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To cite this version:

Guillaume Baudart, Louis Mandel, Florent Jacquemard, Marc Pouzet. A Synchronous Embedding of Antescofo, a Domain-Specific Language for Interactive Mixed Music. EMSOFT 2013 - 13th International Conference on Embedded Software, Sep 2013, Montreal, Canada. hal-00850299

HAL Id: hal-00850299
https://inria.hal.science/hal-00850299
Submitted on 6 Aug 2013

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A Synchronous Embedding of Antescofo, a Domain-Specific Language for Interactive Mixed Music

Guillaume Baudart∗
Louis Mandel†
Marc Pouzet§

Florent Jacquemard

ABSTRACT
Antescofo is recently developed software for musical score following and mixed music: it automatically, and in real-time, synchronizes electronic instruments with a musician playing on a classical instrument. Therefore, it faces some of the same major challenges as embedded systems.

The system provides a programming language used by composers to specify musical pieces that mix interacting electronic and classical instruments. This language is developed with and for musicians and it continues to evolve according to their needs. Yet its semantics has only recently been formally defined. This paper presents a synchronous semantics for the core language of Antescofo and an alternative implementation based on an embedding inside an existing synchronous language, namely ReactiveML. The semantics reduces to a few rules, is mathematically precise and leads to an interpreter of only a few hundred lines. The efficiency of this interpreter compares well with that of the actual implementation: on all musical pieces we have tested, response times have been less than the reaction time of the human ear. Moreover, this embedding permitted the prototyping of several new programming constructs, some of which are described in this paper.

Categories and Subject Descriptors
D.3.2 [Language Classifications]: Concurrent, distributed, parallel languages; D.3.1 [Formal Definitions and Theory]: Semantics; H.5.5 [Information Interfaces and Presentation]: Sound and Music Computing.

∗ENS de Cachan, Antenne de Bretagne, DI École normale supérieure. Email: Guillaume.Baudart@ens.fr
†IRCAM Paris, INRIA Paris-Rocquencourt. Email: Florent.Jacquemard@inria.fr
‡Univ. Paris-Sud 11, DI École normale supérieure, INRIA Paris-Rocquencourt. Email: Louis.Mandel@lri.fr
§Univ. Pierre et Marie Curie, DI École normale supérieure, INRIA Paris-Rocquencourt. Email: Marc.Pouzet@ens.fr

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EMSOFT’13 September 29 – October 04, 2013, Montreal, Canada.

Figure 1: Architecture of the Antescofo system. Continuous arrows represent pre-treatment, and dotted ones real-time communications.

Keywords
Synchronous Programming; Language Embedding; Error Handling and Synchronization Strategies; Mixed Music.

1. INTRODUCTION
Since the 1950s, composers have shown a growing interest in new kinds of music mixing electronic parts and live musicians. Thus, computer music research and industry have focused on real-time interaction between musicians and computers. These considerations have led to the development of programming languages dedicated to musical interaction. Examples include Max/MSP, which resulted from the collaboration of Miller Puckette and the composer Philippe Manoury [13], and James McCartney’s SuperCollider [12].

In the same vein, Antescofo is a system and dedicated programming language developed for the synchronization and control of interactive parameters in computer music. It allows a composer to manage a computer interacting with other musicians at performance time. Using this system, composers can jointly specify both instrumental and electronic parts on the same score.

Since 2008, Antescofo has been used in the creation of more than 40 original mixed electronic pieces by world renowned artists and ensembles, including Pierre Boulez, Philippe Manoury, Marco Stroppa, New-York Philharmonics, Berlin Philharmonics and the Radio France Orchestra.

Figure 1 illustrates the global behavior of the system. It is composed of two distinct subsystems: a listening machine and a sequencer. During a performance, the listening ma-

http://repmus.ircam.fr/antescofo
Antescofo faces some of the major challenges of embedded system design and implementation: the synchronization of all the electronic instruments that play in parallel with the score follower itself; the mix of logical and physical time with slow and fast time scales; the design and implementation of an expressive language where programs are compiled to target code guaranteed to run in real-time. Yet the relationships between Antescofo and existing models and languages for embedded systems have been little studied.

In this article we focus on the sequencer, a typical example of a reactive system that continuously receives inputs from the listening machine. When the listening machine detects an event, the sequencer reacts to produce the corresponding accompaniment. Moreover, the dedicated language includes constructs typical of languages for embedded systems—like a logical global time scale, synchronous parallelism and instantaneous broadcast—but also some original ones for synchronization and error handling strategies.

Among programming languages for embedded systems, synchronous languages [1] are used in the most critical applications including airplanes, trains, and automotive subsystems. They incorporate a mathematically precise model of concurrency and advanced features for communication and code generation. The language of Antescofo can benefit from this research and, more fundamentally, links with this trend of research be investigated.

Contributions of the paper.

This paper presents a new semantics and implementation for the core language of Antescofo. An originality of our approach is to implement the semantics as an interpreter inside an existing synchronous language. In this way, the precise semantics leads directly to an implementation.

For the implementation platform, we chose ReactiveML [11] which appeared to be the best candidate, though we also experimented in the Lustre-like language defined in [9]. Indeed, the ability to define inductive data-types, higher order processes and recursion greatly simplify programming. The implementation is only a few hundred lines of ReactiveML code (see Appendix C) and it competes with the current implementation. In all of our experiments, response time were less than the reaction time of the human ear.

By embedding Antescofo inside ReactiveML, we were able to add and experiment with novel programming constructs and synchronization strategies with little effort. We illustrate this with several examples. Our framework is thus a powerful tool for prototyping new constructs before possibly integrating them into the core language.

The paper is organized as follows. Section 2 defines the core language of Antescofo. Its semantics is defined in Section 3. Section 4 presents the ReactiveML implementation. In Section 5, we present several applications. Related work is discussed in Section 6 and we conclude in Section 7.

Throughout the paper, we present several examples; they are available to the reader together with the ReactiveML source code at http://reactiveml.org/emsoft13.

2. A LANGUAGE FOR MIXED MUSIC

We now describe the kernel of the Antescofo language, a language dedicated to the writing of mixed music scores [5]. This language was developed as a language for coordinating events performed by humans and electronic actions controlled by a computer. It allows a composer to specify both electronic and instrumental parts in the same score. Figure 2 shows a simple example of one such score (the symbol $e_a$ indicates a link to a demonstration video available online).

