

TemPsy-Check: a Tool for Model-driven Trace Checking of Pattern-based Temporal Properties

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Abstract

TemPsy (Temporal Properties made easy) is a pattern-based, domain-specific language for the specification of temporal properties. In this paper we provide an overview of TemPsy-Check, a tool that implements a model-driven approach for performing offline trace checking of temporal properties written in TemPsy. TemPsy-Check relies on an optimized mapping of temporal requirements written in TemPsy into Object Constraint Language (OCL) constraints on a conceptual model of execution traces.

1 Introduction

The tool presented in this paper has been developed as part of a research collaborative project that we run with our public service partner CTIE (Centre des technologies de l'information de l'Etat, the Luxembourg national center for information technology), on model-driven runtime verification of business processes [8]. In this project we have investigated the use of trace checking for detecting anomalous behaviors of eGovernment business processes and for checking whether third-parties (e.g., other administrations, suppliers) involved in the execution of the process fulfill their guarantees.

The context of this project set three main requirements for the development of the solution:

- R1) when analysts do not have adequate skills to make use of temporal logic, an *alternative* domain-specific language should be provided to facilitate the specification of business process requirements;
- R2) to be viable in the long term, any solution shall rely on standard and stable MDE (model-driven engineering) technology for checking the compliance of a system to its application requirements;
- R3) any solution shall be scalable, such that a trace with millions of events could be checked within seconds.

To fulfill requirement R1, in previous work [7] we proposed *OCLR*, a domain-specific language for the specification of temporal properties, based on the catalogue of property specification patterns defined by Dwyer et al. [10], and extended with additional constructs. The language has been defined in collaboration with the CTIE analysts, based on the analysis of the requirements specifications of an industrial case study. The most recent version of the language, now called *TemPsy* (Temporal Properties made easy) [6], sports a syntax close to natural language, has all the constructs required to express the property specification patterns found in our case study, and has a precise semantics expressed in terms of linear temporal traces.

To fulfill requirements R2 and R3, in previous work [9] we proposed a scalable model-driven trace checking procedure, which relies on a mapping of temporal requirements written in *TemPsy* into Object Constraint Language (OCL) [14] constraints on a conceptual model of execution traces. This mapping is optimized based on the structure of the *TemPsy* property to check, in order to achieve better performance.

In this paper we discuss the TEMPSY-CHECK tool¹, which implements the procedure presented in [9]. TEMPSY-CHECK is available at <http://weidou.github.io/TemPsy-Check/>.

2 The *TemPsy* language

TemPsy [6] is the most recent version of our previous proposal [7] for a pattern-based, domain-specific specification language for temporal properties; it is based on an extended version of the catalogue of property specification patterns defined in [10].

The design of *TemPsy* has been driven by the analysis of the requirements documentation of various applications developed as business processes by our partner. This analysis revealed that the vast majority of these requirements could be expressed as temporal properties, enriched with timing information. More specifically, we were able to recast most of specifications written in natural language using the system of property specification patterns of Dwyer et al. In some cases, we extended the original definitions proposed in [10] to match the specifications; these extensions are:

- 1) The possibility, in the definition of a scope boundary, to refer to a specific occurrence of an event, as in “before the second occurrence of event X ...”. In the original definition of the pattern systems, boundaries of scopes refer implicitly to the first occurrence of an event.
- 2) The possibility to indicate a time distance with respect to a scope boundary, as in “at least two time units before the n -th occurrence of event X ...”.
- 3) Support for expressing time distance between events occurrences in the precedence and response patterns as well as in their chain versions, for expressing properties such as “event B should occur in response to event A within 2 time units”.
- 4) Additional variants for the bounded existence and absence patterns.

By design, *TemPsy* does not aim at being as expressive as a full-fledged temporal logic. Instead, its goal is to make as easy as possible the specification of the temporal requirements of business processes, by supporting only the constructs needed to express temporal requirements commonly found in business process applications. *TemPsy* has received positive feedback from our partner, which has deemed it as suitable communication mechanism to express the requirements specifications of business processes. Our partner has integrated *TemPsy* into the SoftwareAG ARIS modeling tool [15], and its analysts have started using it to annotate business process models with *TemPsy* specifications.

