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Programming Mixed Music in ReactiveML

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Abstract
Mixed music is about live musicians interacting with electronic parts which are controlled by a computer during the performance. It allows composers to use and combine traditional instruments with complex synthesized sounds and other electronic devices. There are several languages dedicated to the writing of mixed music scores. Among them, the Antescofo language coupled with an advanced score follower allows a composer to manage the reactive aspects of musical performances: how electronic parts interact with a musician. However these domain specific languages do not offer the expressiveness of functional programming.

We embed the Antescofo language in a reactive functional programming language, ReactiveML. This approach offers to the composer recursion, higher order, inductive types, as well as a simple way to program complex reactive behaviors thanks to the synchronous model of concurrency on which ReactiveML is built. This article presents how to program mixed music in ReactiveML through several examples.

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

Keywords
Synchronous Programming; Language Embedding; Mixed Music; Live Coding.

1. Introduction
Technical progresses since the 1950's have led composers to write music mixing live performers with electronic parts. At first, performers simply followed a pre-registered magnetic band. But the advances in computing rapidly allowed real interaction between musicians and electronic parts.

Developed at IRCAM, Antescofo [5] is a state-of-the-art score following system dedicated to mixed music. Since 2008, Antescofo has been used in the creation of more than 40 original mixed electronic pieces by world renowned artists and ensembles, including


Figure 1 describes the organization of the Antescofo system. It is composed of two distinct subsystems: a listening machine and a sequencer. During a performance, the listening machine estimates the tempo (i.e., execution speed) and the position of the live performers in the score. The role of the sequencer is to use this information to trigger electronic actions by sending control messages to a music programming environment. e.g., Max/MSP. Then, the environment uses these messages to handle complex sound synthesis, manage lights, etc.

The language of Antescofo [9] is a descriptive language inspired by classical western music notation: a score is a interleaving of instrumental notes and electronic actions. An original aspect of this language is that it specifies synchronization and error-handling strategies for the electronic actions. It means that during the performance, depending on the tempo variations and the errors made by the musician or the listening machine, the sequencer will react in a way which is defined by the composer.

The sequencer of Antescofo is a synchronous reactive system: it continuously reads inputs from the listening machine, produces outputs to the musical environment and is subject to the strong timing requirement related to ear tolerance (typically 30 ms). Synchronous languages [2] have been invented and are used widely for programming a wide range of critical control software: on board control of trains and track interlocking, fly-by-wire and cockpit displays for planes, etc. Therefore, they would have been well suited for programming the sequencer. But, to ensure statically that programs execute in bounded time and memory, synchronous lan-

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1. http://repmus.ircam.fr/antescofo
2. http://cycling74.com/
guages like Lustre and Esterel intentionally forbid the dynamic creation of processes which is a feature of the Antescofo language. To overcome this limitation, we have implemented an Antescofo sequencer in ReactiveML [1], an extension of the functional language OCaml\(^4\) with synchronous parallelism. Note that we are interested in the language and the sequencer, the link with live musicians still relies on the actual Antescofo listening machine.

\textbf{Contribution of the Paper} The main contribution of this paper is to show, through a collection of examples, the benefit of the embedding of Antescofo in ReactiveML for programming mixed music. This embedding combines the expressiveness of the two. It facilitates the creation process for the composer by using higher-order combinators. It can be used to prototype new programming constructs for Antescofo. In all our experiments, response times were less than the reaction time of human ear, using the current version of the ReactiveML compiler and run-time.

The paper is organized as follows. Section 2 presents ReactiveML through a simple library for electronic music. In Section 3, we introduce the main features of the Antescofo language. Then, Section 4 illustrates our approach on a complete example. In Section 5, we show how this work can be used to design new kinds of interactions between a live performer and electronic parts. Related work is discussed in Section 6 and we conclude on Section 7.

The code presented in the article is available on a companion web site: \url{http://reactiveml.org/farm13}. Links to music or video demos are indicated with the symbol \(\text{\#}\).

2. Music in ReactiveML

ReactiveML [17] is a synchronous reactive language built as an extension of the functional programming language OCaml. Therefore, following the work of Hudak [12] we can easily define musical structures, in a functional programming style.

This section presents the language ReactiveML and its concurrency model through a simple music library.

