FORMAL ANALYSIS OF SEQUENCE DIAGRAM WITH COMBINED FRAGMENTS

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Abstract: The Combined Fragments of UML Sequence Diagram permit various types of control flow among messages (*e.g.*, interleaving and branching) to express an aggregation of multiple traces encompassing complex and concurrent behaviors. However, Combined Fragments increase the difficulty of Sequence Diagram comprehension and analysis. To alleviate this problem, we introduce an approach to formally describe Sequence Diagrams with Combined Fragments in terms of the input language of the model checker NuSMV. This approach permits the verification of desired properties against Sequence Diagrams.

1 INTRODUCTION

In software development process, models enable software engineers to detect errors during early stage so as to improve the system quality. Scenario-based models have been widely employed for the description of interactions among environmental actors (*e.g.*, human beings) and the components (aka Lifeline) of the software systems through the exchange of messages. UML Sequence Diagrams, which graphically depict scenarios, serve as well-accepted and intuitive media among software engineers and tool builders. UML 2 provides many major structural control constructs, including Combined Fragments and Interaction Use, to allow multiple, complex scenarios to be aggregated in a single Sequence Diagram. However, Combined Fragments introduce concurrent behaviors, making analysis of the Sequence Diagrams difficult for the following reasons.

Combined Fragments permit different types of control flow, such as interleaving and branching, increasing a Sequence Diagram's expressiveness. Further, the Combined Fragments can also be nested to provide more complex control flows. These make it difficult to predict what behavior are represented. For example, if a Combined Fragment presenting branching behavior is nested within a Combined Fragment presenting iteration behavior, different choices may be made in different iterations. The semantics of Sequence Diagram with Combined Fragments is not formally defined compared to their precise syntax descriptions (Object Management Group, 2011), making it is hard to derive the traces from Sequence Diagrams. Thus, subtle errors from concurrency can easily be introduced to Sequence Diagrams to evade discovery via manual inspection.

To address these problems, we introduce an automated technique to facilitate the verification of Sequence Diagrams by leveraging the analytical powers of model checking. Working towards similar goals, many researchers have verified different scenario-based models, including Sequence Diagram, Message Sequence Chart (MSC), and Live Sequence Chart (LSC). However, the previous work does not consider all the aspects of Combined Fragments. Our approach supports all the features of Combined Fragments, including all 12 Interaction Operators, nested Combined Fragments, both asynchronous and synchronous Messages, and Interaction Constraints.

We devise an approach to codify the semantics of Sequence Diagrams and Combined Fragments in the input language of NuSMV by deconstructing Sequence Diagrams and Combined Fragments to obtain fine-grained syntactic constructs (see section 2 and 3). We formally describe each Combined Fragment in terms of NuSMV (Cimatti et al., 2000) modules (see section 4). The model checking mechanism can explore all possible traces specified in the Sequence Diagram, verifying if the desired properties are satisfied. We have developed a tool suite to implement all of the techniques and have validated our technique by analyzing and discovering violations in two design examples taken from an insurance industry software application (see section 5). We have also created an Occurrence Specification Trace Diagram generator that automatically produces Sequence Diagram visualizations from NuSMV-produced counterexamples. This automation will increase the accessibility of our approach by allowing software engineers to remain focused in the realm of Sequence Diagrams.

2 UML 2 SEQUENCE DIAGRAM

In this section, we outline the syntax and semantics of a Sequence Diagram with Combined Fragments provided by OMG (Object Management Group, 2011). As the first step of defining a Sequence Diagram using NuSMV modules, we precisely define the semantics of Sequence Diagram with Combined Fragments, forming the basis of expressing the semantics in term of NuSMV models. We begin with the basic Sequence Diagram, then discuss the structured control constructs, including Combined Fragments and Interaction Use.

2.1 Basic Sequence Diagram

We refer to a Sequence Diagram without Combined Fragments as a basic Sequence Diagram (see figure 1a for an example with annotated syntactic constructs). A **Lifeline** is a vertical line representing a participating object. A horizontal line between Lifelines is a **Message**. A Message is the specification of an occurrence of a message type within the Sequence Diagram, while a message type is the signature of the form $\langle$*message name, source Lifeline, target Lifeline*$\rangle$. Within a Sequence Diagram, a message type can occur multiple times, which are associated with multiple Messages. Each Message is sent from its source Lifeline to its target Lifeline and has two endpoints. Each endpoint is an intersection with a Lifeline and is called an **Occurrence Specification (OS)**, denoting the specification of an occurrence of an event within a certain context, *i.e.*, a Sequence Diagram. Accordingly, multiple OSs within a Sequence Diagram can be associated with an event. Each Message is defined by its sending OS and receiving OS. We associate each OS with a location of a Lifeline. As each location is uniquely defined, each OS is uniquely defined. Thus, each Message is uniquely defined by its sending OS and receiving OS. OSs can also be the beginning or end of an **Execution Specification**, indicating the period during which a participant performs a behavior within a Lifeline, which is represented as a thin rectangle on the Lifeline.

The semantics of a basic Sequence Diagram is defined by a set of traces. A trace is a sequence of OSs expressing Message exchange among multiple Lifelines. We identify four orthogonal semantic aspects that must be considered for the basic Sequence Diagram (Micskei and Waeselynck, 2011; Object Management Group, 2011; Kugler et al., 2005)

1. Each OS can execute only once, *i.e.*, each OS is unique within a Sequence Diagram.
2. On each Lifeline, OSs execute in their graphical order from top to bottom.
3. For a single Message, the sending OS must take place before the receiving OS does.
4. In a Sequence Diagram, only one object can execute an OS at a time, *i.e.*, OSs on different Lifelines are interleaved.