2.1 Syntax

The syntax of *TemPsy* is shown in Fig. 1: non-terminals are enclosed in angle brackets, terminals are enclosed in single quotes, optional elements are enclosed in brackets, the character ‘+’ indicates one or more occurrences of an element, the character ‘*’ indicates zero or more occurrences of an element.

A *TemPsy* property, which is denoted by the non-terminal $\langle TemPsyBlock \rangle$, comprises a set of $\langle TemPsyExpression \rangle$ s combined by conjunction. Each *TemPsy* expression starts with an optional ‘temporal’ keyword and has an optional alphanumeric identifier, followed by a $\langle Scope \rangle$ and a $\langle Pattern \rangle$. A $\langle Scope \rangle$ indicates the segment(s) of an execution trace in which a $\langle Pattern \rangle$ should hold.

The keywords indicating the five $\langle Scope \rangle$ s identify univocally the corresponding scopes from [10] (‘globally’, ‘before’, ‘after’, ‘between’-‘and’, ‘after’-‘until’). As for the $\langle Pattern \rangle$ s,

¹TEMPSY-CHECK can be considered a profound and optimized revision of its predecessor OCLR-CHECK, which was based on OCLR and participated in the 2nd Competition on Runtime Verification in 2015 [13].

```

⟨TemPsyBlock⟩      ::= ⟨TemPsyExpression⟩+
⟨TemPsyExpression⟩ ::= [‘temporal’ ⟨Id⟩ ‘:’] ⟨Scope⟩ ⟨Pattern⟩
⟨Scope⟩           ::= ‘globally’
                    | ‘before’ ⟨Boundary1⟩
                    | ‘after’ ⟨Boundary1⟩
                    | ‘between’ ⟨Boundary2⟩ ‘and’ ⟨Boundary2⟩
                    | ‘after’ ⟨Boundary2⟩ ‘until’ ⟨Boundary2⟩
⟨Pattern⟩         ::= ‘always’ ⟨Event⟩
                    | ‘eventually’ ⟨RepeatableEventExp⟩
                    | ‘never’ [‘exactly’ ⟨Int⟩] ⟨Event⟩
                    | ⟨EventChainExp⟩ ‘preceding’ [⟨TimeDistanceExp⟩] ⟨EventChainExp⟩
                    | ⟨EventChainExp⟩ ‘responding’ [⟨TimeDistanceExp⟩] ⟨EventChainExp⟩
⟨Boundary1⟩       ::= [⟨Int⟩] ⟨Event⟩ [⟨TimeDistanceExp⟩]
⟨Boundary2⟩       ::= [⟨Int⟩] ⟨Event⟩ [‘at least’ ⟨Int⟩ ‘tu’]
⟨EventChainExp⟩   ::= ⟨Event⟩ (‘,’ [‘#’ ⟨TimeDistanceExp⟩] ⟨Event⟩)*
⟨TimeDistanceExp⟩ ::= ⟨ComparingOp⟩ ⟨Int⟩ ‘tu’
⟨RepeatableEventExp⟩ ::= [⟨ComparingOp⟩ ⟨Int⟩] ⟨Event⟩
⟨ComparingOp⟩     ::= ‘at least’ | ‘at most’ | ‘exactly’
⟨Event⟩           ::= ⟨Id⟩
⟨Id⟩              ::= ⟨IdStartChar⟩ ⟨IdChar⟩*
                    | ⟨Id⟩ (⟨IdConnector⟩ ⟨Id⟩)*
⟨IdStartChar⟩     ::= [A-Z] | ‘_’ | [a-z]
⟨IdChar⟩          ::= ⟨IdStartChar⟩ | [0-9]
⟨IdConnector⟩     ::= ‘.’ | ‘::’
⟨Int⟩             ::= [1-9] ([0-9])*

```

Figure 1: Syntax of *TemPsy*

‘always’ corresponds to universality, ‘eventually’ to existence, ‘never’ to absence, ‘preceding’ to precedence and precedence chain, ‘responding’ to response and response chain.

