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Semantic-based Weaving of Scenarios

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ABSTRACT
The notion of aspect looks promising for handling crosscutting concerns earlier in the software life-cycle, up from programming to design, analysis and even requirements. Support for aspects is thus now raising interest also at the modeling level, including with behavioral modeling languages such as scenarios. With this kind of modeling languages, even if aspect weaving can be performed at the abstract syntax level, a weaving at the semantics level seems a far more appealing and powerful mechanism. In this paper we present a semantic-based aspect weaving algorithm for Hierarchical Message Sequence Charts (HMSCs). The algorithm proposed uses a set of transformations that take into account the compositional semantics of HMSCs to weave an initial HMSC and a behavioral aspect expressed with scenarios.

Keywords
Aspects Weaving, Scenarios, Aspect-Oriented Modeling

1. INTRODUCTION
The idea of encapsulating crosscutting concerns into the notion of aspects looks very promising for complementing the usual notion of modules available in most languages. By localizing these crosscutting concerns, the software engineer can get a greater control over variations, either in the spatial dimension (product line context) or in the temporal dimension (software evolutions). The need to isolate these crosscutting concerns has been popularized by the Aspect-J programming language, but there is a growing interest in also handling them earlier in the software life-cycle, for instance at design time [2], or during requirements analysis [1], [17], [16], [10]. Beyond being able to represent aspects at requirement or design time, an automatic aspect weaver at these stages can be very useful for validation purposes (simulation or test case generation) and also for targeting non-aspect-oriented platforms (e.g., vanilla Java).

Many works address aspect weaving at the model level, including with behavioral modeling languages such as scenario languages. Within this paper, we choose High-level Message Sequence Charts (HMSCs) as the scenario model. With behavioral models, aspect weaving can be performed either at the abstract syntax level (where weaving simply consists of searching for a specific pattern that shall be replaced in the syntactic definition of some behaviors), or at the semantic level (where weaving consists of replacing a part of the behaviors defined by the semantics of the description with another behavior). This makes a real difference: syntactic weaving directly transforms a description X into a description X' with aspects, while semantic weaving transforms X into another description X such that the semantics of X' is the semantics of X woven with an aspect.

Consider for instance the simple HMSC H of Figure 1, which contains a loop over a basic scenario with messages 'try again' and 'new attempt'. Suppose we want to weave some extra-behavior into our system every time a message 'try again' directly follows a message 'new attempt'. A simple way to define a behavioral aspect is firstly to specify a pointcut with a scenario representing the behavior to detect, and secondly to specify the expected behavior with another scenario (called the advice in Figure 2). When weaving is performed at a syntactic level, since the pointcut described by our aspect does not appear explicitly in the HMSC of Figure 1, the description would remain unchanged. At the semantic level, some executions defined by our HMSC may contain parts that are matched by our pointcut, and should then be replaced. The main idea is to compute the HMSC of Figure 4, whose semantics is exactly the semantics of H where all join points have been completed by the additional behaviors specified within the advice. Note that this kind of weaving cannot be defined as a simple syntactic replacement since it is applied on the semantics of the model, i.e. on behaviors generated by a HMSC. As we will discuss later in the paper, the weaving of behavioral aspects may even be intractable in some cases.

The rest of the paper is organized as follows. Section 2 presents the scenario language used for behavioral weaving and the general principles of our semantics-based aspect weaving algorithm. Section 3 introduces some definitions related to the detection of a pointcut within a scenario. Section 4 presents several transformations allowing the application of the weaving operation. Section 5 presents limitations of our approach. Section 6 compares our
2. SCENARIOS AND WEAVING

Scenario languages are usually used to describe behaviors of distributed systems at an abstract level or to capture requirements in early development stages with a clear structure. Various languages, such as SDL and UML, define sequence diagrams that describe sequential interactions between system components. However, these languages do not formally define the set of events linked by action names and by the names of each action occurrence. In the sequel, we define MSC to provide a formal approach to sequence diagrams. MSCs (sequence models) describe the set of events linked by action names and the names of each action occurrence.

DEFINITION 1. (Basic MSC) A basic MSC is a triple $M = (E, A, F)$, where $E$ is a set of events, $A$ is a set of action names (or occurrence names), and $F$ is a set of occurrence links. $E$ is ordered by action names, and $A$ is ordered by occurrence links.

DEFINITION 2. (Hierarchical MSC) A hierarchical MSC is a graph $H = (V, E, A, F)$, where $V$ is a set of nodes, $E$ is a set of transitions, $A$ is a set of action names, and $F$ is a set of occurrence links. $V$ is ordered by action names, $E$ is ordered by occurrence links, and $F$ is ordered by occurrence links.

DEFINITION 3. (Sequential Composition of Two MSCs) $M_1 = (E_1, A_1, F_1)$ and $M_2 = (E_2, A_2, F_2)$ are two MSCs. The sequential composition of $M_1$ and $M_2$ is defined as $M_1 \circ M_2 = (E_1 \cup E_2, A_1 \cup A_2, F_1 \cup F_2)$, where $E_1 \circ E_2 = \{ (e_1, e_2) \mid e_1 \in E_1, e_2 \in E_2, e_1 \neq e_2 \}$. The sequential composition is a way to combine two MSCs into a single MSC by connecting their events. The resulting MSC describes the sequence of events in the combined system.

DEFINITION 4. (Parallel Composition of Two MSCs) $M_1 = (E_1, A_1, F_1)$ and $M_2 = (E_2, A_2, F_2)$ are two MSCs. The parallel composition of $M_1$ and $M_2$ is defined as $M_1 \parallel M_2 = (E_1 \cup E_2, A_1 \cup A_2, F_1 \cup F_2)$, where $E_1 \parallel E_2 = \{ (e_1, e_2) \mid e_1 \in E_1, e_2 \in E_2, e_1 \neq e_2 \}$. The parallel composition is a way to combine two MSCs into a single MSC by connecting their events. The resulting MSC describes the parallel execution of the two systems. The events in the parallel composition are executed concurrently.

DEFINITION 5. (Interleaving Composition of Two MSCs) $M_1 = (E_1, A_1, F_1)$ and $M_2 = (E_2, A_2, F_2)$ are two MSCs. The interleaving composition of $M_1$ and $M_2$ is defined as $M_1 \cdot M_2 = (E_1 \cup E_2, A_1 \cup A_2, F_1 \cup F_2)$, where $E_1 \cdot E_2 = \{ (e_1, e_2) \mid e_1 \in E_1, e_2 \in E_2, e_1 \neq e_2 \}$. The interleaving composition is a way to combine two MSCs into a single MSC by connecting their events. The resulting MSC describes the interleaved execution of the two systems. The events in the interleaving composition are executed in an alternating order.