The language permits expressing delays relative to a tempo expressed in beats per minute (bpm). For instance, a duration of 1.0 means 1.0 beat. During a performance, the listening machine estimates both the position in the score and the tempo of the performer. This allows the sequencer to follow the speed of the performer as a trained musician would. Indeed, the tempo is not estimated from the last duration alone but rather from all durations detected since the beginning of the performance. In this way, the listening machine adds some inertia to tempo changes which corresponds to the real behavior of musicians playing together [3]. This feature explains some of the success of Antescofo with composers, as synchronizing different parts using a common tempo is standard practice when writing polyphonic music (in many other environments for mixed music, delays can only be expressed in milliseconds).

2.1 The Core Language

The main idea is to bind electronic actions to instrumental events. During a performance, actions related to an instrumental event are executed when the event is detected. Thus, a score is a sequence of instrumental events and for each such event an associated sequence of electronic actions. It is described by the following grammar (the empty sequence is denoted $\varepsilon$).

\[
\begin{align*}
\text{score} &::= \varepsilon \mid \text{(event : seq) score} \\
\text{event} &::= \text{event } i \ t \\
\text{seq} &::= \varepsilon \mid (\delta \ ae) \ seq \\
\text{ae} &::= \text{action } \mid \text{group} \\
\text{group} &::= \text{group } \text{syncro } \text{error } \text{seq} \\
\text{syncro} &::= \text{tight } \mid \text{loose} \\
\text{error} &::= \text{local } \mid \text{global } \mid \text{partial } \mid \text{causal}
\end{align*}
\]

An instrumental event (e.g., a note, chord, trill, etc.) is denoted by $\text{event } i \ t$, where $i \in \mathbb{N}$ is the index of an event in the score and $t \in \mathbb{Q}$ its duration relative to the tempo.

\[\text{http://cycling74.com/}\]
Indeed, for the sequencer, instrumental events are only triggers for electronic actions. Therefore, the only useful information is the position and the duration of an event. An electronic action (ae) is either an atomic action taken from a finite set (action ∈ A) or a group of electronic actions. A group is a sequence of electronic actions characterized by a synchronization strategy (described in Section 2.2) and an error handling strategy (described in Section 2.3). A sequence (seq) is a list of pairs, each associating an electronic action (ae) with a delay (δ) relative to the tempo (δ ∈ Q).

The most basic actions in a score, called atomic actions, are simple control messages destined for the audio environment (e.g., UDP messages for Max/MSP). Each is bound to an instrumental event, the triggering event, and characterized by a delay. When the listening machine detects the triggering event, the sequencer waits for the specified delay and then sends the corresponding control message. In the example of Figure 2, action a0 is bound to the first note e1 with a delay of 0.0. Thus, when the first note is detected, the message a0 is sent immediately.

Atomic actions can be grouped into control structures called groups. Like an atomic action, a group is triggered by an instrumental event and characterized by a delay. When the triggering event is detected, the sequencer waits for the corresponding delay and then launches the actions contained in the body of the group. In the example, a group is bound to the second instrumental event with a delay of 0.5 beat. When this event is detected, the sequencer waits 0.5 beat and then launches action a1, after another delay of 1.0 beat, the message a2 is sent. Groups can be nested arbitrarily. Actions contained in a nested group are executed in parallel with the actions following them in the embedding group, not in sequence. An electronic voice can be split into two parallel voices which can in turn be split and so on. Thus, a score can faithfully capture the complexity of a musical piece.

There are two kinds of parallelism in the language. First, two sequences bound to different instrumental events are executed in parallel. Second, a nested group inside a sequence is executed in parallel with the rest of the sequence. Note that when two sequences are executed in parallel, it is important that they share the same global time: the time of the performance. That is, they must be synchronous. Otherwise, the performance would not reflect the musical score. To this similarity with synchronous languages, Antescofo adds two original features: synchronization and error handling strategies.

### 2.2 Synchronization Strategies

Groups are characterized by two attributes (see [5]). The first one defines a synchronization strategy. A composer is allowed to specify how actions contained in a group will synchronize with instrumental events that occur during the execution of the group. There are several ways to achieve this synchronization depending on the musical context. Currently, the language proposes two distinct modes of synchronization: loose and tight.

Once a loose group is launched, delays are computed according to the current value of the tempo, regardless of instrumental events that may occur during its execution. Due to the inertia of the tempo inference, an electronic action contained in such a group and an instrumental event that seems to be simultaneous in the score may be desynchronized during the performance. Indeed, a performer may accelerate or decelerate between two events. Typically, this strategy is used in those parts of a score where a performer follows the electronic voices.

In a tight group, every action is triggered by the most recent corresponding instrumental event. In the example of Figure 2, the group has a synchronization attribute set to tight. Thus, although the entire group is bound to the second instrumental event, action a2 will be triggered by e3. Here, the nearest event is computed with respect to the ideal timing of the score regardless of tempo changes. This strategy is ideal when the electronic voice must accompany the interpreter’s voice.

### 2.3 Error Handling Strategies

Antescofo is designed to accompany real musicians and, thus, errors may sometimes occur. By error we mean an instrumental event which is expected and missing, either because it was not played by the musician or not detected by the listening machine. The second attribute of a group defines the error handling strategy which should be taken when an expected triggering event is absent. There are several ways to deal with errors depending on the musical context. Here, we present four exclusive error handling strategies: local, global, partial and causal. Figure 3 illustrates the four different behaviors.

The local and global strategies preserve the integrity of a group. Indeed, if the triggering event is missed, the group is either completely ignored (local) or launched with zero delay (global) as soon as a later event is detected. In both cases, delays between actions within the group are unchanged. The group can thus be seen as a single block with a certain duration.

The other two strategies aim to preserve a simple property: The future of a performance does not depend on past errors, i.e., the show must go on! When an error occurs, the corresponding group is split into two parts: actions that
should already have been launched when the error was detected, termed the past, and actions that should occur after the detection, termed the future. The attributes partial and causal differ only in their treatment of past actions. For causal groups, past atomic actions are launched immediately. For partial groups, past atomic actions are simply discarded. In both cases, future actions are launched as if they were bound to the next detected event. They are performed as if an error never occurred.

3. BEHAVIORAL SEMANTICS

In this section we describe the semantics of the core of Antescofo. The remaining features, like loops and continuous groups, are easily expressed in our kernel (see Section 6). The score given in Figure 4 will serve as a running example. In the following, sync and err stand, respectively, for any of the synchronization and error handling attributes already presented. The semantics rules are given in Figure 5 and explained below.