The definition of *⟨Scope⟩*s and *⟨Pattern⟩*s refers to the concept of *⟨Event⟩*. We assume that an *⟨Event⟩* is represented by an alphanumeric string, to match the event names logged in the execution trace on which the properties specified in *TemPsy* are meant to be checked. *⟨Scope⟩*s contain boundaries (expressed with *⟨Boundary1⟩* or *⟨Boundary2⟩*) that denote a specific occurrence of an event as a boundary, possibly with a time distance; notice that *⟨Boundary2⟩* represents a syntactic restriction of *⟨Boundary1⟩*. Chains of events, used in *precedence* and *response* patterns, are defined as *⟨EventChainExp⟩*, which denotes a comma-separated list of events, possibly with a time distance (*⟨TimeDistanceExp⟩*) between each pair of events (denoted with the ‘#’ symbol). Time distances are expressed with an integer value, followed by the ‘tu’ keyword, which represents a generic time unit (i.e., any denomination of time).

2.2 *TemPsy* at Work

We now present some examples of properties that can be expressed with *TemPsy*, in order to provide the reader with a high-level, intuitive understanding of the language. We consider the

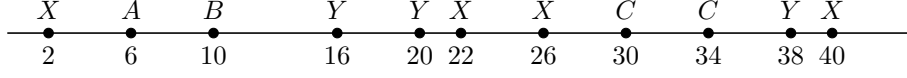


Figure 2: An event trace on which to evaluate the properties described in section 2.2; events are above the line, timestamps below

execution trace shown in Fig. 2 and for each property² indicate whether it is violated or not by the trace. First, we define the properties in English:

- p1) “Event *C* shall happen 8 time units after the second occurrence of event *X*.” (satisfied)
- p2) “Event *A* shall happen within 30 time units after the first occurrence of event *X*.” (satisfied)
- p3) “Event *C* shall eventually happen after at least 3 time units since the first occurrence of event *X*; and it shall happen before event *Y* if the latter happens.” (violated because event *C* occurs after event *Y*)
- p4) “After the second occurrence of event *X*, event *C* shall eventually happen exactly twice.” (satisfied)
- p5) “Event *C* shall happen at least once between every first occurrence of event *X* and the next event *Y*; the time interval between event *X* and the first occurrence of event *C* shall be at least 5 time units.” (violated because event *C* does not occur between the first segment delimited by event *X* on the left and event *Y* on the right)
- p6) “Event *B* shall happen at least 3 time units before the first occurrence of event *Y*.” (satisfied)
- p7) “Before the first occurrence of event *Y*, once event *X* occurs, event *A* shall happen followed by event *B*; the time interval between *X* and *A* shall be at least 3 time units.” (satisfied)

The corresponding *TemPsy* expressions are shown below:

- temporal p1: after 2 *X* exactly 8 tu eventually *C*
- temporal p2: after *X* at most 30 tu eventually *A*
- temporal p3: after 1 *X* at least 3 tu until *Y* eventually *C*
- temporal p4: after 2 *X* eventually exactly 2 *C*
- temporal p5: between *X* at least 5 tu and *Y* eventually at least 1 *C*
- temporal p6: before *Y* at least 3 tu eventually *B*
- temporal p7: before *Y* *A*, *B* responding at least 3 tu *X*

The informal semantics of *TemPsy* is described in the appendix. The formal semantics is described in the online technical report [6].

²These properties are given as an example and should be considered individually, rather than together as a set; they do not correspond to the specification of a real system.

3 Model-driven Trace Checking with *TemPsy*

The idea at the basis of the model-driven trace checking approach implemented by *TemPsy* is to *reduce* the problem of checking a *TemPsy* property ρ over a trace λ , to the problem of evaluating an OCL constraint (semantically equivalent to ρ) on an instance of a conceptual model for execution traces (equivalent to λ).

This reduction allows us to rely on standard and stable MDE technology to perform offline trace checking. Indeed, standard OCL checkers, such as Eclipse OCL [11], can be used to evaluate OCL constraints on model instances. The use of a model-driven approach and of standard technologies fulfills requirement R2 stated in section 1, and enables us to provide a practical and scalable solution for trace checking of temporal properties, which is also viable in the long term.