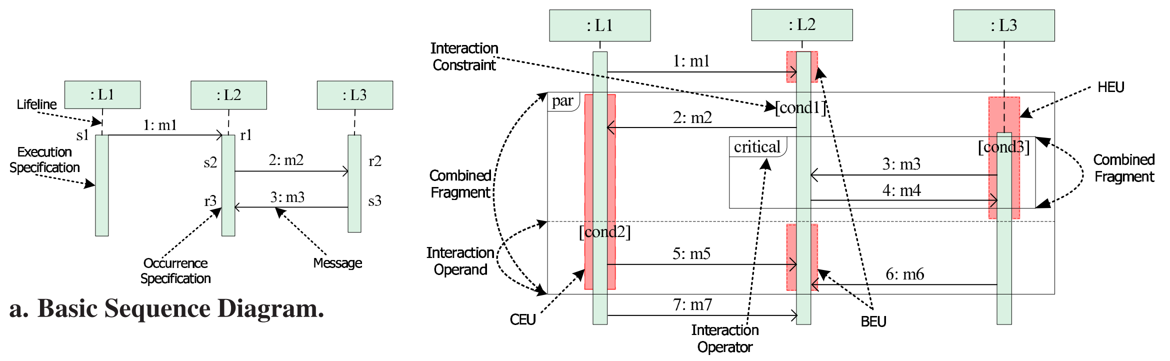
Messages are of two types: asynchronous and synchronous. The source Lifeline can continue to send or receive other Messages after an asynchronous Message is sent. If a synchronous Message is sent, the source Lifeline blocks until it receives the target Lifeline's response (Object Management Group, 2011).

2.2 Combined Fragment

Both Combined Fragments and Interaction Use are structured control constructs introduced in UML 2. A **Combined Fragment** (CF) is a solid-outline rectangle, which consists of an **Interaction Operator** and one or more **Interaction Operands**. Figure 1b shows example CFs with annotated syntactic constructs. A CF can enclose all, or part of, Lifelines in a Sequence Diagram. The Interaction Operands are separated by dashed horizontal lines. The Interaction Operator is shown in a pentagon in the upper left corner of the rectangle. OSs, CFs, and Interaction Operands are collectively called **Interaction Fragments**. An Interaction Operand may contain a boolean expression which is called an **Interaction Constraint** or Constraint. An Interaction Constraint is shown in a square bracket covering the Lifeline where the first OS will happen. BEU, HEU and CEU are defined in Section 3. An **Interaction Use** construct allows one Sequence Diagram to refer to another Sequence Diagram. The referring Sequence Diagram copies the contents of the referenced Sequence Diagram.

We identify three independent semantic rules general to all CFs, in the sense that these rules do not constrain each other.

1. OSs and CFs, are combined using Weak Sequencing (defined below). On a single Lifeline, a CF's preceding Interaction Fragment must complete the execution prior to the CF's execution, and the CF's succeeding Interaction Fragment must execute subsequently.
2. Within a CF, the order of the OSs and CFs within each Operand is maintained if the Constraint of the Operand evaluates to *True*; otherwise, the Operand is excluded.
3. The CF does not execute when the Constraints of all the Operands evaluate to *False*. Thus, the CF's preceding Interaction Fragment and succeeding Interaction Fragment are ordered by Weak Sequencing.



a. Basic Sequence Diagram.

b. Sequence Diagram with Combined Fragment.

Figure 1: Sequence Diagram Syntax.

2.3 Interaction Operator

The semantics of each CF Operator determines the execution order of all the Operands. Each Operator has its specific semantic implications regarding the execution of the OSs enclosed by the CF on the covered Lifelines. The Operators are summarized as follows: **Alternatives**: one of the Operands whose Interaction Constraints evaluate to *True* is nondeterministically chosen to execute. **Option**: its sole Operand executes if the Interaction Constraint is *True*. **Break**: its sole Operand executes if the Interaction Constraint evaluates to *True*. Otherwise, the remainder of the enclosing Interaction Fragment executes. **Parallel**: the OSs on a Lifeline within different Operands may be interleaved, but the ordering imposed by each Operand must be maintained separately. **Critical Region**: the OSs on a Lifeline within its sole Operand must not be interleaved with any other OSs on the same Lifeline. **Loop**: its sole Operand will execute for at least the minimum count (lower bound) and no more than the maximum count (upper bound) as long as the Interaction Constraint is *True*. **Assertion**: the OSs on a Lifeline within its sole Operand must occur immediately after the preceding OSs. **Negative**: its Operand represents forbidden traces. **Strict Sequencing**: in any Operand except the first one, OSs cannot execute until the previous Operand completes. **Weak Sequencing**: *on a Lifeline*, the OSs within an Operand cannot execute until the OSs in the previous Operand complete, the OSs from *different Operands on different Lifelines* may take place in any order (cf. Strict Sequencing). **Consider**: any message types other than what is specified within the CF is ignored. **Ignore**: the specified messages types are ignored within the CF.

The semantics of the *seq* Sequence Diagram is defined by two sets of traces, one containing a set of valid traces, denoted as $Val(seq)$, and the other containing a set of invalid traces, denoted as $Inval(seq)$. The intersection of these two sets is empty, *i.e.*, $Val(seq) \cap Inval(seq) = \emptyset$.

3 SEQUENCE DIAGRAM DECONSTRUCTION

To facilitate codifying the semantics of Sequence Diagrams and nested CFs in NuSMV models, we show how to deconstruct a Sequence Diagram and CFs to obtain fine-grained syntactic constructs. Eichner *et al.* have defined the Maximal Independent Set in (Eichner et al., 2005) to deconstruct a Sequence Diagram into fragments, each of which covers multiple Lifelines. Their proposed semantics defines that entering a CF has to be done synchronously by all the Lifelines, *i.e.*, each CF is connected with adjacent OSs and CFs using Strict Sequencing. Recall that CFs can be nested within other CFs. OSs and CFs directly enclosed in the same CF or Sequence Diagram are combined using Weak Sequencing, constraining their orders with respect to each individual Lifeline only (Object Management Group, 2011). To express the semantics of Weak Sequencing, we further deconstruct a Sequence Diagram into syntactic constructs on each Lifeline, which also helps us to define the semantics of nested CFs.

We project every CF cf_m onto each of its covered Lifelines l_i to obtain a **compositional execution unit (CEU)**, which is denoted by $cf_m \uparrow_{l_i}$. (The shaded rectangle on Lifeline *L1* in figure 1b shows an example).