3.1 Execution Rules

The semantics specifies, given a set of detected events and a score, the intended performance, that is, the desired output of the sequencer relative to the tempo. It is defined by the predicate:

\[ D \xrightarrow{\text{exec}} \text{sc} \Rightarrow p \]

It relates a set of detected events \( D \subseteq \mathbb{N} \), a score \( sc \), and a performance \( p \), which is a set of triplets \((i, \delta, a)\) where \( i \in \mathbb{N} \) is a detected instrumental event (e.g., the index of the position in the score), \( \delta \in Q \) is the delay to wait after the detection of \( i \) and \( a \in \mathcal{A} \) is an atomic action.

A score is a sequence of score events of the form \((\text{event } i \ t \ : \ \text{seq})\) where \( i \in \mathbb{N} \) denotes an instrumental event of duration \( j \in Q \) and \( \text{seq} \) the associated sequence of electronic actions (see Section 2.1). If the score is empty (rule (EMPTY SCORE)), the associated performance is empty. Otherwise (rule (EXEC SCORE)), we collect in parallel the performances generated by every score event contained in the score. This is done by iterating the predicate:

\[ D \xrightarrow{\text{exec}} (\text{event } i \ t \ : \ \text{seq}) \Rightarrow p \]

which relates a score event with a performance.

Now, to obtain the performance associated to such score events \((\text{event } i \ t \ : \ \text{seq})\), the first thing to do is to check whether the corresponding instrumental event \( i \) is detected or missed:

- Rule (Detect): \( i \) is detected, that is, \( i \in D \). We apply a predicate detected to the sequence \( \text{seq} \). Thus:
  \[ D, i, \delta \xrightarrow{\text{detected}} \text{seq} \Rightarrow p \]
  means that sequence \( \text{seq} \), bound to the detected instrumental event \( i \) with a delay \( \delta \), leads to the performance \( p \).

- Rule (Miss): \( i \) is missing, i.e., \( i \notin D \). We apply a predicate missed to the sequence \( \text{seq} \). Thus:
  \[ D, i, \delta \xrightarrow{\text{missed}} \text{seq} \Rightarrow p \]
  means that sequence \( \text{seq} \) related to the missing event \( i \) with a delay \( \delta \) leads to the performance \( p \).

In order to deal with sequences of actions, we introduce two administrative rules (EMPTY SEQUENCE) and (EXEC SEQUENCE). These rules allow us to apply a predicate, detected or missed on a sequence of electronic actions while computing the correct delay for each action. Here, generic can be instantiated by detected or missed.

For example, let us consider a simple sequence of electronic actions \([i(\delta_0 \ a_0) (\delta_1 \ a_1)]\) related to an event \( i \) with a delay \( \delta \). For both actions, the triggering event is \( i \), and the associated delays are \( \delta + \delta_0 \) for \( a_0 \), and \( \delta + \delta_0 + \delta_1 \) for \( a_1 \). More generally, the delay associated to an action in a sequence is the sum of previous delays.

In the following, we will detail the behaviors of the different electronic actions (atomic actions and groups). But first, we need to define some auxiliary functions.

3.2 Notations

Let \( E \) be the function that returns the delay between an instrumental event \( i \) and the beginning of the score, i.e., the date of \( i \) relative to the tempo. This is just the sum of the durations \( t_k \) of all instrumental events \( k \) between the beginning of the score and \( i \):

\[ E(i) = \sum_{k=1}^{i-1} t_k \]

Besides, by definition in Section 2.3, it is impossible to detect a missing event before the next detected instrumental event. Indeed, if the next event is not yet detected, it could simply be a deceleration of the tempo. For a missing event \( i \notin D \), \( M(i) \) denotes the next detected event. Formally:

\[ M(i) = \min(j \in D \mid E(j) > E(i)) \]

3.3 Atomic Actions

Now we define the predicates of the form:

\[ D, i, \delta \xrightarrow{\text{generic}} \text{ae} \Rightarrow p \]

They explain the behavior of an electronic action \( \text{ae} \) bound to an event \( i \) with a delay \( \delta \).

First, let us consider the case of an atomic action \( a \). If the event \( i \) associated to \( a \) is detected, we apply the rule (Detected Action) which leads to the performance \((i, \delta, a)\). Indeed, after the detection of \( i \) we just have to wait out the delay \( \delta \) and then send the message \( a \).

Now, if \( i \) is missing, the error will be detected with the detection of \( j = M(i) \). The behavior of an atomic action when the triggering event is missed is described by the rule (Missed Action). If \( a \) should have been launched before the event \( j \), the message is immediately sent. Otherwise we wait the remaining delay: \( (E(i) + \delta) - E(j) \) before sending the message.

Example. In our example, there is only one atomic action related to \( e_4 \). Thus, if \( e_4 \) is detected, the corresponding performance is the triplet: \((4, 0.5, a_{41})\).

3.4 Synchronization Strategies

Now, recall that actions can also be structured into groups whose synchronization with the instrumental events can be specified with the attributes presented in Section 2.2.

To interpret a group declared as loose, we just apply the detected version of the rule (EXEC SEQUENCE) to the body of the group (rule DETECTED LOOSE GROUP). The triggering event \( i \) remains the same for all these actions.
Figure 4: A simple score and its graphical representation where the $e_i$'s denote instrumental events.

Figure 5: Behavioral Semantics
First we associate a date event $j$ to each subsequence $j$. Delay $\delta_j$ is associated to the nearest instrumental event in the past. Figure 6 illustrates this transformation: the result of the slicing associated to the corresponding performance will be: \{(2, 1.5, a_{22}), (3, 0.5, a_{23})\}.

Example. Imagine that $g_2$ is a group loose and $e_2$ a detected event. Then, the execution of $g_2$ leads to the performance: \{(2, 1.5, a_{22}), (2, 2.5, a_{23})\}.

For a group declared as tight a bit more treatment is needed. Intuitively, the body of the group must be sliced according to an instrumental event that should occur during the execution of the group. Each action in the body is associated to the nearest instrumental event in the past. Figure 6 illustrates this transformation: the result of the slicing of the group in (score 1) is a fresh score (score 2), containing one loose group bound to each instrumental event that should occur during the execution of (score 1).