2.1 Music data types

Traditionally, in western music, a melody is a sequence of \textit{notes}, where a note is a sound event characterized by a pitch and a duration. Notes can be defined with the following types.

\begin{verbatim}
let pitch_class =
  | A | B | C | D | E | F | G |
  | As | Bs | Cs | Ds | Es | Fs | Gs |
  | Af | Bf | Cf | Df | Ef | Ff | Gf |

let octave = int
let pitch = pitch_class * octave
let dur = float
let note = dur * pitch
\end{verbatim}

The pitch is represented by a pair \((\text{pitch\_class}, \text{octave})\), where \(\text{pitch\_class}\) denotes one of the twelve semi-tones, e.g., A, A#, A♭, B, B♯,..., and \(\text{octave}\) is an integer. For instance \((A, 4)\) denotes the famous A 440Hz. Here, as in Hudak’s work, A stands for A sharp and A♭ for A flat.

A classic melody is just a sequence, or list, of notes. For instance, Figure 2 presents the theme of a traditional French musical round: \textit{Frère Jacques} and the beginning of its representation in our data structure.

It is convenient to treat pitches as integers. Functions \text{int\_of\_pitch} and \text{pitch\_of\_int} convert a symbolic pitch, e.g., \((A, 4)\) to an integer and vice versa (one can, for example, associate the corresponding MIDI note, e.g., A4 = 69).

\begin{verbatim}
let jacques =
  [ 1.0, (F,4); 1.0, (G,4); 1.0, (A,4); 1.0, (F,4);
    1.0, (A,4); 1.0, (Bf,4); 2.0, (C,5); ... ]
\end{verbatim}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{frere-jacques.png}
\caption{The traditional French musical round \textit{Frère Jacques} and the beginning of its representation in our data structures.}
\end{figure}

Now that we can represent musical structures, we write functions to manipulate them. For instance, the following defines functions to transpose a sequence.\(^5\)

\begin{verbatim}
let move_pitch inter p =
  pitch_of_int ((int_of_pitch p) + inter)
val move_pitch: int -> pitch -> pitch

let transpose inter sequence =
  List.map (fun (d, p) -> d, (move_pitch inter p))
val transpose: int -> note list -> note list
\end{verbatim}

The function \text{move\_pitch} transposes a symbolic pitch by an interval \text{inter} in semi-tones. To transpose an entire melody, we use the higher-order function \text{List\_map} from the standard OCaml library that applies \text{move\_pitch} to every note in a sequence.

2.2 Time in ReactiveML

ReactiveML is a synchronous language based on the reactive model introduced by Boussinot [4]. It relies on the notion of a global logical time. Time is viewed as a sequence of logical instants. Regular OCaml functions are considered to be instantaneous, i.e., when called it returns its result in the very same instant. In addition, we can define \textit{processes} that may last over several logical instants. It is introduced by the keyword \textit{process}.

To start with, consider the programming of a simple countdown. The following program awaits a given amount of time \text{value} given in seconds.

\begin{verbatim}
let process countdown value =
  let deadline = Unix.gettimeofday () +. value in
  while Unix.gettimeofday () < deadline do
    pause
  done

val countdown: float -> unit process
\end{verbatim}

First, the date of the deadline is computed using the function \text{gettimeofday} of the Unix module\(^6\). Then, while the current date is less than the deadline, the process \text{countdown} awaits the next logical instant (\text{pause}).

Communications between processes are made through signals that are values characterized by a status defined at every logical instant: present or absent. For instance, the following process implements a standard timer similar to the Unix timer. It awaits a first

\(^4\)\url{http://caml.inria.fr}

\(^5\)The type of the functions given in \textit{italic} can be less general than the one inferred by the compiler.

\(^6\)+, *, /, \% are floating-point addition, multiplication and division operators.
duration value, and then periodically emits the signal alarm with a period interval.\footnote{In order to avoid time shifting and floating point errors, the actual implementation is slightly different.}

\begin{verbatim}
let rec process play sequence perf =
  sequence
  from a sequence
  an instant into a list, starting from the default value.
  the list
  function (fun x y -> x::y)
  a signal
  In this case, when the signal is declared, a function defining how to
  can be emitted during an instant, which is termed multi-emission.
  is the duration
  value
  default
  []
  gather (fun x y -> x::y)
  val perf default []

  signal perf default []
  gather (fun x y -> x::y)
  val perf: (note, note list) event