DEFINITION 6. (Iteration Composition of Two MSCs) $M_1 = (E_1, A_1, F_1)$ and $M_2 = (E_2, A_2, F_2)$ are two MSCs. The iteration composition of $M_1$ and $M_2$ is defined as $M_1 \ast M_2 = (E_1 \cup E_2, A_1 \cup A_2, F_1 \cup F_2)$, where $E_1 \ast E_2 = \{ (e_1, e_2) \mid e_1 \in E_1, e_2 \in E_2, e_1 \neq e_2 \}$. The iteration composition is a way to combine two MSCs into a single MSC by connecting their events. The resulting MSC describes the iterative execution of the two systems. The events in the iteration composition are executed in a repeated order.
this definition, $\mathcal{V}$ is the disjoint union of two multisets, i.e. an usual union operation where common elements of both sets are duplicated.

We will also denote by $M^k$ the sequential concatenation of $k$ copies of $M$, and by $M^*$ the set $\bigcup_{k\geq 0} M^k$ with the convention that $M^0 = M$. When two bMSCs $M_1, M_2$ are such that $M_1^* M_2 = M_1^* M_2$, we will say that $M_1$ and $M_2$ are independent, and write $M_1 | M_2$ (this situation occurs only when $\phi(E_1) \cap \phi(E_2) = \emptyset$). A bMSC $B$ will be called an atom if there does not exist two bMSCs $N \neq M$ and $M \neq N$, such that $B = M \cdot N$. For a set of bMSCs $\mathcal{M}$, we will denote by $\mathcal{A}(\mathcal{M})$ the set of all atoms of bMSCs in $\mathcal{M}$. Note that an algorithm to find a decomposition of a bMSC into atoms can be found in [7]. For a given bMSC $M$ such that $M = X_1 \cdots X_k$, where all $X_i$’s are bMSCs, $X_1 \cdots X_k$ will be called a factorization of $M$.

An initial path of a HMSC $H$ is a sequence of transitions $p = t_1 t_2 \ldots t_k$ such that the origin of $t_1$ is the initial node $q_0$. Moreover, the goal of $t_k$ is a node of $Q_{end}$, then $p$ is called an accepting path. The bMSC $\lambda(p)$ associated to a path $p$ is the sequential composition of bMSCs labeling the transitions, $\lambda(p) = \lambda(t_1) \lambda(t_2) \cdots \lambda(t_k)$. The semantics of a HMSC $H$ is the set of behaviors defined by concatenation of labels along all accepting paths, i.e. the set of bMSCs $\mathcal{L}(H) = \{\lambda(p) | p \text{ is an accepting path of } H\}$.

### Figure 4: Result of the weaving

A **behavioral aspect** is a pair $A = (P, Ad)$ of bMSCs. $P$ is a pointcut, i.e. a bMSC interpreted as a predicate over the semantics of HMSCs satisfied by all join points. $Ad$ is an advice, i.e. the new behavior that should replace the base behavior when it is matched by $P$. Similarly to Aspect-J, where an aspect can be inserted 'around', 'before' or 'after' a join point, with our approach, an advice may indifferently complete the matched behavior, replace it with a new behavior, or remove it entirely. For a given bMSC $M$ and a given aspect $A$, we will denote by $M \otimes A$ the bMSC obtained by replacing sequentially every occurrence of $P$ by $Ad$ in $M$ (we will detail in section 3 how this replacement mechanism is implemented).

Consider a HMSC $H$ and a behavioral aspect $A = (P, Ad)$. The goal of the semantic-based weaver is to produce a new HMSC $H'$ where the aspect $A$ is woven every time that the pointcut is detected within a bMSC $M$ of $\mathcal{L}(H)$. More formally, after weaving we should have $\mathcal{L}(H') = \{M \otimes A | M \in \mathcal{L}(H)\}$. Consider for example the HMSC $H$ of Figure 1 and the behavioral aspect of Figure 2. The weaving should produce a HMSC such as $H'$ in Figure 4.

### 3. MATCHING

Let us now describe how a pointcut can be detected within a finite bMSC.

**Definition 4 (Matching).** We will say that a pointcut $P$ matches a bMSC $M$, which will be denoted by $P \triangleright M$, if and only if there exists two bMSCs $X_1$ and $X_2$ such that $M = X_1 \cdot P \cdot X_2$. Furthermore, if $X_1$ is the smallest possible bMSC allowing a decomposition of $M$, we will say that the matching is minimal.

A pointcut $P$ matches a bMSC $M$ $k$ times (denoted by $P \triangleright^k M$) if there are $k + 1$ bMSCs $\{X_i\}_{i \in \{1, \ldots, k+1\}}$ such that

- $M = X_1 \cdot P \cdot X_2 \cdots \cdot X_k \cdot P \cdot X_{k+1}$

- $\forall i, X_i \cdot P \cdot X_{i+1}$ is a minimal matching. This property guarantees the uniqueness of matching: successive join points are detected in sequence at the earliest position where they appear in a bMSC.

Using this definition of multiple matching, we can now formally define bMSC weaving. For a behavioral aspect $A = (P, Ad)$ and a bMSC $M$, if $P \triangleright^k M$, i.e. if $M$ is of the form $M = X_1 \cdot P \cdot X_2 \cdots \cdot P \cdot X_{k+1}$, then the weaving of $M$ and $A$ is defined as $M \otimes A = X_1 \cdot Ad \cdot X_2 \cdots \cdot Ad \cdot X_{k+1}$. In the examples of Figures 1 and 2 the pointcut $P_1$ does not match the bMSC $Retry$ but matches the bMSC $Retry \cdot Retry$ and the bMSC $Retry \cdot Retry \cdot Retry$ twice, etc… A different definition of matching based on the existence of an injective mapping from $P$ to $M$ was proposed in [13, 12]. We think that the pointcut detection approach proposed hereafter can be adapted to work with this definition. However, to keep the weaving process as clear as possible, we will only deal with the simple matching mechanism of definition 4. Since a bMSC is finite, an algorithm to detect a pointcut $P$ within a bMSC $M$ is rather straightforward. In this algorithm, we will denote by $\pi(M) \subseteq E_M$ the projection of a bMSC $M$ on a single instance, and by $\pi_P(M)$ the restriction of a bMSC $M$ to a subset of events $E \subseteq E_M$. Furthermore, we will consider that messages from an instance to another never overlap one another. Note that matching detection remains feasible without these assumptions, but that it slightly complicates the algorithm.

For a pointcut $P$ and a bMSC $M$, the first part of the algorithm (lines 1 to 4) finds for each instance $p$ of $P$, sequences of events of $M$ located on $p$ such that the labeling of these sequences is exactly the labeling of the restriction of $P$ to instance $p$. In other words, $p$ is detected locally on instance $p$ by each sequence extracted from $M$. The second part of the algorithm (lines 5 to 10) checks if all the local sequences can be combined to see whether $P$ is contained or not in $M$. In such a case the maximal solution (the solution where locally matched sequences are located as early as possible on their respective instance) is returned.
To extend the notion of weaving to bMSCs, we have to deal with the following problem: for a path \( p = t_1 \ldots t_k \) of a bMSC \( H \), when \( P^t \models \lambda(p) \), all occurrences of \( P \) are not necessarily detected on a single transition. Indeed, a part of \( P \) can be detected in the label of a transition \( \lambda(t_i) \), and completed later in the label of another transition \( \lambda(t_{i+1}) \).