At the basis of this approach there is the definition of a conceptual model for execution traces, since the transformation of *TemPsy* properties into efficiently checkable *OCL constraints defined on such model* is a key strategy for us to achieve scalability. The model, not depicted here for space reasons, contains a **Trace**, which is composed of a sequence of **TraceElements**, accessed through the association **traceElements**. Each **TraceElement** contains an attribute **event** of type string, which represents the actual event recorded in the trace, and an attribute **timestamp** of type integer, which indicates the time at which the event occurred.

The **Trace** class contains some side-effect-free operations in OCL; operations consist of two types of functions. The first type, of the form **applyScope*S***, are named after the different types of scope (e.g., **applyScopeBefore**) and return segment(s) of a trace (i.e., sub-traces) as determined by the parameters of the scope provided in input. The second type, of the form **checkPattern*P***, are named after the different types of pattern (e.g., **checkPatternExistence**) and check whether the pattern provided in input as the second parameter holds on the sub-trace(s) represented by the first parameter.

TEMPSY-CHECK, when given in input a set of properties to check and a trace file, creates an instance of the **Trace** class based on the trace input file.

The key step of our approach is to evaluate an OCL invariant on this trace instance for every *TemPsy* property provided in input. The checking of this invariant, which can be done using standard OCL checking tools, is semantically equivalent to performing trace checking of the *TemPsy* property. The invariant is roughly equivalent to this OCL expression:

```

1 context Trace
2 inv: let subtraces=applyScope*S*(scope) in
3     subtraces->forAll(subtrace |
4         checkPattern*P*(subtrace, pattern))

```

Notice that in the actual constraints, the placeholder ***S*** is replaced with a string from {Globally, Before, After, BetweenAnd, AfterUntil} and the placeholder ***P*** is replaced with a string from {Universality, Existence, Absence, Precedence, Response}. These strings correspond, respectively, to the scope and the pattern used in the input *TemPsy* property to check. In the invariant, the variable **subtraces** contains the portion(s) of the trace returned by the function **applyScope*S***, which takes an instance of a *TemPsy* **Scope** as input parameter. The invariant checks, by calling the function **checkPattern*P***, whether the input **pattern** holds on each sub-trace in **subtraces**.

The details of the procedure implemented by TEMPSY-CHECK and the definition of the various OCL functions of type **applyScope*S*** and **checkPattern*P*** are available in [9, 6].

4 Implementation

The implementation of TEMPSY-CHECK is based on Xtext [12] and Eclipse OCL [11]. The tool takes as input a list of *TemPsy* expressions represented in an XMI-based format and a trace instance in CSV format. Any *TemPsy* expressions defined in the textual notation shown in Fig. 1 can be converted to the XMI-based format using another tool included in the distribution. TEMPSY-CHECK provides file readers for loading *TemPsy* expressions and trace instances; it can be extended to support other formats thanks to its design following the *Strategy Pattern*. Moreover, we have developed a Java class `ConstraintFactory` to help build OCL constraints corresponding to the input *TemPsy* expressions. The evaluation of the OCL invariants is done using the OCL checker included in Eclipse. The boolean output of the checker is then returned to the user.

5 Summary of Experimental Results

To fulfill requirement R3, we extensively evaluated the scalability of TEMPSY-CHECK by assessing the relationship among the checking time, the structural properties of a trace (e.g., length, distribution of events), and the type of property to check; we used real properties extracted from a case study developed in collaboration with our partner CTIE, on traces with length ranging from 100K to 1M. We also compared the performance of TEMPSY-CHECK with MONPOLY [3], a state-of-the-art alternative technology, selected from the participants to the “offline monitoring” track of the international Competition on Software for Runtime Verification [2, 13].

The experimental results show that TEMPSY-CHECK can load and analyze very large traces (with one million events) in about two seconds and that it scales linearly with respect to the length of the trace to check. The results also show that TEMPSY-CHECK in practice performs similarly to or better than³ the state-of-the-art, depending on the type of properties, confirming the feasibility and benefits of a model-driven approach for trace checking of temporal properties.

The detailed evaluation methodology and the complete evaluation data are available in [9, 6].