Definition 1 A CEU is given by a three tuple $\langle l_i$, *oper, setEU*$\rangle$, where l_i is the Lifeline, onto which we project the CF, *oper* is the Interaction Operator of the CF, and *setEU* is the set of execution units, one for each Operand op_n enclosed in the CF on Lifeline l_i.

Every Operand op_n of CF cf_m is projected onto each of its covered Lifelines l_i to obtain an **execution unit (EU)** while projecting cf_m onto l_i, denoted by $op_n \uparrow_{l_i}$. If the projected Interaction Operand contains a nested CF, a **hierarchical execution unit (HEU)** is obtained; otherwise a **basic execution unit (BEU)** is obtained, *i.e.*, an EU is a BEU if it does not contain any other EUs. (The lower shaded rectangle on Lifeline *L2* in figure 1b shows an example of a BEU and the shaded rectangle on Lifeline *L3* shows an example of an HEU).

Definition 2 A BEU *u* is given by a pair, $\langle E_u$, *cond*$\rangle$, in which E_u is a finite set of OSs on Lifeline l_i enclosed in Operand op_n, which are ordered by the locations associated with them, and *cond* is the Interaction Constraint of the Operand. *cond* is *True* when there is no Interaction Constraint.

Definition 3 An HEU is given by $\langle$*setCEU, setBEU, cond*$\rangle$, where *setCEU* is the set of CEUs directly enclosed in the HEU, *i.e.*, the CEUs nested within any element of *setCEU* are not considered. *setBEU* is the set of BEUs that are directly enclosed in the HEU.

Projecting a Sequence Diagram onto each enclosing Lifeline also obtains an EU whose Constraint is *True*. The EU is an HEU if the Sequence Diagram contains CFs, otherwise, it is a BEU. In an HEU, we also group the OSs between two adjacent CEUs or prior to the first CEU or after the last CEU on the same level into BEUs, which inherit the parent HEU's Constraint, *cond*. (The upper shaded rectangle on Lifeline *L2* in figure 1b shows an example). The constituent BEU(s) and CEU(s) within an HEU execute sequentially, complying with their graphical order, as do the OSs in the BEU.

4 VERIFYING SEQUENCE DIAGRAMS VIA NUSMV

In this section, we develop techniques to translate Sequence Diagrams into the input language of NuSMV. The NuSMV model preserves the structure of the Sequence Diagrams (*e.g.*, Lifelines and CFs), which makes it easier to demonstrate that the semantics of the original notation is maintained.

4.1 NuSMV Overview

NuSMV is a model checking tool, which exhaustively explores all executions of a finite model to determine if a temporal logic property holds. For a property that does not hold, a counterexample is produced showing an error trace. A NuSMV model consists of one main module and may include other modules with formal parameters. An instance of a module can be created using the **VAR** declaration within main module or other module to create a modular hierarchy. To access variables of instance modules, the instance name with **. (DOT)** can be used to follow by the variable name. The composition of multiple modules can be parallel or interleaving.

NuSMV variables must be of finite types, declared inside each module. The initial states are defined by using an **init** statement of the form *init(x) := EXP*, which defines the value or set of values x can assume initially. Transitions are defined by using the **next** statements of the form *next(x) := EXP*, which defines the value or set of values that x can assume in the following state. All the transitions in a module execute concurrently in each step. Derived variables (*i.e.*, macros) are defined by using **DEFINE** statements of the form *x := EXP* and they are replaced by *EXP* in each state. The system's invariant is represented with the **INVAR** statement, which is a boolean expression satisfied by each state.

4.2 Mapping Overview

We base the mapping of a Sequence Diagram to the input language of NuSMV on syntactic deconstruction. A Sequence Diagram is represented as the main module. We map the Lifelines into respective NuSMV modules, which are instantiated and declared in the main module. Recall that a CF is projected onto each of its covered Lifelines to obtain a CEU. Accordingly, its Operand on each of the covered Lifelines forms an EU. Both CEUs and EUs are represented as NuSMV modules.

Each CEU is declared as a module instance, which we call a submodule in its Lifeline module. To enforce that multiple CEUs at the same level on each Lifeline adhere to their graphical order, we define a derived variable, *flag_final*, for each CEU module, to indicate whether the CEU completes its execution (the CF semantic rule 1). A CEU is composed of one or more EUs, each of which is instantiated as a submodule inside the CEU module. The execution order of multiple EUs (*i.e.*, the transfer of control among them) is determined by the Interaction Operator that composes them into the CEU (the translation of each Operator is discussed later in this section). In the case that a Sequence Diagram contains nested CFs (*i.e.*, a CEU consisting of an EU that encloses other CEUs), we map each enclosed CEU as a submodule of the containing EU's module. This procedure is recursively applied until all CEUs and EUs are mapped accordingly.

The semantic rules for a basic Sequence Diagram defined in section 2.1 are codified using NuSMV modules for Lifelines or EUs, and an INVAR statement. Within Lifeline or EU modules, a directly enclosed OS is represented as a boolean variable, which initializes to *False* (note that a CEU module does not contain OS variables). Once an OS occurs, its value is set to *True* and then to *False* in all the following states. This value transition expresses the fact that an OS can occur only once in the Sequence Diagram (the semantic rule 1). To record the execution history of OSs, we introduce an enumerated variable, *state*, for each Lifeline and EU module, expressing that respective OSs have taken place (the semantic rule 2). A CEU module contains one boolean variable, *cond*, for each of its EUs to represent the Interaction Constraint of the EU.

To express the interleaving semantics among Lifelines, we introduce an INVAR statement in the main module to assert that at most one OS on one of the Lifelines can take place in each step (the semantic rule 4). A boolean variable *chosen* is used for each Lifeline to restrict that: (1) a Lifeline is chosen only if it is enabled, *i.e.*, there is an OS that is ready to take place on the Lifeline, represented by the derived variable *enabled*; (2) either only one Lifeline can be chosen to execute an OS in each step if Lifelines are enabled (*i.e.*, before all OSs on the Lifelines have occurred); or no Lifeline can be chosen when all Lifelines are not enabled and all *chosen* variables remain *False* thereafter. A sending OS is enabled to execute if and only if the OSs prior to it on the same Lifeline have already occurred. A receiving OS is enabled to execute if and only if the OSs prior to it on the same Lifeline and the sending OS of the same Message have already occurred (the semantic rules 2 and 3). To execute the OSs enclosed in CFs, the variable *chosen* for each Lifeline is passed to the CEU and EU modules on that Lifeline as a parameter.