Let us again consider the bMSC \( H \) in Figure 1, and its automaton representation in Figure 5a. Consider also pointcut \( P1 \) in Figure 2. The weaver has to detect a message "new attempt" followed by a message "try again" within all executions of \( H \). To explore the paths of \( H \), we start from the initial node of \( H \) and try to see if \( P1 \) matches the transition labeled by bMSC Propose. Since \( P1 \) does not match Propose and since \( P1 \) does not start to match Propose, we can continue our exploration from node \( q1 \) and look at the next transitions, i.e., the transitions labeled by bMSC Accept and bMSC Retry. \( P1 \) does not match Accept and since \( q2 \) is an end node, we know that \( P1 \) does not match after node \( q2 \). \( P1 \) does not entirely match Retry either, but starts to match because the message "new attempt" is detected at the end of bMSC Retry. So, the pointcut could match a longer bMSC. As there are two transitions \( t1 = (q1, \text{Accept}, q2) \) and \( t2 = (q1, \text{Retry}, q1) \) in \( H \), according to the semantics of bMSCs, we can consider a matching of \( P1 \) in bMSCs Retry • Accept and Retry • Retry. \( P1 \) \not\models \text{Retry} • Accept, but \( P1 \models \text{Retry} • Retry \), and a new potential matching of \( P1 \) starts within this second bMSC.

The matching definition indicates how many times a pointcut \( P \) was entirely detected in a bMSC \( M \). In addition to this definition, we also need information about the matches that were started in \( M \), and that could eventually be completed in an extension \( M \cdot M' \). For this, we introduce a new notion called potential match. Roughly speaking, for a bMSC \( M \) and a pointcut \( P \), the potential match \( P \cdot M \) is the biggest concatenation of parts of \( M \) that are completely matched by a part of \( P \) and could eventually be completed to obtain a complete match of \( P \) in \( M \).

Figure 6 shows an example where pointcut \( P2 \) matches bMSC \( M \) once. \( M \) can be written \( X_1 \cdot P2 \cdot X_2 \), but \( P2 \) starts to match the "end" of \( M \). Indeed, if we add bMSC \( N \) to \( M \), \( P2 \) matches \( M \cdot N \) three times, and each of these new matchings involve events of \( M \). The part of \( M \) which participates to the two additional matches is a potential match, and is depicted by the area denoted \( P \cdot M \cdot P2, M \) in Figure 6.

A potential match indicates that currently started matchings have to be studied on longer executions, and that the paths studied can be extended to obtain a longer bMSC where \( P \) matches.

The weaving of an aspect \( A = (P, Ad) \) into a base bMSC \( H \) can be decomposed into two main phases. The first phase consists of detecting join points, and the second phase rewrites them. The main difficulty of weaving resides in the detection: we have to identify all parts of the base bMSC semantics where join points may appear without unrolling...
4. BUILDING MATCHED PATHS

This section presents the detection part of our weaving process. From a pointcut P and a base HMSC H, the goal is to transform H into an equivalent HMSC H_{m,p} such that the weaving consists of rewriting only a finite number of paths of H_{m,p}. This transformation of H into H_{m,p} is performed with several simple transformations.

The first step (implemented by algorithm 2) is to unfold a base HMSC H to exhibit all potential matches of a pointcut and compute an equivalent HMSC H_{x}, such that each node of H_{x} is a pair (q, C), where q is a node of H, and C is the potential match of pointcut P for an initial path that ends at node q (this potential match will hereafter be called the context of q). In this way, for each node with a context, the context indicates if a currently started match has to be studied on longer paths. However, as we will see in subsection 4.2, when P matches an extension of a behavior that has lead to a context C, C is not always entirely used by the matching. For this reason, we have to compute the parts of the potential match which are actually matched by P for some paths of H_{x}. These parts will be called the future matches contained in C. This second step is performed by algorithm 3 which transforms an HMSC H_{x} into an equivalent HMSC H_{y}, such that each node of H_{y} is a triple (q, C, F), where (q, C) is a node of H_{x} and F is a future match contained in C. So, in each node the future match indicates if a currently started match of the context will actually end on longer paths. Figure 9 shows an example of transformation from an HMSC H to another HMSC H_{y}. Note however that this transformation has some limitations, that are described in section 5.

Algorithm 4 allows the resolution of problems related to the loops in a HMSC (subsection 4.3 and 4.4): as soon as a HMSC H_{y} contains at least one loop c such that all nodes of c have a non-empty future, the weaving cannot be performed without suitable permutations of HMSCs. Finally, when algorithm 4 terminates successfully, algorithm 5 (subsection 4.5) builds the set P_{m} of minimal acyclic paths where the pointcut matches. The weaving process finally consists of replacing these paths by a woven transition to obtain the woven HMSC H @ A (algorithm 6).

4.1 Step1: Potential matches

The first transformation, implemented by algorithm 2, is roughly speaking an unfolding of the base HMSC H. This algorithm transforms a HMSC H into an equivalent HMSC H_{x}, such that each node of H_{x} is a pair (q, P,M) where q is a node of H, and P,M is the potential match of pointcut P (called context) for an initial path that ends at node q. For instance, for a pointcut P and an initial path p = (q[0], M[0], q[1]), (q[1], M[2], q[2]), (q[2], M[3], q[3]), we will build the nodes (q[0], M[0], (q[1], P,M,[1], (q[2], P,M,[1], M[2]), (q[3], P,M,[1], M[2], M[3])). These nodes can only be found one after another. The first pair (node, context) created is obviously (q[0], M[0]). Then we can compute P,M,[1] and build the node (q[1], P,M,[1]). To compute the potential part P,M,[1] of node q[2], it is not necessary to entirely consider M[1]: considering the context P,M,[1] of node q[2] created previously is sufficient, since P,M,[1],M[2] = P,M,[1],M[2],M[3]. Finally, to compute P,M,[1],M[2],M[3], we also use a previously discovered context attached to node q[3], that is to say, P,M,[1],M[2], and we simply compute P,M,[1],M[2],M[3]. This way, all reachable contexts can be built inductively from the initial node. To build the possible contexts of a node q, it is not necessary to study all initial paths that end at node q, but only the contexts already computed that are attached to a predecessor of q. This is the approach used by algorithm 2. Since this algorithm is just an unfolding of the initial graph, it is obvious that the set of executions generated by H and H_{x} are equivalent. Note however that this algorithm terminates if and only if the number of potential matches for each node of H is finite (\mathcal{N} is finite by definition), which is not always the case. This problem will be developed in section 5.

For the pointcut P1 in Figure 1, algorithm 2 transforms the HMSC H in Figure 5-a into the HMSC H_{x} in Figure 6-a where M_{x} represents the empty bMSC and P,M is a bMSC with a single message "new attempt" from the instance customer to the instance server. The context associated with q1 for path p = (q[0], Propose, q[1]) is M_{x}, since P1 matches Propose neither fully nor partially. For any path ending with transition (q[1], Retry, q[1]), the context associated to q1 is P,M since P1 starts to match the message "new attempt".