  The default value is set to the empty list, []
  in
  the list
  value x to the head of
  this function is used to fold all the values emitted during an
  instant into a list, starting from the default value.
  Now, we write a process play which iteratively emits the notes
  from a sequence sequence on the signal perf.

  let rec process play sequence perf =
    match sequence with
    | [] -> ()
    | ((dur, pitch) as note) :: s ->
      emit perf note;
      run (wait dur);
      run (play s)
    val play:
      note list -> (note, note list) event ->
      unit process

  The process timer is the interface between physical time and
  synchronous logical time. This process is non-deterministic: the
  number of logical instants between two emissions of the signal
  alarm is not necessarily constant. Yet, if the duration of every
  logical instant is much smaller than an interval, the error between
  two emission of the signal alarm will be negligible with respect to
  the reaction time of the human ear, i.e., 30 ms \cite{10}. The important
  point is that we have isolated the source of non-determinism in the
  program. Now, it is possible to express delays with respect to a
  signal which is supposed to be periodic.

  In the following, alarm denotes a global signal. It will be gen-
  erated by the process timer described above, with period period
  defined as a global constant. Using this signal, one can write a pro-
  cess that does nothing but wait for a duration dur. For simplicity,
  we assume in this section that all durations are expressed in sec-
  onds:

  let process wait dur =
    let d = int_of_float (dur /. period) in
    for i = 1 to d do
      await alarm
    done
  val wait: dur -> unit process

  This process waits for \(d\) occurrences of the signal alarm where \(d\)
  is the duration dur expressed as a number of instants.

  In ReactiveML, signals can also carry values. Different values
  can be emitted during an instant, which is termed multi-emission.
  In this case, when the signal is declared, a function defining how to
  combine the multiple emissions must be provided. Here, we declare a
  signal perf which accumulates in a list the multiple simultaneous
  emissions.

  signal perf default [] gather (fun x y -> x::y)
  val perf: (note, note list) event

  The default value is set to the empty list, [], and the gathering
  function (fun x y -> x::y) appends the value \(x\) to the head of
  the list \(y\). This function is used to fold all the values emitted during an
  instant into a list, starting from the default value.

  Now, we write a process play which iteratively emits the notes
  from a sequence sequence on the signal perf.

  let rec process play sequence perf =
    match sequence with
    | [] -> ()
    | ((dur, pitch) as note) :: s ->
      emit perf note;
      run (wait dur);
      run (play s)
    val play:
      note list -> (note, note list) event ->
      unit process

  To play a note, the program sends it on the signal perf. Then,
  it waits for the delay corresponding to the note duration before
  sending the next note.

  To produce sound, notes emitted on signal perf are sent to the
  audio environment.

  let process sender perf =
    loop
      await perf (notes) in
      List.iter (fun n -> send_to_audio n) notes
    end
  val sender: (note, note list) event -> unit process

  This process loops infinitely: it waits for an emission on signal
  perf and sends all received notes to the audio environment, by
  calling the function send_to_audio.

  A musical performance is the parallel composition of the two
  previous processes.\footnote{In order to avoid time shifting and floating point errors, the actual implementation is slightly different.}

  2.3 Parallel and Sequential Execution

  Thanks to the notion of global logical time inherited from the
  synchronous model, it is easy to combine processes. Two expressions
  can be evaluated in sequence \((e_1 \& e_2)\) or in parallel \((e_1 || e_2)\).
  In the latter case, they execute synchronously (or lockstep).
  Therefore, they remain synchronous during an execution.

  Imagine we want to double a voice one third higher (i.e., four
  semi-tones). Of course, it is possible to write a function that takes
  a list of notes and returns a new list of notes containing the two
  voices. But, we can also use the deterministic parallel execution
  provided by ReactiveML to play in parallel the voice and its trans-
  position. This construct will be very useful to combine the musical
  performance with other processes (see for instance Section 5.2).

  let process double sequence =
    run (play sequence) ||
    run (play (transpose 4 sequence))
  val double: note list -> unit process

  In ReactiveML, processes are first class citizens. Thus, it is
  possible to write higher order processes. For instance, the following
  code delays the execution of a process \(p\) by a duration in seconds.

  let process delayed p dur =
    run (wait dur);
    run p
  val delayed: unit process -> dur -> unit process

  Finally processes can be iterated with the classical constructs:
  loop/end for an infinite loop, for/do/done for a finite sequential
  loop and for/dopar/done for a finite parallel loop.