Formally, let $g$ be a tight group bound to event $i$ with a delay $\delta$ and body $seq = [\{(\delta_1, x_1), (\delta_2, x_2), ... (\delta_n, x_n)\}]$. Here $x$ denotes any kind of electronic action, group or atomic action. First we associate a date $d_k$, relative to the tempo, to each element $x_k$.

$$d_k = \mathcal{E}(i) + \delta + \sum_{p=1}^{k} \delta_p$$

Then, for each instrumental event $j \geq i$, we compute the subsequence $s_j$ of $seq$ such that the date of electronic actions is between the date of $j$ and the date of $j + 1$:

\[
s_j = [(\delta_{j_0}, x_{j_0}) ... (\delta_{j_1}, x_{j_1})] \quad \text{where} \quad d_{j_{n-1}} < \mathcal{E}(j) \leq d_{j_0} \leq d_{j_1} < \mathcal{E}(j + 1) \leq d_{j_1 + 1}
\]

Each subsequence $s_j$ is associated to the corresponding event $j$ instead of $i$. Therefore, we need to update delays such that the dates of the electronic actions remain the same: \(\delta_j' = d_j - \mathcal{E}(j)\). Finally, the resulting sequence: \(s_j' = [(\delta_{j_0}', x_{j_0}'), (\delta_{j_1}', x_{j_1})] \) becomes the body of a fresh loose group with the same error handling strategy as $g$. Thereby we preserve the error handling strategy for the future: $g_j = \text{group loose err } s_j'$.

The result of the slicing is a fresh score containing one score event for each group $g_j$: $se_j = \{\text{event } j \mid (0.0 g_j)\}$.

Slice(i, d, g) = [se_i ... se_{i+k}] where \(\mathcal{E}(i+k+1) \geq d_n\)

The last thing to do is to execute the resulting score. This behavior is described by the rule (Detected Tight Group).

Example. Suppose that $g_2$ is declared as tight and $e_2$ is detected. The result of the slicing is (see Figure 4):

\[
\text{Slice}(2, 1.5, g_2) = \{\text{event } 2 2.0 : (0.0 g_2') \mid (\text{event } 3 1.0 : (0.0 g_2'))
\]

where $g_2' = \text{group loose err } (1.5 a_{22})$

and $g_2 = \text{group loose err } (0.5 a_{22})$

Assuming that $e_3$ is detected, the corresponding performance will be: \{(2, 1.5, a_{22}), (3, 0.5, a_{23})\}.

3.5 Error Handling Strategies

Groups are also characterized by an error handling strategy: local, global, partial or causal. These attributes allow a composer to specify how the group will behave if the triggering event is missed (see Section 2.3). When the triggering event is missing, a local group is completely ignored (rule Missed Local Group). Conversely, a global one is launched with zero delay, as if the next detected event was the triggering event (rule Missed Global Group).

Example. For example, assume that $g_2$ is declared as global, $e_2$ is missing and $e_3$ is detected. Then, the corresponding performance will be: \{(3, 0.0, a_{22}), (3, 1.0, a_{23})\}. Similarly, if $e_2$ and $e_3$ are missing and $e_4$ is detected, then, the performance corresponding to $g_2$ will be: \{(4, 0.0, a_{22}), (4, 1.0, a_{23})\}. If the group is declared local, the performance will be empty.

For the two other attributes, the first thing to do is to split the body of the group into two subsequences (see Section 2.2): actions that should have been launched before the error detection (past), and actions that should occur after the error detection (future).

Formally, let $g$ be a group declared as causal or partial, with body $seq = [\{(\delta_1, x_1), (\delta_2, x_2), ... (\delta_n, x_n)\}]$. We suppose that $g$ is bound to a missing event $i \notin D$ such that $\mathcal{M}(i) = j$. First, we associate a date $d_k$, relative to the tempo, to each element $x_k$ (see the slicing of tight groups in Section 3.4). Then we can split the sequence $seq$ into the two subsequences, past and future. This is done by the function Split:

$$\text{Split}(i, j, \delta, seq) = (\text{past, future})$$

where past = \[\{(\delta_1, x_1), ... (\delta_p, x_p)\} \mid d_p < \mathcal{E}(j) \leq d_p + 1\] and future = \[\{(\delta_{p+1}, x_{p+1}), ... (\delta_n, x_n)\}\]

Attributes partial and causal only differ in the treatment of past actions. The difficulty comes from the hierarchical structure of the score. Indeed a group that appears in the past could contain an action that should be launch in the future. Hence, nested groups must be split as well. We solve this problem by recursively applying the missed version of the rule (EXEC SEQUENCE) on past actions sequences.

If the past contains an atomic action this action will be launched immediately. This is described by the rule (Missed ACTION). This is the desired behavior for a causal group. On the other hand, to achieve the partial behavior, we need to ignore past atomic actions. In other words, the past of a partial group only contains past nested groups.

Thus for a partial group, we need to compute a new sequence which contains only past nested groups. The past is a sequence of actions, therefore the delay associated to each action is relative to the previous one. Hence we must re-compute the delays associated to each group while extracting them. Let $x_{g_i}$ be the first group of the past, $x_{g_2}$ the second one and so on. Since $x_{g_1}$ is the first group, actions $x_{g_1}, x_{g_2}, ..., x_{g_{n-1}}$ are atomic actions. Thus in the new sequence, the delay associated to $x_{g_1}$ is $\delta_1 + \delta_2 + ... + \delta_{g_1}$. More generally, the new delay of a group $x_{g_i}$ is the sum of delays between $x_{g_i}$ and the previous group $x_{g_{i-1}}: \delta_{g_{i-1} + 1} + \delta_{g_{i-1} + 2} + ... + \delta_{g_i}$.

Extract(past) = \[\{(\delta_{g_1}', x_{g_1}), (\delta_{g_2}', x_{g_2}), ... (\delta_{g_p}', x_{g_p})\} \mid \forall 1 \leq i \leq p \quad \delta_{g_i}' = \sum_{k=g_{i-1}+1}^{g_i} \delta_k\]
Finally we wrap the future into a fresh group with the synchronization attribute and the error handling attribute of the original group. We thereby preserve both the synchronization strategy and the error handling strategy for the future. The last thing to do is to execute the missed synchronization strategy and the error handling strategy for the rest of the score is executed as if the error never occurred. These behaviors are described by the rules (Missed Causal Group) and (Missed Partial Group).