Algorithm 2 Context(P,H)

\textbf{input:} pointcut P, HMSC H = (N,T,q[0],Q_{end},M)
\textbf{output:} HMSC H_{+} = (N_{+},T_{+},q[0],Q_{end+},M_{+})

1: \quad M_{+} = M, q[0] = (q[0], M_{x})
2: \quad \textit{CurrentStates} = \{q[0]\}, \textit{FutureStates} = \emptyset
3: \quad N_{+} = \{q[0]\}, T_{+} = \emptyset
4: \textbf{while} \textit{CurrentStates} \neq \emptyset \textbf{do}
5: \textbf{for all} q_{+} = (q, M_{p}) \in \textit{CurrentStates} and t = (q, M_{p}, q') \in T \textbf{do}
6: \quad q'_{+} = (q', P,M_{p},M_{+})
7: \quad \textbf{if} q'_{+} \notin N_{+} \textbf{then}
8: \quad \quad \textit{FutureStates} = \textit{FutureStates} \cup q'_{+}
9: \quad \quad N_{+} = N_{+} \cup q'_{+}
10: \quad \textbf{end if}
11: \quad T_{+} = T_{+} \cup t_{+}
12: \quad \textbf{if} t_{+} \notin T_{+} \textbf{then}
13: \quad \quad T_{+} = T_{+} \cup t_{+}
14: \quad \textbf{end if}
15: \textbf{end for}
16: \quad \textit{CurrentStates} = \textit{FutureStates}, \textit{FutureStates} = \emptyset
17: \textbf{end while}
18: \quad Q_{end+} = \{(n, M) \in N_{+} | n \in Q_{end}\}
19: \quad \textbf{return} H_{+} = (N_{+}, T_{+}, q[0], Q_{end+}, M_{+})
4.2 Step2: Future matches

For a pointcut \( P \) and two bMSCs \( M \) and \( M' \), the context \( PM_{P,M} \) is not always entirely used when \( P \) matches \( M \) \( \ast \) \( M' \). Consider for example the bMSC \( M \) and the pointcut \( P2 \) in Figure 6, and the bMSC \( M' \) in Figure 7. The bMSC \( M \ast \) \( M' \) is depicted in Figure 7 and we can see that the part of the context \( C = PM_{P,M} \) which is actually used when \( P \) matches \( M \ast \) \( M' \), only consists of a message ‘m1’. This part of a context \( C \), will be called the future match of context \( C \) when \( M' \) follows, and it will be denoted \( FM_{P,C,M'} \).

![Image 317x189 to 556x190]

**Figure 7: An example of Future Match**

Similarly, for a peculiar node \( q_x = (q, C) \) of a HMSC \( H_x \), the part of \( C \) that will be used to find a join point depends on the path that may start from \( q \). If \( q_x \in Q_{end+} \), it is obvious that the future match associated to the node \( (q, C) \) is \( M_x \), since no extension of a path ending in \( q_x \) is possible. If \( q_x \notin Q_{end+} \), then the part of \( C \) that is matched by a pointcut depends on the transitions that follow. Even if the number of paths starting from a node \( q_x \) and ending on an end node can be infinite, the set of possible future matches can be defined inductively as follows:

**Definition 5.** Let \( H_x \) be a HMSC (with context), \( P \) be a pointcut, and \( q_x = (q, C) \) be a node of \( H_x \). A future match associated to node \( q_x \) is a subset \( F(q_x) \) of \( C \) defined as follows:

1. \( F(q_x) = M_x \) if \( q_x \in Q_{end+} \).
2. \( F(q_x) = FM_{P,C,M} \cup (C \cap F_x) \) if \( q_x \notin Q_{end+} \), and if there exists a node \( q'_x = (q', C') \) and a transition \( t = (q_x, M, q'_x) \in T_x \) such that \( F' \) is a future match of \( q'_x \).

Let us discuss the second item of this definition. The element that appears in \( FM_{P,C,M} \) is the part of the context \( C \) which is actually matched if the bMSC \( M \) follows. However, some other events of \( C \) can be matched with a longer bMSC, but these events necessarily appear in the future match \( F' \) associated to \( q'_x \). So these other events are contained in \( C \cap F_x \).

According to this definition, algorithm 3 that computes all possible futures matches for a contextual HMSC immediately follows. This algorithm transforms a HMSC \( H_x \) into an equivalent HMSC \( H_x ' \), such that each node of \( H_x ' \) is a triple \((q, C, F'M)\) where \((q, C)\) is a node of \( H_x \), and \( F'M \) is a future match for context \( C \). Like algorithm 2, the transformation implemented by algorithm 3 is roughly speaking an unfolding of \( H_x \), and hence produces an equivalent HMSC. The main difference is that this unfolding starts from end nodes.

Consider the HMSC \( H \) and the pointcut \( P \) in Figure 8. Figure 9 presents \( H \) as an automaton labeled by bMSC names, and the HMSCs \( H_x \) and \( H_x ' \) obtained by applying algorithms 2 and 3. In \( H_x ' \), \( C1 \) is the context of node \( q_x \). \( C1 = X \), and after each transition \((q_1, Y, q_1) \), \( C1 \) remains unchanged. In \( H_x \), node \((q_1, C1) \) is duplicated with two different future matches, as the part of bMSC \( X \) that will be used to match \( P \) is not the same when \( Z \) immediately follows \( X \) and when at least a copy of \( Y \) is inserted between \( X \) and \( Z \). Figure 10 shows another example of a HMSC \( H_x ' \) obtained from the HMSC \( H_x \) in Figure 5.

Note that if algorithm 2 terminates, then algorithm 3 also terminates. Indeed, if the number of potential matches is bounded for a HMSC \( H \) and a pointcut \( P \) (condition of convergence for algorithm 2), then the number of future matches is also bounded because a future match is always a subset of a potential match.