4.3 Basic Sequence Diagram with Asynchronous Messages

In this subsection, we illustrate our mapping strategy with an example basic Sequence Diagram as shown in figure 1a. Figure 2 shows the NuSMV description of the example, which contains a main module for the Sequence Diagram. We map the three Lifelines to three modules, which are instantiated as submodules *l_L1*, *l_L2*, and *l_L3* in the main module. We show the implementation of module *L2* here. Module *L2* takes modules *L1, L3* as parameters. Three OSs on Lifeline *L2* are defined as boolean variables *OS_r1*, *OS_s2*, and *OS_r3* in the VAR section. We define each OS as *OS_sx* or *OS_rx*, where *s* and *r* denote they are sending or receiving OSs, and *x* is the corresponding Message name. The enumerated variable *state* has four values, including an initial value *sinit* and three values to record the execution of the three respective OSs. A derived variable *enabled* for each OS represents the enabling condition of the OS by using the variable *state* in the DEFINE section. For instance, *r3_enabled* for OS *r3* is *True* if and only if the sending OS of Message *m3* and the preceding OS, *OS_s2*, on Lifeline *L*2 have occurred, *i.e.*, *state* on Lifelines *L*2 and *L*3 set to *s2* and *s3* respectively. The Lifeline *L2* can be enabled if and only if one of *r1, s2*, and *r3* is enabled. The variable *flag_final* checks whether the last OS, *r3*, on *L2* takes place (*i.e.*, *state* sets to *r3*). If so, all OSs in module *L2* have occurred. The ASSIGN section defines the transition relation of module *L*2. For example, *OS_r3* is set to *False* initially. When it is chosen and enabled, it is set to *True*. It is set to *False* in the subsequent states to represent that an OS can execute exactly once. *OS_r1* and *OS_s2* take the same transition as *OS_r3*. Variable *state* is set to *r*1 in the same state where OS_r1 occurs.

```
MODULE main
 VAR
  l_L1 : L1(l_L2, l_L3);
  l_L2 : L2(l_L1, l_L3);
  l_L3 : L3(l_L1, l_L2);
 INVAR
  ((l_L1.chosen -> l_L1.enabled)
  &(l_L2.chosen -> l_L2.enabled)
  &(l_L3.chosen -> l_L3.enabled)
  &((l_L1.chosen & !l_L2.chosen & !l_L3.chosen)
   |(!l_L1.chosen & l_L2.chosen & !l_L3.chosen)
   |(!l_L1.chosen & !l_L2.chosen & l_L3.chosen)
   |(!l_L1.enabled & !l_L2.enabled & !l_L3.enabled)))
MODULE L2(L1, L3)
 VAR
  OS_r1 : boolean;
  OS_s2 : boolean;
  OS_r3 : boolean;
  state : {sinit, r1, s2, r3};
  chosen : boolean;
 DEFINE
  r1_enabled := state=sinit & L1.state=s1;
  s2_enabled := state=r1;
  r3_enabled := state=s2 & L3.state=s3;
  enabled := r1_enabled | s2_enabled | r3_enabled;
  flag_final := state=r3;
 ASSIGN
  init(state) := sinit;
  next(state) := case
   state=sinit & next(OS_r1)    :r1;
   state=r1 & next(OS_s2)       :s2;
   state=s2 & next(OS_r3)       :r3;
   1                            :state;
  esac;
   ...
  init(OS_r3) := FALSE;
  next(OS_r3) := case
   chosen & r3_enabled    :TRUE;
   OS_r3                  :FALSE;
   1                      :OS_r3;
  esac;
```

Figure 2: Basic Sequence Diagram to NuSMV.

4.4 Basic Sequence Diagram with Synchronous Messages

Sequence Diagram with synchronous Messages restricts that the sending Lifeline blocks until a reply Message is received. We introduce a boolean variable, *isBlock*, for each Lifeline to capture this semantic aspect. All OSs on a Lifeline include *isBlock* as an enabling condition, thus preventing the OSs from occurring while *isBlock* is *True*.

4.5 Combined Fragments

A CF enclosing multiple Lifelines is projected onto all the Lifelines to obtain a collection of CEUs, one for each Lifeline. A CEU contains a collection of EUs, one for each Operand on the same Lifeline. To preserve the structure of the Sequence Diagram during translation, we map a CF to NuSMV submodules, one for each Lifeline module, while the EUs are mapped to NuSMV sub-submodules of their parent CEU submodule separately. We implement the Interaction Constraint for each Operand with a boolean variable *cond*. We do not control the value of *cond* until the Operand is entered, representing the fact that a condition may change during the execution of the Sequence Diagram. If *cond* evaluates to *True*, the Operand is entered, otherwise, the Operand is skipped (the CF semantic rule 2). Afterwards, the value of *cond* stays the same. While there is no Constraint in an Operand, *cond* is defined as constant *True*. An extra variable *op_eva* for each Operand indicates its respective execution status, including "not ready" (the OSs that may happen prior to the Operand on the Lifeline have taken place) by enumeration element *-1*, "ready but not enabled" (the Constraint evaluates to *False*) by enumeration element *0*, and "start" (Constraint evaluates to *True*) by enumeration element *1*. *cond* is evaluated when *op_eva* evaluates to either *0* or *1*. Both *cond* and *op_eva* for each Operand are instantiated and declared in the CEU module on the Lifeline where the Interaction Constraint of the Operand is located. The value of *op_eva* is passed to other CEUs of the same CF as parameters, which is further passed to all the EUs of the same Operand to coordinate multiple EUs. From the deconstruction of Sequence Diagrams and CFs (see section 3), we define the OSs as boolean variables in the respective EUs that directly enclose them, instead of the CEUs; OSs that are not enclosed in any CF are declared as boolean variables in their Lifeline module.