Example. To illustrate the case of nested groups, let us assume that the groups \( g_{11} \) and \( g_{12} \) have been declared partial, and that \( e_1 \) is missed and \( e_2 \) is detected, i.e., \( 1 \notin D \) and \( \mathcal{M}(1) = 2 \). When \( g_{11} \) is split, \( a_{12} \) is in the future and \( g_{12} \) appears in the past.

\[
\text{Split}(1,2,0.0,g_{11}) = ((1.0 g_{12}), (0.0 a_{12})) \\
\text{Extract}(1.0 g_{12}) = (1.0 g_{12})
\]

However, \( a_{13} \) which is bounded to \( g_{12} \), must be launched after \( e_2 \) (see Figure 4). By recursively applying a predicate missed, \( g_{12} \) is split in turn. Thus, \( a_{13} \) appears in the future and will be launched after \( e_2 \).

\[
\text{Split}(1,2,1.0,g_{12}) = ((0.0 a_{11}), (0.5 a_{13})) \\
\text{Extract}(0.0 a_{11}) = \varepsilon
\]

The resulting performance is: \( \{(2,0.0,a_{12}), (2,0.5,a_{13})\} \)

4. A SYNCHRONOUS EMBEDDING

The implementation of the sequencer is divided into two parts (see Figure 7). The module Time interfaces the abstract time relative to the tempo (in beats) with the physical time (in ms) (Section 4.2).\(^3\) \(^4\) The module Motor receives the current position in the score and triggers atomic actions (Section 4.3).\(^5\)

4.1 Survival Kit for ReactiveML

ReactiveML\(^4\) is a synchronous language which combines functional features found in ML-like typed functional languages with synchronous features à la Esterel [2]. It borrows the basic principles and constructs of OCAML\(^5\) on which it is built and compiled to. Like other synchronous languages, it provides a notion of global logical time on which all processes can synchronize. Semantically, processes execute in lock step and they communicate with each other in zero time.

\(^3\)The symbol \(^\star\) denotes source code available online.

\(^4\)A tutorial is available at http://reactiveml.org/tryxml.


Time and Signals.

In ReactiveML, a process is a function that lasts for several logical instants. It is introduced with a special keyword process. The following program defines the process emit_clock which takes two arguments period and clock. Its purpose is to emit a signal every period second.\(^6\)

\begin{verbatim}
let process emit_clock period clock = 
let next = ref (Unix.gettimeofday () +. period) in
loop
  let current = Unix.gettimeofday () in
  if current >= !next then begin
    emit clock ();
    next := !next +. period
  end;
  pause;
end

let process wait_abs dur period clock = 
  let period = 0.001 in
  let d = int_of_float (dur /. period) in
  do for i = 1 to d do pause done when clock done

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ())

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ())

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (emit_clock period clock) ||
   run (wait_abs dur1 period clock); emit a ()) ||
   run (wait_abs dur2 period clock); emit b ()

let process ab dur1 dur2 a b = 
  let period = 0.001 in
  (run (em...
4.2 Following the Tempo

Remember that, in our version of Antescofo, all delays are expressed relative to the tempo in beats. In practice, the tempo is computed by the listening machine: for each detection, the listening machine sends the label of the detected instrumental event and the estimated tempo.

We need to compute the elapsed delay, relative to the tempo, since the beginning of the performance. This is just like calculating the distance an object travels by integrating its speed. It is a simple fixed-step integrator of a piecewise constant function \( \text{bps} \) (the tempo only changes when an instrumental event is detected). In the following, \( \text{clock} \) denotes a global signal. It will be generated with the process \( \text{emit} \_\text{clock} \) above, with period \( \text{period} \) defined as a global constant.

The process \( \text{elapsed} \) integrates the value of tempo since the beginning of its execution. Here, \( \text{bps} \) is a signal that carries the value of the tempo in beats-per-second. For each step of the integration, we send the result on a signal \( \text{date} \).*

\[
\text{let process elapsed bps date =}
\]

\[
\begin{aligned}
\text{let } x = & \text{ ref } 0.0 \text{ in} \\
\text{do}
\end{aligned}
\]

\[
\begin{aligned}
\text{loop}
\end{aligned}
\]

\[
\begin{aligned}
x := & x + \text{ last } ?\text{bps } \times \text{ period} \\
\text{emit} \text{ date } !x; \\
\text{pause}
\end{aligned}
\]

\[
\text{end when clock done}
\]

The variable \( x \) contains the current value of the integrator, initialized to 0.0. Thus, at the \( n \)-th occurrence of \( \text{clock} \), the signal \( t \) is emitted with a value \( x(n) \) such that:

\[
x(n) = \sum_{i=0}^{n} \text{last(bps)}(i) \times \text{period}
\]

The construct \( \text{last } ?\text{bps} \) denotes the last value of the signal \( \text{bps} \). It only changes when a new \( \text{bps} \) value is emitted. Placing the \text{loop/}end construct within do/when means that the loop is only executed when the signal \( \text{clock} \) is present.

Now that we can measure time relative to the tempo, we can write a process that waits for a duration \( \text{delta} \) relative to the tempo.

\[
\begin{aligned}
\begin{array}{l}
\text{let process wait date delta =} \\
\text{let ending = last } ?\text{date} + \text{ delta in} \\
\text{while last } ?\text{date} \leq \text{ending do pause done}
\end{array}
\end{aligned}
\]

The signal \( \text{date} \) will be produced by the process \( \text{elapsed} \). The process \( \text{wait} \) first computes the future date of the end of the waiting: \( \text{ending} \). We compare the last computed value of \( \text{date} \) with the deadline \( \text{ending} \), and wait until \( \text{last } ?\text{date} \) reaches the deadline. Note that delays \( \delta \in \mathbb{Q} \) relative to the tempo are implemented using floating-point numbers.

In practice, the waiting process is implemented using signals and a priority queue. The process \( \text{wait} \) sends a signal and a deadline to the priority queue. Then the only thing to do is to wait for the return of this signal. Therefore, only the scheduler requires computation at each instant.*

4.3 Translating Semantic Rules

\text{ReactiveML} extends the language OCaml. Therefore, the grammar presented in Section 2.1 can be represented by the declaration of an inductive type (given in Appendix A).* For every predicate defined in Figure 5, (i.e., \( \text{exec}, \text{detected}, \text{and missed} \)), we define a corresponding process in \text{ReactiveML}.*

\text{Execution Rules.}

To execute a score, we launch in parallel a process \( \text{exec} \_\text{score} \_\text{event} \) for each score event. Therefore, all electronic actions stay synchronous during the performance. In particular, when an event is detected, the execution of missed electronic actions remains synchronous with the execution of detected ones.

\[
\text{let rec process exec score =}
\]

\[
\begin{aligned}
\text{match score with} \\
\mid [] -> (* \text{rule (Empty Score)} *) () \\
\mid se::sc ->
\end{aligned}
\]

\[
\begin{aligned}
(* \text{rule (Exec Score)} *)
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec} _\text{score} \_\text{event se) ||}
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec sc)}
\end{aligned}
\]

Note the similarity with rules (\text{Empty Score}) and (\text{Exec Score}) of Figure 5.