**Algorithm 3 Future\((P, H_x)\)**

**Input:** pointcut \( P \),
HMSC \( H_x = (N_x, T_x, Q_{end+}, M_x) \)

**Output:** HMSC \( H_x = (N_x, T_x, Q_{end+}, M_x) \)

1: \( M_x = M_x ' \), \( Q_{end+} = \{(n, M, M_x) | (n, M) \in Q_{end+}\} \)
2: for \( currentStates = Q_{end+} \), futureStates = \( \emptyset \), do
3: \( N_x = currentStates, T_x = \emptyset \)
4: while \( currentStates \neq currentStates ' \) do
5: for all \( q_x = (q, C, F) \in currentStates \) and \( t_x = ((q_x, C'), M, (q_x', C')) \in T_x \) do
6: \( F' = F \cup FM_{P,C,M} \cup (C \cap F) \)
7: \( q_x = (q_x', C', F') \)
8: if \( q_x \notin Q_x ' \) then
9: \( futureStates = futureStates \cup q_x ' \)
10: \( N_x = N_x ' \cup q_x \)
11: end if
12: \( t_x = (q_x', M, q_x) \)
13: if \( t_x \notin T_x \) then
14: \( T_x = T_x ' \cup t_x \)
15: end if
16: end for
17: \( currentStates = futureStates, futureStates = \emptyset \)
18: end while
19: \( q_{en} = (q_0, M_x, M_x) \)
20: return \( H_x ' \)

4.3 Unbreakable loops

From a pointcut \( P \) and a HMSC \( H_x \) we have built a HMSC \( H_x ' \) whose nodes contain a context and a future. As we want to isolate the join points into a finite number of paths of
a transformed HMS, the next thing to do is to rewrite $H_\kappa$ into an equivalent HMS where the number of paths starting from nodes with an empty future $M_e$ and ending on nodes with also an empty future is finite. Algorithm 5 builds the set $\mathcal{P}_m$ of these paths and defines them more formally. This set $\mathcal{P}_m$ ensures that $P$ matches entirely bMSC $\lambda_p$ associated to any path $p$ of $\mathcal{P}_m$ a certain number of times, and that a potential matching is not initiated from this path.

However, algorithm 5 cannot be directly applied on $H_\kappa$. If $H_\kappa$ contains at least one loop $c$ such that all nodes of $c$ have a non-empty future, then the algorithm diverges. Consider, for example, the HMS in Figure 10: there is an infinite number of paths starting and terminating with an empty future: $\text{Retry} \cdot \text{Retry} \cdot \text{Accept}, \text{Retry} \cdot \text{Retry} \cdot \text{Retry} \cdot \text{Accept}$, etc...

So, before using Algorithm 5, we have to break the cycles of $H_\kappa$ that loop infinitely on nodes with non-empty future. Let us denote by $C_{H_\kappa}$ the set of elementary cycles of $H_\kappa$ and $\mathcal{UC}_{H_\kappa}$ the set of "unbreakable" elementary cycles, i.e. cycles for which algorithm 5 generates an infinite set of paths. Formally, we have $\mathcal{UC}_{H_\kappa} = \{c = t_1,t_2...t_k \in C_{H_\kappa} | \forall i \in \{1...k\}, \text{FM}(\lambda_c(t_i)) \neq M_e \}$. Sometimes, breaking a cycle just consists of splitting a bMSC labeling a transition into smaller parts, so that an empty future appears. For instance, in Figure 10, the transition $l = (q_{k-1}, \text{Retry}, q_{k+1})$ can be split into two transitions $l_1 = (q_{k-1}, \text{Retry}_1,q_{\text{new}})$ and $l_2 = (q_{\text{new}}, \text{Retry}_2,q_{k+1})$ such that $\text{Retry}_1$ is a bMSC with a single message 'try again' and $\text{Retry}_2$ is a bMSC containing a single message 'new attempt'. After this transformation, one can easily note that the future of node $q_{\text{new}}$ is the empty bMSC $M_e$.

However, things are not always so easy. Consider for example HMS $H_3$ of Figure 11: pointcut P3 matches an infinite number of bMSCs $(X1XY2, X1Y1X2, X1Y2Y1X2, ...)$, but for each of these matched bMSCs, the events of $Y_1$ associated to the loop are never matched by P3. Algorithm 5 cannot be applied to a HMS containing this kind of cycle because there is an infinite number of paths starting and ending at nodes with empty future. Since bMSCs $X1$ and $Y1$ are independent, one possible solution is to rewrite the HMS of Figure 11 into an equivalent one, where the loop on $Y1$ is performed before bMSC $X1$. We obtain the HMS $H^F$ in Figure 11. Note that within this new HMS the matching of pointcut P3 no longer involves an infinite number of occurrences of $Y1$. Let us now try to formalize this transformation, and see whether it can be applied in a systematic way to solve loop problems.

**Definition 6.** Let $H_\kappa$ be a HMS augmented with potential and futures matches, $P$ be a pointcut. Let $\mathcal{UC}_{H_\kappa}$ be the set of unbreakable cycles of $H_\kappa$. An unbreakable generator of $H_\kappa$ and $P$ is an acyclic path $p = t_1...t_k$ of $H_\kappa$ such that:

- starts from a node with an empty future, i.e., $F(\lambda_c(t_1)) = M_e$
- ends on a node with empty future, i.e. $F(\lambda_c(t_k)) = M_e$
- never passes through a node with empty future other than $\lambda_c(t_1)$ and $\lambda_c(t_k)$, i.e. $\forall i \in 2...k$, $F(\lambda_c(t_i)) \neq M_e$
atom $\Sigma_1$ is an expression of the form $E := \sigma E \mid (E)^* \mid E_1 + E_2 \mid M$, where $\sigma \in \Sigma_1$ is an atomic bMSC, $(E)^*$ denotes iteration, and $E_1 + E_2$ is an alternative.

Regular expression and finite automata have the same expressive power. Moreover, from a regular expression we can compute an automaton generating the same language (using Brzozowski’s algorithm [8]), and from an automaton, we can compute an equivalent expression (using a reduction algorithm). Hence, we can manipulate differently regular expressions on bMSCs or HMSCs, and get back to the other model. For a given regular expression $E$, we will call $H_E$ the HMSC generating the same set of scenarios, and for a given HMSC $H$, we will call $E_H$ the equivalent regular expression on bMSCs. For details about this well-known relation between automata and regular expressions, interested readers may consult [8], chapter 2.

Similarly to what is done for HMSCs, we can associate a context to an expression $E = X_1 \ldots X_k$, just by computing the potential match of a pointcut $P$ in $X_1 \ldots X_k$. For any sub-expression $E' = X_i X_j$ of $E$, we can also compute a future match $\text{Future}(E')$ similarly to what have already been proposed for HMSCs: $\text{Future}(E') = P M_{P, E'} X_{i-1} \ldots X_k$.

Let $p = t_1 t_2 \ldots t_q$ be a disjunctive unbreakable cycle CONNECTED to a pointcut $\ell = \text{Future}(E)$.

We can associate to $p$ an expression $E_p = X_{11} \ldots X_{1q}(Y_{11} \ldots Y_{q})^{*} X_{21} \ldots X_{2q2}(Y_{21} \ldots Y_{2q2})^{*} \ldots (Y_{d1} \ldots Y_{dq})^{*} X_{d1} \ldots X_{dqa}$

where all $X_{ij}$ and $Y_{ij}$’s are atoms, and that generates the same set of behaviors as $\lambda(t_1) \cdot \ldots \cdot \lambda(t_i) \cdot \lambda(c_1)^* \cdot \lambda(t_{i+1}) \cdot \ldots \cdot \lambda(t_j) \cdot \ldots \cdot \lambda(t_q)$, for all $i, j \in 1, k$, $\lambda(c_j) = \lambda(c_i)$. Note that this expression is never of the form $E_1 + E_2$. Consider for instance the HMSC H3 and the pointcut P3 in Figure 11. The path $p = (q_3, X_1, q_5) (q_6, X_2, q_8)$ is an unbreakable generator since the cycle $c = (q_3, Y_1, q_5)$ is CONNECTED to $p$ and it does not contain a node with empty future. Each bMSC of H3 is an atom. So, we can associate to $p$ the expression $E_p = X_1(Y_1)^* X_2$.