4.5.1 Concurrency

In a Parallel CF, the Operands are interleaved, which is captured using a strategy similar to the implementation of interleaved Lifelines modules. We introduce a boolean variable *chosen* for each EU module to indicate whether the EU is chosen to execute. We add an INVAR statement for each CEU to assert that (1) either only one EU module is chosen to execute or no EUs are enabled (*i.e.*, all EUs have completed execution or their Constraints evaluate to *False*), and (2) an EU module can be chosen only if it is enabled (*i.e.*, an OS within the EU is enabled to execute). All INVAR statements are combined using logical conjunctions to form a global invariant in the main module.

Figure 1b shows an example Sequence Diagram, in which a Parallel contains a Critical Region. The implementation of its main module and the modules of Lifeline *L2* and its CEU of the Parallel are shown in figure 3. In the module of Lifeline *L2*, the Parallel's CEU module is initialized as a module instance. Two EUs of the Parallel's Operands are initialized as two module instances within its CEU module.

In the Parallel, the Interaction Constraint of its Operand, *op1*, is located on *L2*. Thus, *cond1* for *op1* is initialized and declared in the Parallel's CEU module on *L2*. It is set to the value of the evaluation step and remains that value in the following steps. Variable *op1_eva* is initialized to *-1*, and then is set depending on the value of *cond1* when entering the CEU, *i.e.*, it is set to *1* if *cond1* evaluates to *True* or *0* otherwise. In each EU module of the Parallel, a variable *chosen* is used to denoted whether the EU is chosen to execute.

4.5.2 Atomic execution

A Critical Region has a sole Operand while each CEU module having a single EU submodule. We use a boolean variable, *isCritical*, for each EU of the Critical Region's Operand, to restrict the OSs within the EU from interleaving with other OSs on the same Lifeline. Variable *isCritical* is initialized to *False* in each EU module of the Critical Region's Operand. It is set to *True* if the EU starts to execute OSs and stays *True* until the EU finishes execution. Once the EU completes, *isCritical* is set to *False*. The negation of *isCritical* of an EU is considered as an enabling condition for each variable of other OSs, which may interleave the EU, on the same Lifeline. See figure 1b for an example. On Lifeline *L3*, the sending OS of Message *m6* takes the negation of *isCritical* for the EU on Lifeline *L3* as an enabling condition.

4.5.3 Branching

Collectively, we call Alternatives, Option, and Break branching constructs.

In an Alternatives CF, each Operand must have an explicit or an implicit or an "else" Constraint. An implicit Constraint always evaluates to $True$. The "else" Constraint is the negation of the disjunction of all other Constraints in the enclosing Alternatives. The chosen Operand's Constraint must evaluate to $True$. If none of the Operands whose Constraints evaluate to $True$, the Alternatives is excluded. For each Operand, a boolean variable *exe* indicates the execution status of the applicable Operand, *i.e.*, *exe* is set to *True* if the Operand is chosen to execute. The variable *exe* for each Operand is initialized and declared in the CEU module on the Lifeline where the Operand's Constraint is located. The Constraint under INVAR restricts that an Operand's *exe* can be set to *True* only if

```
MODULE main
 VAR
  l_L1 : L1(l_L2, l_L3);
  l_L2 : L2(l_L1, l_L3);
  l_L3 : L3(l_L1, l_L2);
 INVAR
  ((l_L1.chosen -> l_L1.enabled)
  &(l_L2.chosen -> l_L2.enabled)
  &(l_L3.chosen -> l_L3.enabled)
  &((l_L1.chosen & !l_L2.chosen & !l_L3.chosen)
   |(!l_L1.chosen & l_L2.chosen & !l_L3.chosen)
   |(!l_L1.chosen & !l_L2.chosen & l_L3.chosen)
   |(!l_L1.enabled & !l_L2.enabled & !l_L3.enabled)))
 INVAR
  ((l_L1.CF1.op1.chosen -> l_L1.CF1.op1.enabled)
  &(l_L1.CF1.op2.chosen -> l_L1.CF1.op2.enabled)
  &((l_L1.CF1.op1.chosen & !l_L1.CF1.op2.chosen)
   |(!l_L1.CF1.op1.chosen & l_L1.CF1.op2.chosen)
   |(!l_L1.CF1.op1.enabled & !l_L1.CF1.op2.enabled)))
 INVAR
  ((l_L2.CF1.op1.chosen -> l_L2.CF1.op1.enabled)
  &(l_L2.CF1.op2.chosen -> l_L2.CF1.op2.enabled))
  &((l_L2.CF1.op1.chosen & !l_L2.CF1.op2.chosen)
   |(!l_L2.CF1.op1.chosen & l_L2.CF1.op2.chosen)
   |(!l_L2.CF1.op1.enabled & !l_L2.CF1.op2.enabled)))
 INVAR
  ((l_L3.CF1.op1.chosen -> l_L3.CF1.op1.enabled)
  &(l_L3.CF1.op2.chosen -> l_L3.CF1.op2.enabled))
  &((l_L3.CF1.op1.chosen & !l_L3.CF1.op2.chosen)
   |(!l_L3.CF1.op1.chosen &  l_L3.CF1.op2.chosen)
   |(!l_L3.CF1.op1.enabled & !l_L3.CF1.op2.enabled)))
MODULE L2(L1, L3)
 VAR
  CF1 : par_L2(state, chosen, L1.CF1, L3.CF1);
  ...
 DEFINE
  r7_enabled := state=r1&CF1.flag_final&L1.state=s7;
  enabled := r1_enabled | r7_enabled | CF1.enabled;
  ...
MODULE par_L2(state, L2_chosen, par_L1, par_L3)
 VAR
  op1 : par_op1_L2(L2_chosen, par_L1.op1, par_L3.op1,
                                                  op1_eva);
  op2 : par_op2_L2(L2_chosen, par_L1.op2, par_L3.op2,
      par_L1.op2_eva, state, op1.CF2.op1.isCritical);
  cond1 : boolean;
  op1_eva : -1..1;
 DEFINE
  enabled := op1.enabled | op2.enabled;
  flag_final := op1.flag_final & op2.flag_final;
 ASSIGN
  init(op1_eva) := -1;
  next(op1_eva) := case
   op1_eva=-1 & next(state)=r1 & !next(cond1) :0;
   op1_eva=-1 & next(state)=r1 &  next(cond1) :1;
   1                                          :op1_eva;
  esac;
  init(cond1) := {TRUE, FALSE};
  next(cond1) := case
   op1_eva=-1                        :{TRUE, FALSE};
   op1_eva!=-1                       :cond1;
   1                                 :cond1;
  esac;
```