  With these constructs, we are able to execute the round pre-
  sented in Figure 2.\footnote{In order to avoid time shifting and floating point errors, the actual implementation is slightly different.} Four different voices play the theme in loop.

  Each voice starts two measures, i.e., 8s after the previous one.

  let process theme =
    loop
      run (play jacques)
    end
  val theme: unit process

  let process round =
    run theme ||
    run (delayed theme 8.0) ||
    run (delayed theme 16.0) ||
    run (delayed theme 24.0)
  val round: unit process
This process can also be written with a parallel loop:

```ocaml
let process round =
  let process round nb_voices =
    if nb_voices <= 0 then ()
    else begin
      run theme ||
      run (delayed (round (nb_voices - 1)) 8.0)
    end
  in
  val round: unit process

or, using a recursive process taking the number of voices as an argument.

We are now able to describe and execute electronic music in ReactiveML. But what about mixed music?

3. Toward Mixed Music

Mixed music is about interaction between a live musician and electronic parts. The Antescofo language [9] allows a composer to specify electronic parts and how they interact with musicians during a performance. This language is the result of a close collaboration between composers and computer scientists. Figure 3 shows a graphical representation of a very simple Antescofo score.

Figure 3. Representation of an Antescofo score. Musical notes correspond to the musician’s part and the rest to electronic actions.

This problem is that during a performance, the computer is supposed to act as a trained musician, following the other performers. Thus, the specification of mixed music scores faces two major challenges:

- During a live performance a musician can make a mistake, or worse, the listening machine may fail to recognize an event. In both cases, an expected event is missing. But what happens to actions bound to this event?
- Sometimes, a sequence of actions bound to an instrumental event may last longer than the duration of the triggering event. For instance, on our example, actions a2 and a3 should occur after event e3 although they are triggered by event e2. In this case, the question is: how should an electronic part synchronize with instrumental event that occur during its execution?
Error-handling and synchronization strategies depend very much on the musical context. The Antescofo language proposes solutions to reflect different musical behaviors. Groups are characterized by two attributes [6], a synchronization attribute (see Section 3.4) and an error handling attribute (see Section 3.3).

3.3 Error Handling

The error-handling attribute defines the behavior of the group when the expected triggering event is absent. There are several ways to deal with errors depending on the musical context. We present here four exclusive error handling strategies: Partial, Causal, Local and Global. Figure 4 illustrates the four different behaviors.

The most basic accompaniment is perhaps a simple harmonization of the musician’s voice. In this case, if a triggering event is missed, electronic part must keep on going as if the error never occurred. This is, for instance, the behavior of a pianist accompanying a beginner. Thus, attributes Partial and Causal aim to preserve a simple property: the future of a performance does not depend on past errors.

Now, the question is: what about actions that should already have been launched when the error was detected? If the error-handling attribute is set to Partial, these actions are simply discarded. On the other hand, if the error handling attribute is set to Causal, these actions are immediately launched. This strategy could be useful if some actions are used to initialize an external process, e.g., turn on the light.

Moreover, a group can be used to define a complex control unit, e.g., parameters needed to synthesized the sound of a gong. Then, the integrity of the group must be preserved. Thus, when an error is detected, Global groups are launched with a zero delay, whereas Local groups are completely ignored.

3.4 Synchronization Strategies

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. Currently, the language proposes two distinct strategies: Tight and Loose.

If the synchronization attribute is set to Tight, every action contained in the group is triggered by the most recent corresponding instrumental event. The nearest event is computed with respect to the ideal timing of the score regardless of tempo changes. This strategy is ideal when electronic parts and the musician must remain as synchronous as possible, e.g., if an electronic voice is a simple harmonization of the performer’s part. In the example of Figure 3, if the group has a synchronization attribute set to Tight, actions a2 and a3 will be triggered by e3 even though the entire group is bound to the second instrumental event.

The strategy Loose allows the composer to define groups that, once triggered, only synchronize with the tempo. 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. This strategy is used to preserve temporal relations between actions contained in the group. For instance, it can be very useful when the electronic part is treated as an independent background sound.

4. A First Example: The House of the Rising Sun

As a first example, let us take a classical folk song, The house of the rising sun. The score is presented in Figure 5. In this example, we want to define an electronic accompaniment which follows the main theme played by a real musician.7