The process \( \text{exec} _\text{score} \_\text{event} \) is the implementation of the two rules (\text{Detect}) and (\text{Miss}). The parameter \( \text{se} \) is a structure which denotes a score event where \( \text{se}.seq \) is the corresponding sequence of electronic actions and \( \text{se}.event \) is the associated instrumental event. The process \( \text{wait} _\text{event} \) awaits an instrumental event. Then, if this event is detected, it returns the value \text{Detected}. On the other hand, if the event is missed, the process returns the value \text{Missed} where \( j = M(i) \) is the next detected event (see Section 3.2).

\[
\begin{aligned}
\text{let rec process exec} _\text{score} \_\text{event se =}
\end{aligned}
\]

\[
\begin{aligned}
\text{let status = run (wait} _\text{event se.event) in}
\end{aligned}
\]

\[
\begin{aligned}
\text{match status with}
\end{aligned}
\]

\[
\begin{aligned}
\mid \text{Detected} ->
\end{aligned}
\]

\[
\begin{aligned}
(* \text{rule (Detect)} *)
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec} \_\text{seq (detect i) 0.0 se.seq)}
\end{aligned}
\]

\[
\begin{aligned}
\mid \text{Missed} (j) ->
\end{aligned}
\]

\[
\begin{aligned}
(* \text{rule (Miss)} *)
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec} \_\text{seq (missed i j) 0.0 se.seq)}
\end{aligned}
\]

Each score event is related to one instrumental event. Thus, during the performance the only thing to do is to wait for the detection of this event. In ReactiveML, such waiting requires no computing at all. Indeed, one important characteristic of the ReactiveML implementation is the absence of busy waiting: nothing is computed when no signal is present.

The process \( \text{exec} \_\text{seq generic delta s} \) implements the behavior described by the rules (\text{Exec Sequence}) and (\text{Empty Sequence}) (see Section 3.1). This process computes the delay corresponding to each action in the sequence \( s \) and runs a process \( \text{wait} _\text{event} \) in parallel for each of these actions with the computed delay.

All electronic actions are executed in parallel. Thus nested groups can be treated as atomic actions.

\[
\begin{aligned}
\text{let rec process exec} \_\text{seq generic delta seq =}
\end{aligned}
\]

\[
\begin{aligned}
\text{match seq with}
\end{aligned}
\]

\[
\begin{aligned}
\mid [] -> (* \text{rule (Empty Sequence)} *) () \\
\mid (\text{dae},ae)::se ->
\end{aligned}
\]

\[
\begin{aligned}
(* \text{rule (Exec Sequence)} *)
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec} \_\text{seq generic (delta +. dae) ae) ||}
\end{aligned}
\]

\[
\begin{aligned}
\text{run (exec} \_\text{seq generic (delta +. dae) s)}
\end{aligned}
\]

\text{Detected and Missed Rules.}

The next process is the encoding of the predicate \text{detected} of Figure 5. It matches the type of an electronic action \( \text{ae} \), bound to an instrumental event \( i \) with a delay \( \text{delta} \), and executes the corresponding behavior. When an atomic action \( a \) is reached, the corresponding triplet \((i,\text{delta},a)\) is
sent on the global signal perf. In parallel, another process listens for this signal and sends control messages to the audio environment (Max/MSP).

Here date is the signal produced by the process elapsed described previously. The function slice is the implementation of Slice defined in Section 3.4.

val slice : label -> delay -> group -> score

It returns a fresh score where each score event contains one zero delay loose group. Then, the process detected is implemented as follows:*`

and process detected i delta ae =
  match ae with
  | Action(a) -> (* rule (Detected Action) *)
    run (wait_date delta);
    emit perf (i,delta,a)
  | Group(g) ->
    begin match g.group_synchro with
      | Loose -> (* rule (Detected Loose Group) *)
        let bg = g.group_seq in
        run (exec_seq (detected i) delta bg)
      | Tight -> (* rule (Detected Tight Group) *)
        let gs = slice i delta g in
        run (exec gs)
    end

In the same way, the process missed is the transcription of the missed rules (see Appendix B).

4.4 Evaluation and Limitations

While the original system is developed as an object in the Max/MSP programming environment, our interpreter communicates with this environment via UDP sockets in a local network. The communication latency between the two applications is negligible (around 10ms). The original sequencer, embedded in the ANTESCOFO object, is disabled as the synchronous one replaces it. Hence, during the performance, Max/MSP sends the output of the listening machine. Then, the synchronous sequencer treats this information and sends control messages back to Max/MSP.

Currently, there is no proper benchmark to evaluate the sequencer part of the system. Each modification is tested with real scores written by composers. Nonetheless, we exercised our application on several toy examples (traditional songs, violin concertos, etc). In these examples, the accomplishment is a set of groups bound to the first note of the performer. They are relatively simple because the electronic part does not have a complex hierarchical structure. However, they are still meaningful for an experimental validation because the sequencer handles a realistic number of electronic actions. For instance, in the second and third movements of the Tchaikovsky’s violin concerto, there are 3705 instrumental events for 11062 electronic actions.

The synchronous sequencer is used to control a MIDI synthesizer which accompanies a solo musician. We test these examples with random faults and a randomly changing tempo. On these examples, our sequencer compares well to the original one. Indeed, the latency between the two applications remains under 30ms, the reaction time of the human ear [8].

Nonetheless, there is one major difference between our implementation and the original one. ANTESCOFO is embedded in Max/MSP which provides precise timers and the means to wake-up processes on timers. When ANTESCOFO is activated by Max/MSP, it possibly emits some control messages to Max/MSP, and then computes the next deadline to be activated. Max/MSP wakes ANTESCOFO up when the deadline expires or because an instrumental event is detected. As our implementation is not embedded in Max/MSP, we have experimented with a different approach. The REACTIVEML compiler generates a step function. It is sampled using an (imprecise) UNIX timer on which a regular signal clock is built (see Section 4.1). For any sampling value between 1ms (the refresh frequency of Max/MSP) to 30/2 = 15ms (half of the reaction time of the human ear), the implementation is fast enough. However, if the sampling value is greater than 15ms, one can hear a noticeable delay between electronic and instrumental parts. Besides that, when executed at full speed, the implementation keeps respecting deadlines but monopolizes the CPU uselessly.