Figure 3: NuSMV module for Parallel.

the Operand's *cond* evaluates to *True*. It also restricts that at most one Operand can be chosen to execute, *i.e.*, at most one *exe* can be set to *True* at a time, or all Operand Constraints evaluate to *False*. The use of *exe* guarantees that all the enclosed Lifelines choose the same Operand's EU module to execute to avoid inconsistent choices (*e.g.*, Lifeline *L1* chooses Operand *1*'s EU whereas Lifeline *L2* chooses Operand *2*'s EU). The *cond* of the chosen Operand stays *True* and those of the unchosen Operands are set to *False* and stay *False*.

The NuSMV representation of Option and Break can be derived from the one of Alternatives. The details of translation are described in (Shen et al., 2011).

4.5.4 Iteration

The Loop represents its sole Operand's iterations, which are connected by Weak Sequencing. To restrict the number of iterations, the Operand's Constraint may include a lower bound, *minint*, and an upper bound, *maxint*, *i.e.*, a Loop iterates at least the *minint* number of times and at most the *maxint* number of times. If the Constraint evaluates to *False* after the *minint* number of iterations, the Loop will terminate.

Bounded Loop, whose *maxint* is given, can be translated to NuSMV modules. To keep each OS and Constraint within different iterations of a Loop unique, one way to implement an OS or a Constraint is defining an array to rename the OS or the Constraint of each iteration. For each Lifeline, We use n to represent the current iteration number. In this way, an OS within the Loop's Operand, OS_r1, and Constraint *cond* in iteration n can be represented as $OS\_r1[n]$ and $cond[n]$ respectively. For example, if a Loop iterates at most three iterations, OS_r1 in different iterations are defined as $OS\_r1[1]$, $OS\_r1[2]$ and $OS\_r1[3]$. The graphical order of the OSs within the same iteration is maintained, and the OSs among iterations execute sequentially along a Lifeline, *i.e.*, OSs in iteration n take place before OSs in iteration $n+1$.

We need to evaluate the Interaction Constraint of its sole Operand after minimum number of iterations. If $n \leq minint$, the Loop executes. If $minint < n \leq maxint$, the Loop executes only if $cond[n]$ evaluates to $True$. Otherwise, the Loop terminates and the values of the Constraint of remaining iterations (*i.e.*, from $cond[n+1]$ to $cond[maxint]$) set to *False*. The Loop no longer executes when its iteration reaches $maxint$.

4.5.5 Assertion

An Assertion represents that, on each Lifeline, a set of traces of its Operand are the only valid traces following the Assertion's preceding OSs. The mapping strategy of the Assertion is very similar to the one of the Critical Region. For each Lifeline, a boolean variable *inAssertion* is initialized and declared in the EU module of the Assertion's Operand, restricting the OSs within the EU from interleaving with other OSs on the same Lifeline if the OSs prior to the CEU of the Assertion finish execution. The variable *inAssertion* is *False* initially, and is set to *True* when the OSs in the set of *pre(CEU)* have executed. Function *pre(CEU)* returns the set of OSs which may happen right before the CEU of the Assertion. If the EU of the Assertion's Operand completes execution, *inAssertion* is set to *False* and other OSs may execute. For each Lifeline, the negation of *inAssertion* is used as an enabling condition for each variable of other OSs, which may interleave the EU of the Assertion's Operand.

4.5.6 Negation

We translate the Operand of a Negative into NuSMV modules, deriving all possible invalid traces.

4.5.7 Weak Sequencing and Strict Sequencing

The semantics of a Weak Sequencing enforces the total order among EUs of Operands on the same Lifeline. In any EU module of an Operand (except the first one), the first OS takes the variable *flag_final* of the EU of the preceding Operand on the same Lifeline as an enabling condition, *i.e.*, the EU cannot execute before the preceding one completes. Figure 4 is an example of Weak Sequencing. In the EU module of the second Operand on Lifeline *L2*, the first OS, *r4*, takes *flag_final* of the EU occurring immediately before this EU (*i.e.*, the EU of the first Operand) as an enabling condition. The semantics of a Strict Sequencing en-

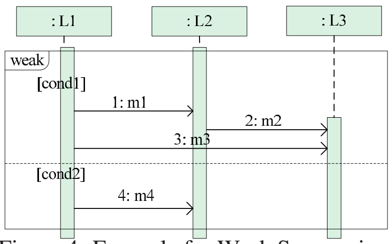


Figure 4: Example for Weak Sequencing.

forces the total order between adjacent Operands. An EU module of an Operand (other than the first one) within a Strict Sequencing takes variable *flag_final* of every EU module within the preceding Operand as enabling conditions of the first OS. It asserts that all EUs cannot execute until its preceding Operand completes execution. We can alter the Interaction Operator of the CF in figure 4 to *strict* to make it as an example of Strict Sequencing. Comparing to the example of Weak Sequencing, OS *r4* also takes the variable *flag_final* of the EUs of the first Operand on Lifelines *L1* and *L3* as enabling conditions additionally.