First, we need to create and initialize the asco environment that contains the instrumental score. This environment allows us to manage inputs from the listening machine and the outputs destined for the audio environment.

\[
\text{let asco = create_asco "rising_sun.asco" 120.}
\]

To create the environment, we need the instrumental score of the future performance, here "rising_sun.asco" and an initial tempo, typically 120 bpm.

4.1 The Basics

The accompaniment is roughly described in the score by a sequence of chords: Am, C, D... bound to instrumental events. For instance, the first chord is related to the second instrumental event, the second to the fourth one and so on.

First, we need a symbolic description of chords. Like pitch described in Section 2.1, a chord is characterized by a pitch class: A, C, D... and a color: major or minor.

\[
\text{type color = Maj | Min}
\]

\[
\text{type chord = pitch_class * color}
\]

We can define the bass line of our example as a sequence of chords characterized by a delay:

\[
\text{let bass = [0.0, (A, Min); 2.0, (C, Maj); ...]}
\]

\[
\text{val bass: (delay * chord) list}
\]

Then, we need to turn this sequence of chords into a sequence of electronic actions. Perhaps the most simple accompaniment is to play only the roots of the bass line.

\[
\text{let root_of_chord chord octave =}
\]

\[
\text{let (pitch_class, color) = chord in}
\]

\[
\text{val root_of_chord: chord -> octave -> pitch}
\]
let only_roots chords octave dur =
List.map
  (fun (delay, chord) ->
    let root = root_of_chord chord octave in
delay, action_note (dur, root))
chords
val only_roots:
  (delay * chord) list -> octave -> dur -> sequence

Given an octave, the function root_of_chord returns the pitch corresponding to the root of a chord. Then, the function only_roots defines the sequence of electronic actions corresponding to the roots of a sequence of chords, chords. Function action_note converts a note into an atomic action destined for the audio environment (a value Action message where the message contains the characteristics of the note).

Remark that in Figure 5, no octave is specified on the score for the bass. We choose to instantiate the bass with the octave set to 3 (i.e., the first root of the bass is set to A3 = 220 Hz) and the duration to 2.0 beats which corresponds to the delay between two chords.

let roots = only_roots bass 3 2.0
val roots: sequence

The next thing to do is to build the link between the instrumental part and the electronic accompaniment. The process link asco evt seq links a sequence of actions seq to an instrumental event evt, in the environment asco. This process waits for the event to be detected or missed and it triggers the sequence. For instance, on the example of Figure 5, the first chord is bound to the second instrumental event. We can link the sequence roots to this event to obtain a basic accompaniment.

let process basic_accomp =
run (link asco 2 roots)
val basic_accomp: unit process

If the performer does not play at constant speed, the accompaniment part may become desynchronized at some point. We can easily avoid this behavior if we put the bass line inside a Tight group (see Section 3.4). Moreover, it allows us to specify an error-handling strategy for the accompaniment. In our case, if an instrumental event is missed we do not want to hear the associated chord. Therefore we use the Partial strategy (see Section 3.3).

let process tight_accomp =
let g = group Tight Partial roots in
run (link asco 2 [(0.0, g)])
val tight_accomp: unit process

Here, the function group sync err seq is a simple constructor for a group with attributes sync and err containing the sequence of actions seq.

Note that the sequence bound to the second instrumental event contains only one zero delay electronic action: the group that defines the entire accompaniment. When this instrumental event is detected, each chord of the accompaniment is linked to its closest preceding instrumental event.

The last thing to do is to launch the listening machine and the reactive accompaniment.

let process main =
run (init_asco asco);
begin
run (listener asco) ||
run (tight_accomp) ||
run (sender asco)
end
val main: unit process

It first initializes the environment. Then, the process listener links the listening machine of Antescofo to the environment. In parallel, it executes the accompaniment part, and sends it to the audio environment sender asco.

4.2 Hierarchical structure

The harmonization defined above is a bit minimalist. One solution could be to add several other voices following the previous method. But we can do better.

In the original song, the accompaniment is made with arpeggio over the bass line. Thanks to functional composition, such an accompaniment is very easy to define.

First, we define the arpeggio style we want to apply:

let arpeggio chord octave =
let fond = root_of_chord chord octave in
let third =
  match color with
  | Min -> move_pitch 3 fond
  | Maj -> move_pitch 4 fond
in
let fifth = move_pitch 7 fond in
let dur = 0.125 in

The last thing to do is to launch the listening machine and the reactive accompaniment.

An arpeggio corresponds to a Loose Local group. Thus, an arpeggio related to a missing event is entirely dismissed (Local). Besides, the synchronization strategy preserves the rhythm of the arpeggio (Loose). The function move_octave is similar to move_pitch and shift the pitch a given number of octaves.
Then, we can define the accompaniment by applying the function arpeggio to the bass line.