Moreover, if the period of the clock signal is too small or if the sequencer requires a lot of computations, the sequencer may fail to produce the signal on time. This is of no importance because it does not change the next deadline for the signal clock. Thus, if there is nothing to do during the next steps, the sequencer will quickly catch up. In practice, the sequencer waits during most of the steps and catches up very quickly. On the other hand, the period of the clock signal is limited by the score. It can not be higher than the minimal delay between two actions.

5. APPLICATIONS

Our implementation provides a powerful tool for prototyping. After defining the semantics of the core of ANTESCOFO, we were able to implement it directly in REACTIVEML. Therefore, new features of the language can be added with little effort. For instance, we proposed two new synchronization strategies partial and causal which fit perfectly in the semantics framework and have been implemented in REACTIVEML and tested on some examples.

5.1 Prototyping New Features

In the same way, we can rely on REACTIVEML features to implement more complex structures. Assume that we want to introduce a new preemption construct to stop the execution of a sequence when a particular instrumental event is detected. Typically, this construct is difficult to add to an implementation that only uses priority queues. But, thanks to the preemptive construct do/until, the integration of this new feature in the language is immediate. The only thing to do is to add a case in the processes detected and missed. Here, u is an instance of our new construct, u.until_seq denotes a sequence of electronic actions and u.until_event denotes the control event.*`

and process detected i delta ae =
  match ae with
  | Until(u) ->
    signal kill in
    do
      (run (exec_seq (detected i) delta u.until_seq);
       emit kill)
    | (run (wait_event u.until_event);
       emit kill)
    until kill done
5.2 Towards New Interactions

Moreover, coupling the sequencer with ReactiveML via signals is another valuable asset for prototyping. Indeed, in our application, actions consist in either sending a control message to Max/MSP or emitting a ReactiveML signal (see Appendix A). Therefore, it is easy to link a score with a ReactiveML program. One of the main advantages of our approach is that the program and the sequencer remain synchronous. We can use this property, for instance to write a performance simulator which runs in parallel with the sequencer and sends messages containing the index of an instrumental event and the value of the tempo, instead of the listening machine.

This technique can also be used to write pieces with complex interactions between the performer and the accompanying. For example, Piano Phase is a piece written in 1967 by the minimalist composer Steve Reich. In this piece, two pianists begin by playing a rapid twelve-note melodic figure over and over again in unison. Then, one of the pianists begins to play his part slightly faster than the other. When the first pianist plays the first note of the sequence as the second is playing the second note, they resynchronize for a while. The process is repeated, so that the second pianist plays the third note as the first pianist is playing the first, then the fourth, etc.

We implemented this piece using both our sequencer and ReactiveML. The real musician plays the part with the constant tempo, while the accompaniment alternates between desynchronization and resynchronization. First, the two pianists play at the same speed. Then, the electronic accompaniment begins to play its part slightly faster and emit a signal first_note each time it plays the first note of the sequence. Meanwhile, we track the position of the performer and emit a signal kth_note each time the performer plays the second note of the sequence. When the two signals are close enough we resynchronize the accompaniment and the two pianists play at the same tempo again. Then, we restart the desynchronization but, this time, we track the third note of the performer, and so on. The difficulty comes from the fact that we do not know a priori when the pianists resynchronize (in the original score, the composer only specifies bounds on the number of iterations of the sequence during the desynchronization). Programming such a behavior is not possible to achieve with the language described in [5]. In Antescofo, the electronic part only synchronizes using the output of the listening machine and a static score. Here, the sequencer has to synchronize with both the listening machine and an external program running in parallel and sharing the same notion of time. A very recent extension of the Antescofo language, developed independently from the present work, allows the simulation of this new feature [4].

5.3 Toplevel and Live Coding

Finally, ReactiveML has a toplevel [10], and it is thus possible to dynamically write, load and execute ReactiveML code. This feature allowed our implementation to be extended to support live coding. It is now possible to write and/or correct an accompaniment during the performance using our kernel of the Antescofo language.

Dedicated languages and applications already exist for live coding (i.e., real-time synthesis and control during a performance) [14, 12]. The main advantage of our proposal is that composers can rely on the features of the Antescofo language during live coding, e.g., for synchronization and error handling strategies. However, it only works in interaction with Max/MSP. Therefore it is much more limited than languages dedicated to, and optimized for, live coding.

6. RELATED WORK AND DISCUSSION

Differences with the original language.

The most notable differences between this core language and Antescofo as defined in [5] are the specifications of group attributes. In the original language, there are only two error handling attributes: global (g) and local (l) whose meaning depends on the synchronization strategy. To make synchronization and error handling attributes independent of each other, we have changed the meaning of the local and global attributes and introduced the new attributes partial and causal. The 2 × 4 following combinations are now possible whereas the original system only provided 4. The combination of tight (T) and partial was named tight local (T 1) and the combination of tight and causal was named tight global (T g):

<table>
<thead>
<tr>
<th>local</th>
<th>global</th>
<th>partial</th>
<th>causal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T l</td>
<td>T g</td>
</tr>
<tr>
<td>loose(L)</td>
<td>.</td>
<td>L l</td>
<td>.</td>
</tr>
<tr>
<td>tight(T)</td>
<td>.</td>
<td>.</td>
<td>T g</td>
</tr>
</tbody>
</table>

Furthermore, the semantics proposed in [5] is based on a normalized subset of the language: a pre-processing converts tight groups into loose groups, and tight groups nested inside a loose group are interpreted as loose groups. There is no such pre-processing in our proposal. Our semantics gives a precise meaning to arbitrary nestings of any kind of group and directly reflects the hierarchical structure of a score.

We focus here on a subset of the language, but the omitted control structures can be easily expressed in our kernel. For instance, in the original language, a loop is just a succession of groups characterized by the same attributes. In the same way, the original language allows the use of continuous groups [5]. Messages contained in a continuous group correspond to the sampling of piece-wise linear functions specified by a sequence of control vectors. Thus, it can be easily translated into a simple group containing all the desired actions. As explained above, we can attain sampling values down to 1 ms which is comparable to the current Antescofo system. This is satisfying enough for control, e.g., of amplitude, but not for audio synthesis for which a sampling period of 0.02 ms is needed.