4.5.8 Ignore and Consider

Ignore and Consider make it possible to execute the Messages not explicitly appear in the CF. To map an Ignore (Consider) into NuSMV modules, we can explore all the traces of OSs in which Messages are ignored (not considered). We assume the signature of any Message of ignored (considered) types is given, *i.e.*, the Lifelines where the sending OS and receiving OS of a Message occur are known. The Messages of ignored types can occur and interleave with the OSs appearing in the CF. In an Ignore, the OSs appearing in the CF are translated as usual. Each OS of any ignored Message is mapped to a boolean variable in the EU module on the Lifeline where it is located. An OS of the ignored Messages can be enabled if it has not executed and the control is in the EU module. To record the status of each ignored Message's OS, an enumeration type variable *os_chosen* is introduced, which is initially *-1*. It is set to *0* if the OS is chosen to execute and is set to and stays *1* in the following steps. In each EU module of the Ignore, the OSs of ignored Messages and other OSs are interleaved, which is captured by INVAR statements using the same strategy as the implementation of Parallel.

A Consider specifies a list of message types which should be considered within the CF. It is equivalent to ignore other message types, *i.e.*, the message types not in the list cannot appear in the CF, but they may occur. If a message type is considered but does not appear in the CF, the Messages of the type cannot occur within the CF. For example, if a Consider CF considers message type *q, v,* and *w*, but only Messages of message type *q* and *v* appear in the CF. Thus, Messages of message type *w* cannot occur within the CF. In a Consider, each OS of the considered Messages can be defined as a boolean variable in the EU module on the Lifeline where it is located. If the OS does not appear in the Consider, it is defined as a derived variable, whose value is *False* to indicate the OS will never occur. For other known but not considered Messages, their OSs are defined in the same way as the OSs of the ignored Messages.

We also provide the mapping of Interaction Use, Coregion, and General Ordering to the NuSMV modules. Due to space limitation, please refer to (Shen et al., 2011) for the details of translation.

5 Tool Suite Implementation and Evaluation

As a proof-of-concept, we have developed a tool suite, implementing the techniques described in this paper. Figure 5 is a data flow diagram, illustrating the architecture of our tool suite.

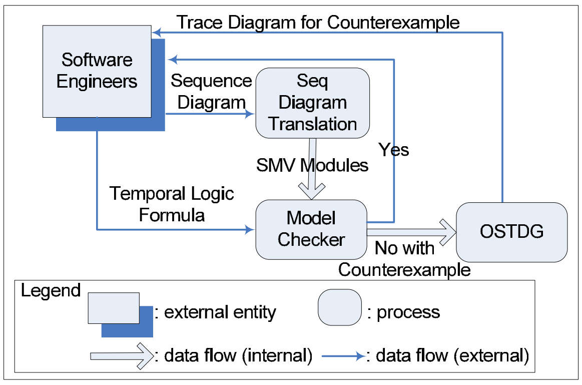


Figure 5: Architecture of Tool Suite.

The software engineer uses MagicDraw to create a Sequence Diagram, which can be converted to a textual representation in terms of XML using our MagicDraw plugin. The Sequence Diagram Translation tool takes the XML representation as input, parses it into a syntax tree, and transforms it into a NuSMV model. NuSMV model checker takes as input the generated NuSMV model and a temporal logic formula that is specified by the software engineer. If there are no property violations, the software engineer receives a positive response. If property violations exist, NuSMV generates a counterexample which is then passed to our Occurrence Specification Trace Diagram Generator (OSTDG) tool. The output from the OSTDG is an easy-to-read Sequence Diagram visualization of the counterexample to help the software engineer locate the property violation faster. Thus, the software engineer may transparently verify a Sequence Diagrams using NuSMV, staying solely within the notation realm of Sequence Diagrams.

We evaluate our technique with a case study of ISIS (Insurance Services Information System), a web application currently used by the specialty insurance industry. Our evaluation uses two Sequence Diagram examples from the design documentation of ISIS. We check the example on a Linux machine with a 3.00GHz, 8 cores CPU and 32GB of RAM. One example executed in 19 minutes 49 seconds with 3,825 reachable states out of total 3.71e+012 states, while the other example executed in 18 minutes 14 seconds with 192 reachable states out of total 4.95e+012 states. Please refer to (Shen et al., 2011) for more details of the case study and our tool suite.

6 RELATED WORK

Verification of scenario-based notation is well-accepted as an important and challenging problem. To the best of our knowledge, our technique is the first to support all CFs and the nested CFs. Lima *et al.* provide a tool to translate UML 2 Sequence Diagrams into PROMELA-based models and verify using SPIN, with counterexample visualizations (Lima et al., 2009). Their translation does not support Critical Region, Strict Sequencing, Negative, Assertion, Consider, Ignore, synchronous Messages and Interaction Constraint. Van Amstel *et al.* present four complementary approaches for analyzing UML 1.5 Sequence Diagrams, which do not support CFs (van Amstel et al., 2007). They model check Sequence Diagrams using SPIN. Alawneh *et al.* introduce a unified paradigm to verify and validate prominent UML 2 diagrams, including Sequence Diagrams, using NuSMV (Alawneh et al., 2006). Their approach supports Alternatives and Parallel.

To model check MSCs, Alur *et al.* (Alur and Yannakakis, 1999; Alur et al., 2005) formalize MSC using automata. They examine different cases of MSC verification of temporal properties and present techniques for iteratively specifying requirements (Alur et al., 2003). They focus on MSC Graph, which is an aggregation of MSCs. We extend their work to encompass more complicated aggregations using CFs. Peled *et al.* perform intensive research on the verification of MSCs (Muscholl et al., 1998; Gunter et al., 2001), in particular, they present an extension of the High-Level MSC (Peled, 2000). They specify MSC properties in temporal logic and check for safety and liveness properties. Leue *et al.* translate the MSC specification, especially branching and iteration of High-Level MSC, into PROMELA to verify MSCs using the XSPIN tool (Leue and Ladkin, 1996). As Sequence Diagrams have similar expressive features, our technique can be extended to work with their approach. Kugler *et al.* improve the technique of smart play-out, which is used to model check LSCs to avoid violations over computations (Kugler et al., 2009). Walkinshaw and Bogdanov (Walkinshaw and Bogdanov, 2008) detail an inference technique to constrain a finite-state model with LTL. These constraints reduce the number of traces required as input to a model checker for discovery of safety counter examples. Our work can automatically model check each Sequence Diagram of a system against LTL properties separately, which helps to alleviate the state explosion problem.