6 Discussion and Future Work

In this paper we have provided an overview of our tool TEMPSY-CHECK, a practical and scalable solution for trace checking of pattern-based temporal properties written in *TemPsy*. TEMPSY-CHECK relies on an efficient mapping of requirements written in *TemPsy* into regular OCL constraints on a conceptual model for execution traces. We have applied TEMPSY-CHECK for the verification of real properties derived from a case study of our public service partner in the context of eGovernment business process modeling. More in general, TEMPSY-CHECK can be used in contexts where model-driven engineering is already a practice and where relying on standards and industry-strength tools for property checking is a fundamental prerequisite.

As part of future work, we plan to extend TEMPSY-CHECK to provide a more informative output than the boolean result currently returned when violations are detected in a trace, by adding support for interactive inspection of violations. We also plan to extend *TemPsy* and TEMPSY-CHECK to support the service provisioning specification patterns introduced in [4] and implemented in the SOLOIST language [5].

³ We remark that the specification language of MONPOLY (MFOTL) is more expressive than *TemPsy* (e.g., by supporting first-order quantification), hence the performance of MONPOLY could have been negatively affected by the more complex implementation needed to support a richer specification language.

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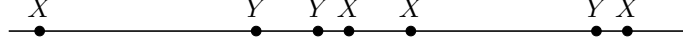


Figure 3: A sample trace for the description of scopes

A Informal semantics of *TemPsy*

In this section we present the informal semantics of the scopes and the patterns supported in *TemPsy* expressions; they correspond to non-terminals $\langle Scope \rangle$ and $\langle Pattern \rangle$, respectively. In the following, symbols A, B, C, D, X, Y, Z represent strings that can be derived from non-terminal $\langle Event \rangle$; ‘m’, ‘m1’, ‘m2’, ‘n’, ‘n1’, and ‘n2’ are integers derived from the non-terminal $\langle Int \rangle$; ‘tu’ stands for “time unit(s)”.

A.1 Scopes

For the description of scopes, we refer to the trace of events depicted in Fig. 3; to avoid cluttering, the figure does not show the events not used in the explanations. We use symbols X and Y as shorthands for events that can be derived from the non-terminal $\langle Event \rangle$.

Globally. This scope corresponds to the entire trace shown in Fig. 3.

Before. The general template for this scope in *TemPsy* is “before [m] X [$\langle ComparingOp \rangle$ n tu]”; it can be expanded in four forms: 1) “before X ”, 2) “before X [$\langle ComparingOp \rangle$ n tu]”, 3) “before m X ”, 4) “before m X [$\langle ComparingOp \rangle$ n tu]”. The first two forms are convenient shorthands for the third and fourth ones, respectively, with $m = 1$. The form “before m X ” selects the portion of the trace up to the m -th occurrence of event X ; see, for example, the top row in Fig. 4a, where the interval from the origin of the trace up to the third occurrence of X is highlighted with a thick line. The form “before m X [$\langle ComparingOp \rangle$ n tu]” has three variants, depending on the possible expansions of non-terminal $\langle ComparingOp \rangle$:

- “before m X at least n tu” identifies the scope from the origin of the trace up to n time units before the m -th occurrence of X ;
- “before m X at most n tu” identifies the scope starting at n time units before the m -th occurrence of X and bounded to the right by the m -th occurrence of X ;
- “before m X exactly n tu” pinpoints the time instant at n time units before the m -th occurrence of X .

Examples of the first two variants of scopes are shown with thick segments in the second and third rows of Fig. 4a; for the last variant, see the last row of Fig. 4a, where the time instant selected by the scope is enclosed with a circle. In all examples, we have $m=3$ and $n=2$.

After. It has a dual semantics with respect to the *before* scope. We provide an intuition of its semantics using Fig. 4b.

Between-And. The general template for this scope in *TemPsy* is “between [m1] X [at least n1 tu] and [m2] Y [at least n2 tu]”; it can be expanded in four forms:

- “between m_1 X [at least n_1 tu] and m_2 Y [at least n_2 tu]”;
- “between X [at least n_1 tu] and m_2 Y [at least n_2 tu]”;
- “between m_1 X [at least n_1 tu] and Y [at least n_2 tu]”;
- “between X [at least n_1 tu] and Y [at least n_2 tu]”.