The idea behind the following algorithms is to rewrite these expressions up to permutation of independent atoms so that cycles become splittable or null-match. The new expressions can then be used to compute a new HMSC without problematic paths. Consider again the HMSC H3 and the pointcut P3 in Figure 11. The expression $E_p = X_1(Y_1)^* X_2$ is equivalent to the expression $E_p' = (Y_1)^* X_1 X_2$ for which the path $p = (q_3, X_1, q_5) (q_6, X_2, q_8)$ is no longer unbreakable.

We will use several types of permutations: Let $E = X_1 X_2 \ldots X_k$ be a regular expression on a set of bMSCs. A simple permutation is to exchange the respective order of two bMSCs when possible, i.e. $E$ can be rewritten into an equivalent regular expression $E' = X_1 X_3 \ldots X_{i+1} X_i \ldots X_k$ whenever $X_{i+1}$ and $X_i$ are independent. Indeed, when both bMSCs $M$ and $N$ are independent, then $M \cdot N = N \cdot M$, and this property extends to any sequence of bMSCs. In the same way, if $E$ contains loops, a loop can be moved upward (or forward) in a string if all the bMSCs it contains are independent from all atoms that are overtaken. Finally, two loops can be permuted if they are independent.

DEFINITION 7. A regular expression on an alphabet of
When two regular expressions \( E \) and \( E' \) are equivalent we will note \( E \equiv E' \). For a given expression \( E \) on a set of atoms \( \Sigma_{at} \), we will denote by \([E]\) its equivalence class, i.e. the set of all expressions on \( \Sigma_{at} \) containing \( E \) such that \( \forall v \in [E], \forall v' \equiv e, e' \in [E] \). In addition to the permutations, we can use a classical property of regular expressions such as \( a(ba)^*bc = ab(ab)^*c \) to find the equivalence class of an expression \( E \). Finally, when two expressions are equivalent, then their iterations are also equivalent. Let note that for any expression \( E \), since the definition of equivalence never unfolds any starred expression, \([E]\) is finite and can be effectively computed.

**Definition 8.** Let \( E_1, E_2 \) be two regular expressions over an alphabet \( \Sigma \) of bMSCs, generating words in two languages \( L_1 \subseteq \Sigma^* \) and \( L_2 \subseteq \Sigma^* \). The left quotient of \( E_1 \) by \( E_2 \) is the regular expression \( E_1 / E_2 \) that generates words of \( L_1 | L_2 = \{ w \in \Sigma^* | w \in L_1 \wedge w. w \in L_2 \} \).

The right quotient of \( E_1 \) by \( E_2 \) is the regular expression \( E_1 \backslash E_2 \) that generates words of \( L_1 \backslash L_2 = \{ w \in \Sigma^* | w \in L_1 \wedge v. w \in L_2 \} \).

The complement of an expression \( E \) is an expression \( \bar{E} \) that generates words of \( \Sigma^* - L \).

These definitions of quotients and complements are useful for the definition of the replacement of a sub-expression by another, which is central in the weaving process.

**Definition 9.** Let \( H = (N, T, \mathcal{Q}, Q_{\text{end}}, \mathcal{M}) \) be a bMSC, \( E \) be a regular expression over \( \mathcal{M}^* \), and \( E' \) be an equivalent regular expression over \( \mathcal{M} = \mathcal{M} \cup \mathcal{A}(\mathcal{M}). \) The bMSC obtained by replacement of \( E \) by \( E' \) in \( H \) will be denoted \( H_{E \rightarrow E'} \), and is the bMSC \( H_{E \rightarrow E'} \) associated with the regular expression \( E \).

\[
E_{\text{new}} = (E_{\text{old}} / (E, \mathcal{M}^*)).E'.(E_{\text{old}} \backslash (E', \mathcal{M}^*) \cup (E_{\text{old}} \cap (E', \mathcal{M}^*)
\]

This definition of replacement can be used to replace an unsplittable expression \( E \) by a splittable expression \( E' \) everywhere in the semantics of \( H \). We can also use this definition to replace one specific occurrence of an expression \( E_\phi \) corresponding to an unsplittable generator \( p \). To do so, it is sufficient to label differently the bMSCs associated with each transition (i.e. ensure that \( \forall t, t' \in T, \lambda(t) \neq \lambda(t') \) even if the bMSCs are isomorphic). With this convention, the replacement of an expression \( E \) rewrites only a single path of \( H_{\phi} \) with all its connected unsplittable loops.

Note that for all generators \( p \) of a bMSC \( H_{\phi} \), since all expressions \( e \in [E_\phi] \) generate the same scenarios, all bMSCs obtained by replacing an expression \( e \in [E_\phi] \) by another expression \( e' \in [E_\phi] \) are equivalent.

For a behavioral aspect \( A = (P, \mathcal{A}) \), and a bMSC \( H_{\phi} \) augmented with potential and future matches computed from a bMSC \( H \) and the pointcut \( P \), we compute the set \( \mathcal{P}_\phi(H_{\phi}) \) of bMSCs \( H_{\phi} \), and the set \( \mathcal{P}_\phi \) of the associated expressions. Then, if for all \( e \in \mathcal{P}_\phi \), there is an expression \( e \in [E_\phi] \) in which all starred subexpressions of \( e \) are either splittable or null-match, then there exists a bMSC \( H_{\phi} \) equivalent to \( H_{\phi} \) that does not contain infinite path passing infinitely often through non-empty futures. If not, the weaving cannot be performed. Finally, when \( H_{\phi} \) is computed, each expression \( E_\phi \) related to an unsplittable generator \( p \) is replaced by the splittable or null-match expression found. The replacement of unsplittable generators is implemented by Algorithm 4.