```ocaml
let arpeggio_bass chords octave =  
  List.map  
    (fun (delay, chord) ->  
      (delay, arpeggio chord octave))  
  chords  
val arpeggio_bass:  
  (delay * chord) list -> octave -> sequence
```

As for the basic accompaniment, we encompass the resulting sequence inside a Tight Partial group.

```ocaml
let process arpeggio_accomp =  
  let chords = arpeggio_bass bass 3 in  
  let g = group Tight Partial chords in  
  run (link asco 2 [0.0, g])  
val arpeggio_accomp: unit process
```

This accompaniments illustrates the possibility of defining hierarchical structures in the score. Indeed, a global Tight group contains a succession of arpeggios also defined as groups.

Finally we can replace the process tight_accomp in the main process by `arpeggio_accomp`.

### 4.3 Live Coding

A benefit of the embedding of Antescofo in ReactiveML is the ability to use its read–eval–print loop, called toplevel [16]. For example, if we execute the example of the rising sun in the toplevel, while it is playing, we can define a percussion part (we assume here that the environment asco has been properly initialized and that processes listener and sender are already running):

```ocaml
let process drums_accomp =  
  let rhythm = [0.0; 0.625; 0.5; 0.5; ... ] in  
  let drums =  
    List.map (fun d -> d, action_beat) rhythm  
  in  
  let accomp = group Tight Partial drums in  
  run (link asco 2 [0.0, accomp])  
val drums_accomp: unit process
```

First, we define a sequence of delays, rhythm, to represent the rhythm of the drum part. Then, we turn this rhythm into a sequence of electronic actions, drums. Here, action_beat is a value Action message such that whenever the audio environment receives one of these messages, it plays a drum beat. Finally the result is a Tight Partial group containing the entire percussion part bound to the second instrumental event.

Dynamically during the performance, we can ask that this part be played:

```ocaml
#run drums_accomp
```

This new voice will synchronize automatically with the others, even if the triggering event already passed, thanks to the error-handling strategy.

The expressiveness of the language and this dynamic aspect allows us to build more complex interactions with musicians during a performance.

Let us start with a simple example: a higher order process `replaceable` that allows a process given as argument to be stopped whenever a signal `k` is emitted. This process can be used to control the execution of an accompaniment.

```ocaml
let process killable k p =  
  do  
    run p  
  until k done  
val killable:  
  ('a, 'b) event -> unit process -> unit process
```

The construction `do/until` is not a looping structure. It stops the execution of its body when the signal is emitted.

Now, we can define a signal `kill_drum` in the toplevel:

```ocaml
signal kill_drum default () gather (fun x y -> ())  
val kill_drum:  
  (unit, unit) event
```

Instead of simply executing the percussion part, we execute it under the supervision of the `killable` combinator.

```ocaml
#run (killable kill_drum drum_accomp)
```

Then, we can stop the drum part during the performance whenever we want.

```ocaml
emit kill_drum ()
```

A more interesting example is to dynamically replace an accompaniment. First, let us define a signal `replace` on which we can send the processes.

```ocaml
signal replace  
  default (process ())  
  gather (fun x y -> process (run x || run y))  
val replace:  
  (unit process, unit process) event
```

Note that if several emissions occur during the same instant, the result will be the parallel composition of all the emitted processes.

Using the previous signal, we can define another higher order process `replaceable` which executes processes emitted on the signal `replace`.