Micskei and Waeselynck survey comprehensively formal semantics proposed for Sequence Diagrams by 13 groups and present the different semantic options (Micskei and Waeselynck, 2011). In these groups, Knapp and Wuttke present an operational semantics for a translation of an Interaction into automata, which is used to model check UML state machines with SPIN or UPPAAL (Knapp and Wuttke, 2006).

Their approach does not support all CFs and the interpretation of automata restricts the specification of Interaction Constraints. Haugen *et al.* present the formal semantics of UML 2 Sequence Diagram through an approach named STAIRS (Haugen et al., 2005). STAIRS provides a trace-based representation for a subset of CFs, focusing on the refinement for Interactions. To relate state-based behaviors with scenario-based descriptions, Bontemps *et al.* formally study the problem of scenario checking, synthesis, and verification of the LSC (Bontemps et al., 2005). Their work focuses on providing an algorithm and proving the complexity for each problem. Uchitel *et al.* (Uchitel et al., 2003) synthesize a behavioral specification in the form of a Finite Sequential Process, which can be checked using their labeled transition system analyzer. With the semantic definition of Uchitel *et al.*, Damas *et al.* synthesize a labeled transition system model from both positive and negative scenarios, expressed in MSC (Damas et al., 2005).

7 CONCLUSIONS

In this paper, we present an approach to transform Sequence Diagrams and all CFs into NuSMV models. This enables software engineers to verify if a Sequence Diagram satisfies desired properties and visualize counterexamples as Sequence Diagrams to help user locate violations. We supplement our technique with a proof-of-concept tool suite and perform an evaluation using a case study of an industry web application. We believe our approach can be adapted to model check MSCs and High-Level MSCs.

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REFERENCES

Alawneh, L., Debbabi, M., Hassaine, F., Jarraya, Y., and Soeanu, A. (2006). A unified approach for verification and validation of systems and software engineering models. In *ECBS 2006*, pages 409–418.

Alur, R., Etessami, K., and Yannakakis, M. (2003). Inference of Message Sequence Charts. *TSE*, 29(7):623–633.

Alur, R., Etessami, K., and Yannakakis, M. (2005). Realizability and verification of MSC graphs. *Theoretical Computer Science*, 331(1):97–114.

Alur, R. and Yannakakis, M. (1999). Model checking of Message Sequence Charts. In *CONCUR*, volume 1664 of *LNCS*, pages 114–129.

Bontemps, Y., Heymans, P., and Schobbens, P.-Y. (2005). From Live Sequence Charts to state machines and back: A guided tour. *TSE*, 31(12):999–1014.

Cimatti, A., Clarke, E., Giunchiglia, F., and Roveri, M. (2000). NuSMV: a new symbolic model checker. *Int. Journal on Soft. Tools for Tech. Transfer*, 2:410–425.

Damas, C., Lambeau, B., Dupont, P., and van Lamsweerde, A. (2005). Generating annotated behavior models from end-user scenarios. *TSE*, 31(12):1056–1073.

Eichner, C., Fleischhack, H., Meyer, R., Schrimpf, U., and Stehno, C. (2005). Compositional semantics for UML 2.0 Sequence Diagram using Petri Nets. In *Int. SDL Forum*, volume 3530 of *LNCS*, pages 133–148.

Gunter, E. L., Muscholl, A., and Peled, D. (2001). Compositional Message Sequence Charts. In *TACAS*, volume 2031 of *LNCS*, pages 496–511.

Haugen, O., Husa, K. E., Runde, R. K., and Stolen, K. (2005). STAIRS towards formal design with Sequence Diagrams. *Soft. and Sys. Modeling*, 4(4):355–357.

Knapp, A. and Wuttke, J. (2006). Model checking of UML 2.0 interactions. In *MODELS*, volume 4364 of *LNCS*, pages 42–51.

Kugler, H., Harel, D., Pnueli, A., Lu, Y., and Bontemps, Y. (2005). Temporal logic for scenario-based specifications. In *TACAS*, volume 3440, pages 445–460.

Kugler, H., Plock, C., and Pnueli, A. (2009). Controller synthesis from LSC requirements. In *FASE*, volume 5503 of *LNCS*, pages 79–93.

Leue, S. and Ladkin, P. B. (1996). Implementing and verifying MSC specifications using PROMELA/XSPIN. In *SPIN96*, volume 32 of *DIMACS*, pages 65–89.

Lima, V., Talhi, C., Mouheb, D., Debbabi, M., Wang, L., and Pourzandi, M. (2009). Formal verification and validation of UML 2.0 Sequence Diagrams using source and destination of messages. *Electron. Notes Theor. Comput. Sci.*, 254:143–160.

Micskei, Z. and Waeselynck, H. (2011). The many meanings of UML 2 Sequence Diagrams: a survey. *Software and Systems Modeling*, 10(4):489–514.

Muscholl, A., Peled, D., and Su, Z. (1998). Deciding properties of Message Sequence Charts. In *Int. Conf. on Foundations of Soft. Sci. and Computation Structure*, volume 1378 of *LNCS*, pages 226–242.

Object Management Group (2011). Unified Modelling Language (Superstructure), v2.4.1, 2011. Internet: www.omg.org.

Peled, D. (2000). Specification and verification of Message Sequence Charts. In *FORTE*, pages 139–154.

Shen, H., Robinson, M., and Niu, J. (2011). A logical framework for Sequence Diagram with Combined Fragments. Technical Report CS-TR-2011-015, UTSA.

Uchitel, S., Kramer, J., and Magge, J. (2003). Synthesis of behavioral models from scenarios. *TSE*, 29(2):99–115.

van Amstel, M., Lange, C., and Chaudron, M. (2007). Four automated approaches to analyze the quality of UML Sequence Diagrams. In *COMPSAC*, volume 2, pages 415–424.

Walkinshaw, N. and Bogdanov, K. (2008). Inferring finite-state models with temporal constraints. In *ASE*, pages 248–257.