### Algorithm 4 Permutations(\( H_{\phi}, H_{E \rightarrow E'} \))

**Input:** a bMSC \( H_{\phi} \) with contexts and futures \( \mathcal{U} \), set of unbreakable generators

**Output:** a bMSC \( H_{\phi} \) without unbreakable generators.

1. Compute \( \mathcal{P}_\phi(H_{\phi}) \), set of unbreakable generators.
2. \( \mathcal{P}_\phi = \{ [E_\phi] \mid \mathcal{P}_\phi \}(H_{\phi}) \}
3. Compute \( H_{\phi} \), regular expression associated to \( H \)
4. For all \( e \in \mathcal{P}_\phi \) do
5. Compute \( [E_\phi] \)
6. If \( \exists e \in [E_\phi] \) such that \( \forall v \in \mathcal{P}_\phi \) connected to \( e \), \( c \) is splittable or null-match then
7. Weaving cannot be performed \; STOP
8. else
9. Choose \( c \) with splittable or null-match cycles
10. Replace \( \mathcal{P}_\phi \) with \( \mathcal{P}_\phi \)
11. end if
12. end for
13. For all \( (E_\phi, e) \in \mathcal{P}_\phi \)
14. /* replace \( E_\phi \) with \( e \) in \( \mathcal{P}_\phi \)
15. \( H_{\phi} = (E_{\text{new}} / (E_{\phi}, \mathcal{M}^*)) \cup (E_{\text{old}} \cap (E_{\phi}, \mathcal{M}^*)) \)
16. end for
17. \( H_{\phi} \) = \( H_{\phi} \) /* compute the bMSC equivalent to the expression \( E_{\phi} \)
18. return(\( H_{\phi} \))

Note that some generators do not have equivalent expressions with splittable or null-match cycles. Consider the bMSC \( H \) and the pointcut \( P \) in Figure 12. The path \( p = (q_{\phi_1}, X_1, q_{\phi_2})(q_{\phi_2}, Y, q_{\phi_3})(q_{\phi_3}, X_2, q_{\phi_4}) \) is clearly an unbreakable generator. The bMSCs \( X_1 \) and \( X_2 \) are atoms and the bMSC \( Y \) can be split into two atoms \( Y_a \) and \( Y_b \) where \( Y_a \) is a bMSC with a single local event ‘a’ on instance \( I1 \) and \( Y_b \) is a bMSC with a single local event ‘b’ on instance \( J3 \). An expression associated to path \( p \) is \( E_\phi = X_1.Y_a.Y_b(Y_a.Y_b)^* \). The equivalence class of \( E_\phi \) contains neither a splittable nor a null-match cycle. The only way to obtain an infinite future is to consider the expression \( E_\phi^* = (Y_a.Y_b.X_1.X_2(Y_a.Y_b)^*)^* \). However, \( E_\phi^* \) is \( \notin [E_\phi] \), and even if it is equivalent to \( E_\phi \), \( E_\phi^* \) is not a regular expression anymore. So, the bMSC of Figure 12 cannot be transformed into an equivalent bMSC to avoid unbreakable generators.

### 4.5 \( H_{\phi} \) and woven bMSC

So far, if algorithms 2, 3 and 4 have succeeded, we have obtained a bMSC \( H_{\phi} \) such that all loops pass through a node labeled with an empty future. The goal of Algorithm 5 is to build a finite set \( \mathcal{P}_m \) of paths of \( H_{\phi} \) such that \( \forall P \in \mathcal{P}_m \), the pointcut \( P \) matches exactly \( k \) times \( \lambda(p) \). \( \mathcal{P}_m \) contains all join points that may appear in the semantics of \( H_{\phi} \). Hence, the weaving only consists of a rewriting of paths in \( \mathcal{P}_m \).

More specifically, \( \mathcal{P}_m \) is the set of paths of a bMSC \( H_{\phi} \) such that for each path \( p \) of \( \mathcal{P}_m \):

1. \( p \) starts from a node with future match equal to \( M_\phi \),
2. \( p \) terminates on a node with future match equal to \( M_\phi \),
3. All other nodes of \( p \) are labeled by future matches different from \( M_\phi \).
iv) \( \exists k \in \mathbb{N} \) such that \( P \) matches the bMSC \( \lambda(p) \) associated to \( p \) \( k \) times.

We know that after algorithm 4, all loops participating in a match pass through at least one node labeled with an empty future. So, for a HMSC \( H_{mp} \) obtained using Algorithms 2, 3 and 4, each path of \( \mathcal{P}_m \) is acyclic, and \( \mathcal{P}_m \) is finite. The construction of \( \mathcal{P}_m \) is performed by algorithm 5.

Now that we have detailed how to transform a base HMSC \( H \) into a new equivalent HMSC \( H_{mp} \) and identified all join points in a finite set \( \mathcal{P}_m \) of paths of \( H_{mp} \), the only remaining work is to replace all parts matched by the pointcut with the advice. As for permutations, this can be performed through a rewriting of a regular expression. Algorithm 6 below describes the overall weaving process.

5. LIMITATIONS

The algorithms described in section 4 have some inherent limitations. Semantic weaving is not always a tractable problem: for some HMSCs and some pointcuts, there might be no way to build a HMSC generating the woven semantics. Hence, the algorithms described in section 4 do not always work. This section identifies sufficient conditions on pointcuts and HMSCs so that our algorithms terminate with a correct result.

The first limitation of our approach is a termination problem for Algorithm 2. From a HMSC \( H \), Algorithm 2 builds a HMSC \( H_t \), where the nodes of \( H \) are transformed into nodes containing a context (a potential match). Since the number of nodes of the HMSC \( H \) is finite, the algorithm terminates if and only if the number of potential matches is finite.

Applying algorithm 2 on the HMSC of Figure 5-b generates a new HMSC that exhibits only two different contexts: \( M_e \) and \( P.M \). Consider now HMSC \( H^4 \) and pointcut \( P^4 \) in Figure 13. For this case, the size of contexts can grow infinitely, and it is impossible to build a finite HMSC with a finite set of contexts. From node \( q_0, (M_e) \), the potential match obtained in \( M_e, G \) contains a single local event 'a'.

![Image 12: Impossible weaving](image)

Algorithm 5 BuildP(\( P, H_{mp} \))

input: pointcut \( P \),
HMSC \( H_{mp} = (N_{mp}, T_{mp}, q_{0_{mp}}, Q_{end_{mp}}, M_{mp}) \),

output: \( P_m \) set of matched paths.

1: \( P_m = \{ (q_x, M, q'_x) \in T_{mp} \mid F(q_x) = F(q'_x) = M_e \land \exists k \in \mathbb{N}, P \vdash^k M \} \)
2: Path = \{ (q_x, M, q'_x) \in T_{mp} \mid F(q_x) = M_e \land F(q'_x) \neq M_e \}
3: while Path \( \neq \emptyset \) do
4: \( FuturePath = \emptyset \)
5: for all \( p = t_1, t_2, \ldots, t_n \in Path \) do
6: for all \( (q_x, M, q'_x) \in T_{mp} \), such that \( q_x = \lambda(p) \) do
7: if \( F(q'_x) = M_e \) then
8: \( P_m = P_m \cup (p,t) \)
9: else
10: \( FuturePath = FuturePath \cup (p.t) \)
11: end if
12: end for
13: end for
14: Path = FuturePath
15: end while
16: return \( P_m \)

Algorithm 6 Weave(H,A)

input: a HMSC \( H_{\mathcal{A}} = (N, T, q_0, Q_{end}, M) \), a behavioral aspect \( \mathcal{A} = (P, Ad) \),

output: a woven HMSC \( H' \).

