. K. Aichernig. "The Formal Foundations in RSL for UML Statechart Diagrams". Technical Report 299, UNU/IIST, July 2004.

[Merz00] S. Merz. "Model checking : A Tutorial Overview". In *MOVEP*, volume 2067 of *Lecture notes in Computer Science* Franck Cassez, Claude Jard, Brigitte Rozoy, and Mark Dermot Ryan, editors, pages 3–38. Springer, 2000.

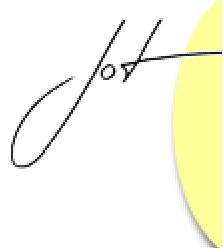
[Merz01] S. Merz, T. Schäfer and A. Knapp. "Model checking UML state machines and collaborations". *Electronic Notes in Theoretical Computer Science*, volume 55 (no. 3), 13 pages, 2001.

[Lam04] V. S. W. Lam and J. A. Padget. "Symbolic Model Checking of UML Statechart Diagrams With an Integrated Approach". In *ECBS*, pages 337–347, 2004.

[Lam05] V. S. W. Lam and J. A. Padget. "An Integrated Environment for Communicating UML Statechart Diagrams". IEEE Computer Society, 2005.

[Meseguer90] J. Meseguer. "Rewriting as a unified model of concurrency". In *Proceedings of the Concur'90 Conference*, Amsterdam, Pages 384-400, Springer LNCS Vol. 458, 1990.

[Meseguer92] J. Meseguer. "A Logical Theory of Concurrent Objects and its Realization in the Maude Language". In *Research Directions in Object-*



Based Concurrency, G. Agha, P. Wegner, and A. Yonezawa, Editors. MIT Press, 1992.

[Meseguer03] J. Meseguer. "Software Specification and Verification in Rewriting Logic". Unpublished work. Computer Science Department, University of Illinois at Urbana-Champaign, 2003.

[Mokhati06] F. Mokhati, M. Badri and P. Gagnon. "Translating UML Diagrams into Maude Formal Specification: A Systematic Approach". In *SEKE'06: Proceedings of the 18th International Conference of Software Engineering and Knowledge Engineering*, San Francisco, 2006.

[Muller00] P.A. Muller et N. Gaertner. *Modélisation objet avec UML*, Deuxième Edition, Paris, 2000.

[OMG05] Object Modeling Group. "Unified Modeling Language Specification", version 2.0, July 2005.

[Paige02] R.F. Paige, L. Kaminskaya, J.S. Ostroff and J. Lancaric. "BON-CASE: an Extensible CASE Tool for Formal Specification and Reasoning". In *Journal of Object Technology*, volume 1 no. 3, pages 65-87, August 2002. http://www.jot.fm/issues/issue_2002_08/article5/

[Paige04] R.F. Paige and P.J. Brooke. "Integrating BON and Object-Z". in Journal of Object Technology Vol. 3, No. 3, pages 121-141, March-April 2004. http://www.jot.fm/issues/issues_2004_03/article3/

[Reggio04] G. Reggio and R. Wieringa. "Thirty one Problems in the Semantics of UML 1.3 Dynamics". In *OOPSLA'99 – Workshop "Rigorous Modeling an Analysis of the UML Challenges and Limitations"*, 1999.

[Schmidt99] J. W. Schmidt and F. Matthes. "State Diagrams". Presentation Slides, 1999.

[Snook04] C. Snook, and M. Butler. "U2B - A tool for translating UML-B models into B", In *UML-B Specification for Proven Embedded Systems Design*, Springer (In press), 2004.

[Taibi03] T. Taibi, D. Check Ling Ngo. "Formal Specification of Design Patterns – A Balanced Approach", in *Journal of Object Technology*, vol. 2, no. 4, 2003, pp. 127-140. URL: http://www.jot.fm/issues/issue_2003_07/article4/

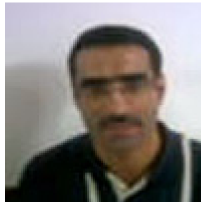
[Tigris02] ArgoUML Tigris Organisation. (2002): *ArgoUML User Manual 2002*, URL: http://argouml.tigris.org/ documentation /defaulthtml/manual/.

[Wahl03] Thomas Wahl. "(Yet Another) Introduction to Model Checking". Presentation Slides, Spring 2003.

[Wegner90] Peter Wegner. "Concepts and Paradigms of Object-Oriented Programming". In *SIGPLAN OOPS* Mess., Vol. 1(No. 1) : pages 7–87, 1990.

About the authors

Patrice Gagnon (Patrice.Gagnon@uqtr.ca) is a Master's Degree student at the University of Québec at Trois-Rivières (Quebec, Canada). His field of study is Software Engineering, and more specifically Formal Methods. His Master's thesis is on the formal verification of UML diagrams.



Farid Mokhati (Mokhati@yahoo.fr) is an assistant professor of computer science at the Department of Computer Science of the University of Oum El-Bouaghi in Algeria. He holds a Ph.D. in computer science (Distributed Artificial Intelligence) from the University of Annaba in Algeria. His main areas of interest include object and agent-oriented software engineering, and formal methods.

Mourad Badri (Mourad.Badri@uqtr.ca) is professor of computer science at the Department of Mathematics and Computer Science of the University of Quebec at Trois-Rivières (Quebec, Canada). He holds a Ph.D. in computer science (software engineering) from the National Institute of Applied Sciences in Lyon (France). His main areas of interest include object and aspect-oriented software engineering, software quality assurance, and formal methods.