The first form is the most general: it selects the single segment of the trace delimited by the m_1 -th occurrence of event X and the m_2 -th occurrence of event Y happening after the m_1 -th

occurrence of X . The second and third forms are shorthands for the first one, with $m1=1$ and $m2=1$, respectively. The fourth form is the closest to the original definition in [10], since it selects all the segments in the trace delimited by the boundaries. In this regard, notice the difference with respect to the expression “**between 1 X and 1 Y** ”, which selects the segment delimited by the first occurrence of X and the first occurrence of Y after X . In all forms it is possible to use the expression **at least n tu** when defining boundaries, with the same meaning described for the scope *before*. Four examples of the *Between-and* scope are shown in Fig. 4c.

After-Until. This scope is similar to *Between-and*, with the difference that each identified segment extends to the right in case the event defined by the second boundary does not occur; this peculiarity can be noticed in the first two rows of Fig. 4d (also by comparing them with the corresponding ones in Fig. 4c), as well as in the last row.

Note that all scopes are open on the bounds delimited by a boundary events: i.e., in general⁴, the *before* scope is closed on the left and open on the right; the *after* scope is open on the left and closed on the right; the *between-and* scope is open on both bounds; the *after-until* scope is open on both bounds when the right boundary event occurs, or is open on the left and closed on the right when the right boundary event does not occur.

A.1.1 Patterns

TemPsy supports eight of the nine patterns defined in [10]; below we only highlight the semantics for the patterns that have been extended upon inclusion in *TemPsy*.

Existence. This pattern comes in four forms:

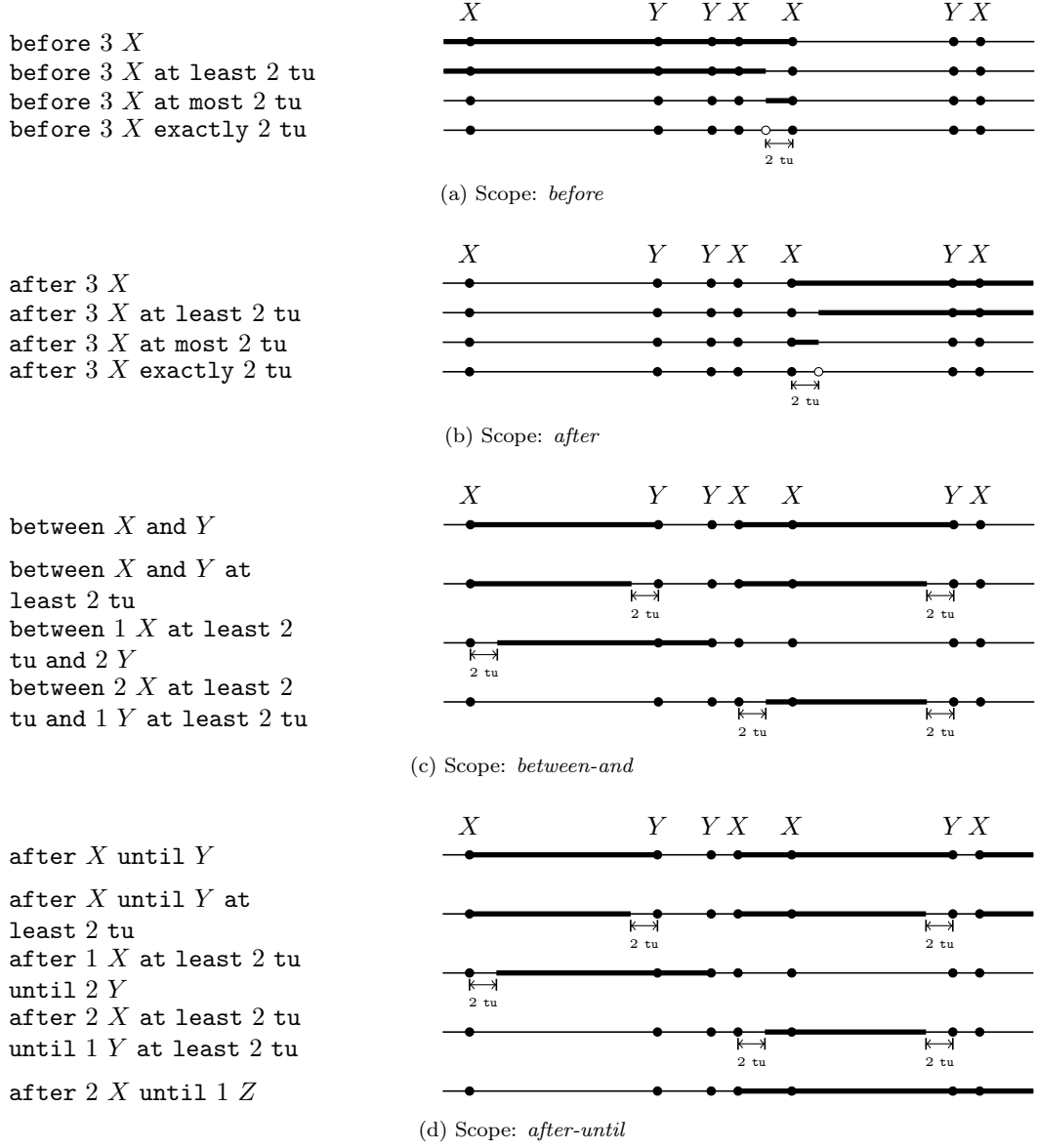
- “**eventually A** ” indicates that event A will eventually happen at least once;
- “**eventually at least m A** ” indicates that event A will eventually happen at least m times;
- “**eventually at most m A** ” indicates that event A will eventually happen at most m times;
- “**eventually exactly m A** ” indicates that event A will eventually happen exactly m times.