The original language offers the possibility to specify delays in seconds instead of delays relative to the tempo. This feature can easily be added to our interpreter. The only change required is to use the process wait_abs defined in Section 4.1 instead of wait for delays expressed in seconds.

Finally, a denotational semantics in term of a datation function of actions can be found in [6]. We believe that the deduction rules of Section 3 are easier to understand, permit some reasoning and a natural translation into a synchronous implementation. Moreover, this formalism is also more open in the sense that it is easy to extend with new constructs like new group attributes. It is not clear for instance whether the error handling attributes partial and causal can be described in the semantics of [6].
Modeling of real-time.
Recent work in the Berkeley PTIDES project [15] extends the Ptolemy\textsuperscript{7} system with real-time features. Basically, signals are tagged with time-stamps as they move through a distributed data-flow network: input tokens are stamped at occurrence, dates are incremented as tokens pass through delays within the system and finally actuator tokens are queued to take effect when their time stamps expire. In our context, time-tags are not simply a real-time date but a couple \((i, \delta)\) where \(i\) is a detected event and \(\delta\) a delay relative to the tempo. Tags are completely ordered with the following relation:

\[(i_1, \delta_1) < (i_2, \delta_2) \iff E(i_1) + \delta_1 < E(i_2) + \delta_2\]

Thus, our semantics rules can be viewed as a way to compute tags associated to each atomic action.

Language Embedding.
This work is influenced by Conal Elliott’s shallow embedding of FRAN [7], a language for defining reactive animations in Haskell. We took a similar approach by embedding a domain-specific language inside a functional language. Yet, our approach is novel as we embed a reactive language into a more expressive one. By reusing the synchronous parallelism of ReactiveML, we reduced much of the work of compilation. Moreover, the implementation closely follows the semantics rules.

7. CONCLUSION
In this paper, we proposed a semantics for the core language of Antescofo, a system dedicated to mixed music. This semantics highlights its synchronous nature: all running processes execute in lock-step according to a global time scale. Moreover, this semantics naturally yields a synchronous implementation. We used ReactiveML for its expressiveness and efficiency.

By embedding Antescofo in an existing synchronous language, much compilation work is avoided. The implementation is small (a few hundred lines of ReactiveML) and efficient enough so that no perceptible difference has been noticed with respect to the current implementation. We experimented with it on several musical pieces and computation delays were always below human ear tolerance (30ms).

This embedding allows the writing of complex reactive programs in ReactiveML capable of interacting with the rest of the musical score. We believe therefore that our application is a powerful tool for prototyping all kinds of new features such as new synchronization or error handling strategies, but also for other types of new interactions between live performers and computers.

Acknowledgement
The authors would like to thank Arshia Cont and Gérard Berry who were at the origin of these ideas. We are also grateful to Jean-Louis Giavitto, Timothy Bourke and the anonymous reviewers for their kind and valuable remarks.

8. REFERENCES

\textsuperscript{7}http://ptolemy.berkeley.edu/index.htm
APPENDIX

A. STRUCTURE OF THE SCORE

We present here the translation of the grammar presented in Section 2.1 in terms of OCaml types.

```ocaml
(* Asco action: control message or RML signal *)
type action =
   | Message of string (* Max/MSP control message *)
   | Signal of (unit, unit list) event (* RML signal *)

(* Synchronization strategies *)
type sync = Tight | Loose

(* Error handling strategies *)
type err = Local | Global | Causal | Partial

(* Asco group *)
type group =
   { group_synchro : sync;
     group_error : err;
     group_seq : sequence; }

(* Generic asco action *)
and asco_event = Group of group | Action of action

(* Sequence *)
and sequence = (delay*asco_event) list

(* Electronic score event *)
type score_event =
   { event : instr_event_label;
     seq : sequence; }

(* Score *)
type score = (score_event list)

(* Instrumental score *)
type instr_score = delay array

(* Performance element *)
type perf_elem = instr_event_label * delay * action
```

B. THE MISSED RULES

The process missed is the transcription of the missed predicate (see Figure 5). Here ae is an electronic action related to a missing event i, with a delay \( \delta \), and \( M(i) = j \) (see Section 3.2). The function split is the implementation of Split (see Section 3.5). It returns two sequences of actions, the past and the future.*

```ocaml
let split : label -> label -> delay -> group -> sequence * sequence

The function, extract_groups is the implementation of Extract (see Section 3.5). It returns groups contained in a sequence.*

val extract_groups : sequence -> sequence

Finally instr_sc is a map structure that contains dates of instrumental events. It plays the role of the function \( E^e \) (see Section 3.2). Then, the process missed is implemented as follows.*

```ocaml
and process missed i j delta ae =
let dj = instr_score.find j in
let di = instr_score.find i in
match ae with
| Action(a) ->
   (* rule (Missed Action) *)
   let d = \( \max \{0.0, \delta + di - dj\}\) in
   run (wait d);
   emit perf (j,d,a);
| Group(g) ->
   begin
     match g.group_error with
     | Local -> (* rule (Missed Local Group) *) ()
     | Global -> (* rule (Missed Global Group) *)
        run (detected j 0.0 ae)
     | Partial ->
       (* rule (Missed Partial Group) *)
       let past, future =
         Groups.split instr_score i j delta g in
       let gpast = Groups.extract_group past in
       let gfuture =
         Group({group_synchro = g.group_synchro;
               group_error = g.group_error;
               group_seq = future;})
       in
       (run (exec_seq (missed i j) delta gpast) ||
        run (detected j 0.0 gfuture))
     | Causal ->
       (* rule (Missed Causal Group) *)
       let past, future =
         Groups.split instr_score i j delta g in
       let gfuture =
         Group({group_synchro = g.group_synchro;
               group_error = g.group_error;
               group_seq = future;})
       in
       (run (exec_seq (missed i j) delta past) ||
        run (detected j 0.0 gfuture))
   end
```

Note that processes exec, detect and missed are mutually recursive. Indeed, the process exec launches detect or missed, detect sometimes executes exec, and missed sometimes launches detect. Thus the three processes must know each other.

C. SOURCE LINES OF CODE

We computed the number of lines of code with ocamlwc.²

<table>
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<tr>
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</tr>
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<tbody>
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<td>types.rml</td>
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<td>reactive_queue.rml</td>
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²https://www.lri.fr/~filliatr/software.en.html