1: \( H' = Context(P, H) \)
2: \( H_s = Future(P, H_s) \)
3: compute \( UC_{H_s} \)
4: if \( \forall c, c' \in UC_{H_s}, c \) and \( c' \) are disjoint then
5: \( H_{mp} = Permutation \circ S(H_s, UC_{H_s}) \)
6: \( P_m = BuildP(P, H_{mp}) \)
7: for all \( p \in P_m \) do
8: Compute \( E_p \)
9: Find the minimal factorization \( x_1 \cdot P \cdot x_2 \cdot \ldots \cdot P \cdot x_k \) of \( E_p \)
10: \( E'_p := x_1 \cdot Ad \cdot x_2 \cdot \ldots \cdot Ad \cdot x_k \)
11: \( H_{mp} = H_{mp} \{ t_p \mapsto E'_p \} \)
12: end for
13: Return \( H_{mp} \)
14: else
15: Weaving cannot be performed ; STOP
16: end if
(bMSC A1). From the node \((q_0, A1)\), the potential match relating to \(A1 \bullet G\) contains two local events 'a' (bMSC A2), and from the node \((q_0, An)\), \((An \in n \text{ local events 'a'})\) the potential match relating to \(An \bullet G\) contains \(n + 1\) local events 'a' (bMSC An+1). From a node and a context, there is always a way to find an extension to transform a potential match into a complete match, but this extension creates a new and bigger potential match than previously.

Note that the problem is not due to the algorithms, and is really intractable for HMSC HA, and aspect \(A = (P4, Ad1)\) the semantics of weaving is a set of behaviors containing scenarios of the kind \(Ad^n.P\).n \in N\). This expression is not a regular expression on a set of bMSCs, and hence cannot be represented by a HMSC.

![Figure 13: An example where algo. 2 does not terminate.](image)

To avoid the problem of infinite number of contexts, we will only use connected bMSCs as pointcuts, for which the possible number of bMSC potential match is finite. A bMSC \(M\) is connected if and only if there does not exist two bMSCs \(M1\) and \(M2\) (different from \(M\)) such that \(M = M1 \bullet M2\). For example, in Figure 2, the bMSCs P1 and A1 are connected, whereas in Figure 13, the bMSC P4 is not connected (\(P4 = P0 \bullet Pb\) with \(P0\) a bMSC with only a local event 'a' and \(Pb\) a bMSC with only a local event 'b', and \(P0\)\([Pb]\)).

An interesting property is that for a HMSC \(H\) and an aspect \(A = (P, Ad)\), if the pointcut \(P\) is connected, then the number of potential matches generated by \(H\) is bounded. We do not give here a complete formal proof of that property but only the main idea of the demonstration. Consider Figure 14 where a pointcut \(P\) is depicted (the same pointcut as in Figure 6). It is clear that for this pointcut and for any \(H\), there exist only three possible potential matches noted \(PM1\), \(PM2\), and \(PM3\). Let us call potential part a beginning of match into a potential match. For instance, the potential match \(PM1\) contains two potential parts:

one, noted \(PP1\) in Figure 14, with the two first messages 1 and 2; the other, noted \(PP2\), with the last message 1. The main idea is to show that, in the general case, the size of a potential part \(PPi+1\) is always strictly smaller than a potential part \(PPi\). In your example, the potential part \(PP2\) contains only one message whereas \(PP1\) contains two messages. Since the size of potential parts in a potential match is strictly decreasing, when the pointcut is connected, the number of potential matches is bounded.

Another limitation is that the treatment of unbreakable generators is restricted to situations where unbreakable cycles are disjoint. With this situation, loops have the same properties as atoms in an expression, and the permutation are more or less permutations over finite words. The permutation algorithm could be extended as long as the equivalence class for an expression remains a finite set of expressions.

![Figure 14: A bounded number of potential matches.](image)

6. RELATED WORK

Clarke [2] uses UML templates to define aspects. The question addressed by her work is more the specification of aspects than the weaving process into non-aspectual models, but our semantic-based weaving can be easily adapted to this work to keep the advantages of the two approaches.

Similarly to our approach, Whittle and Araujo ([17] and [1]) represent behavioral aspects with scenarios. Aspectual scenarios are modeled as interaction pattern specifications (IPSs introduced in [5]) and are composed with specification scenarios. The weaving process defined in [17] composes scenarios with instantiation and ad-hoc composition operators. The weaving process proposed by [1] is performed into two steps. The first step is to generate state machines from the aspects and from the specification. The weaving process then is a composition of these state machines. However, in these two approaches, the detection of join points is not automated: users have to specify them with a binding relation between an aspect and a specification. Moreover, they do not address specification scenarios defining infinite behavior. Another difference is that none of these scenario-based weaving address the weaving at the semantic level as we propose here.

More generally, in [3] and [4], Douence et al. are interested in event pattern matching, which is close to our approach. A significant difference is that they use a monitor to perform event pattern matching at runtime on a program execution,
whereas our weaving is made statically at a modeling level.

The aspect model and in particular the mechanism to identify join points (the pointcut definition language) plays a critical role in the applicability of the aspect-oriented methodology. According to Kiczales et al. [11], the pointcuts definition language probably has the most relevant role in the success of the aspect-oriented technology but most of the solutions proposed so far are too tied to the syntax of the programs manipulated.

Ostermann et al. [15] try to address this problem by proposing a static joint point model that exploits information from different models of program semantics. They show that this model of joint points increases the abstraction level and the modularity of pointcuts.

Note however that the semantics matching is not only a problem studied in the aspect community, but has also met considerable interest in the community of concurrency and verification. Muscholl and Al. ([12,13]) have studied the problem of matching for Message Sequence Charts, and shown some limits to the matching problem. For example, they have shown in [13], that it is undecidable whether the behavior of a HMSC \( H \) is included within the behavior of a HMSC \( H' \).

This result means that a behavioral weaving using the full HMSC language as a definition of pointcut is not possible. This is why we had to limit the expressiveness of our pointcut language as explained in Section 5.

7. CONCLUSIONS

This paper has proposed a definition of behavioral aspect weaving. Behaviors and aspects are defined using Message Sequence Charts and the weaving is performed at the semantic level. More precisely, an aspect defines a part of behavior that should be replaced by another one whenever it appears in the semantics of the base specification. This approach suffers from several limitations: the matching process can only be performed if each join point appears inside a bounded fragment of a behavior. We have shown that this is always the case when pointcuts are defined with connected HMSCs.

Another limitation is that the base HMSC should not exhibit two non-disjoint cycles where the pointcut matches. This second property is not a structural property of the base HMSC, and can only be checked during the weaving process. When it holds, we have a procedure to rewrite the base HMSC \( H \) into an equivalent HMSC \( H' \) using unfolding and commutations. The HMSC \( H' \) obtained is such that the semantics weaving \( H \otimes A \) simply consists of a syntactic weaving in transitions of \( H' \). Note that the property on loops is only a sufficient condition to apply the proposed algorithm. It does not mean that weaving is impossible for specifications that do not fulfill the loop condition. This has to be considered for further research. Another extension of this work is an improvement of the aspect description to deal with more abstract scenarios, or with different definition of matching (using for example the definition of [13]).

Finally, we are currently implementing our matching and weaving algorithm within the UMLAUT model transformation framework.

8. REFERENCES