The last three forms are variants of the *bounded existence* pattern, a subclass [1] of the *existence* one.

Absence. This pattern states that a certain event *never* occurs in the given scope. In addition, *TemPsy* makes also possible to specify that a specific number of occurrences of the same event should not happen, as in “**never exactly 2 X** ”, which indicates that X should never occur exactly twice.

Precedence. This pattern (also available in the variant called *precedence chain*) indicates the precondition relationship between a pair of events (respectively, the two blocks of a chain) in which the occurrence of the second event (respectively, block) depends on the occurrence of the first event (respectively, block). Based on this original definition, we added support for timing information to enable expressing the time distance between two adjacent events. The semantics can be explained using the following example and the event trace in Fig. 5; the expression “ **A preceding at most 10 tu B , #at least 5 tu C** ” indicates that the event A is the precondition of the block “ B followed by C ”, that the time distance between A and B should be at most 10 time units, and the time distance (expressed using the # symbol) between events B and C should be at least 5 time units. Here, A (left-hand side of ‘preceding’) represents the

⁴The scopes that contain constraints on time distance from the boundary events (with “**at least**” and “**exactly**”) are closed.


 Figure 4: Examples of *TemPsy* scopes

first block of the chain, while the expression “ B , #at least 5 tu C ” represents the second block (right-hand side of ‘preceding’).

Response. This pattern (also available in the variant called *response chain*) specifies the cause-effect relationship between a pair of events (respectively, the two blocks of a chain) in which the occurrence of the first event (respectively, first block) leads to the occurrence of the second event (respectively, second block). Similarly to the previous pattern, we added support for timing information to enable expressing the time distance between two adjacent events. The semantics can be explained using the following example and the event trace in Fig. 5;

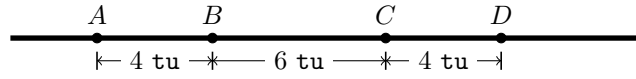


Figure 5: Example trace for illustrating the precedence and response patterns

the expression “ C, D **responding at most 10 tu** A , **#at least 5 tu** B ” specifies that two successive events A and B stimulate the sequential occurrence of C and D , the time interval between A and B should be at least 5 time units, and the time interval between B (second element of the first block) and C (first element of the second block) should be at most 10 time units. This property is violated by the example in Fig. 5, because the time distance between A and B is only 4 time units.