```ocaml
let rec process replaceable replace p =  
  do  
    run p  
  until replace (q) ->  
    run (replaceable replace q)  
  done  
val replaceable:  
  (unit process, unit process) event ->  
  unit process
```

First, the process `replaceable` launches the process `p`. Then, whenever a process `q` is emitted on signal `replace`, the execution of `p` stops and the process `q` is launched in turn.

For instance, we can use this feature to dynamically switch between the different styles of accompaniment: basic, arpeggio or drums.

```ocaml
#run (replaceable replace tight_accomp)  
emit replace arpeggio_accomp  
emit replace drums_accomp
```

The first instruction launches the basic accompaniment (see Section 4.1). After a while, we can evaluate the second or the third instruction to stop the electronic part and start the complete accompaniment, `arpeggio_accomp` or the percussion part, `drums_accomp`.

Thus, it is possible to compose, correct and interact with the score during the performance.
5. Reactive Interactions

The main advantage of embedding the Antescofo language in ReactiveML is that the reactive accompaniment is now able to interact with regular ReactiveML processes. Indeed, atomic actions of the Antescofo language can be ReactiveML signals. This feature can be used to program musical pieces where the interaction between the performer and the accompaniment is more subtle than in the previous examples.

5.1 Piano Phase

Piano Phase is a piece written in 1967 by the minimalist composer Steve Reich. In this piece, two pianists, Alice and Bob, begin by playing the melodic figure presented in Figure 6 over and over again in unison. Then, one of the pianists, let us say Alice, begins to play her part slightly faster than Bob. When Alice plays the first note of the melody as Bob is playing the second note, they resynchronize for a while, i.e., Alice slows down to play at the same speed as Bob. The process is repeated. Alice accelerates again and then resynchronizes when she plays her first note as Bob is playing the third, then the fourth, etc.

If playing a simple melody at constant speed is relatively easy (Bob’s part), Alice’s part which alternatively desynchronizes and resynchronizes is much harder to achieve. Fortunately, we can program this part as an electronic accompaniment of a pianist that always plays at constant speed, here Bob.

The difficulty comes from the fact that we cannot easily compute a priori when Alice and Bob will resynchronize. Even in the original score, the composer only specifies bounds on the number of iterations of the sequence during the desynchronization (between four and sixteen times). How can we program this behavior?

Let us start with a simple process that plays the twelve note melody at a given speed and sends a signal first_note each time the first note is played. This code corresponds to Alice’s part.

```ml
let process melody evt n delay first_note =
  let period = 12.0 *. delay in
  let seq = [0.0, action_note (delay, (E,4));
             0.0, action_note first_note;
             delay, action_note (delay, (F,4));
             delay, action_note (delay, (B,4));
             ...
           ]
  in
  let run = [0.0, pattern] in
  run (link_and_loop asco evt period n seq)
val melody:
  instr_event_label -> int -> delay ->
  (unit, unit) event -> unit process
```

First, we define a simple Tight Partial group that contains the melodic pattern presented in Figure 6. The second action, introduced with the function action_signal sends the signal first_note. Since the delay of this action is set to 0.0, the signal will be emitted simultaneously with the first note of the sequence. Then we compute the period of the pattern which is the duration of the twelve note melody, i.e., 12.0 *. delay. The process link_and_loop evt n period seq links a sequence of electronic actions to an instrumental event evt in the environment and loops n times over the sequence seq where each iteration is separated by a delay period. If the period is shorter than the duration of the pattern, the execution of the loop leads to overlapping executions of the pattern.

The electronic part resynchronize when Bob plays the k-th note of the sequence as the electronic part is playing the first note. Thus, we need to track the k-th note of Bob’s part.

```ml
let process track k kth_note =
  let ie = instr_event asco in
  loop
    await ie (evt) when (evt.index mod 12 = k) in
    emit kth_note ()
  end
val track:
  int -> (unit, unit) event -> unit process
```

The function instr_event returns the signal carrying the output of the listening machine. Whenever an instrumental event is detected the index of the event in the score and the estimated tempo is sent on this signal. The construct await ie (evt) when ... binds the value received on ie to evt when the signal is emitted.

The execution can then continue only if the condition of the when is satisfied. Here, if the detected position evt.index corresponds to the k-th note of the sequence, the signal kth_note is emitted.

The last thing to do is to compare the emissions of the two signals first_note and kth_note. If two emissions are close enough it emits a signal sync. We can split this process into three steps.

The process stamp s r asco associates a date to each emission of signal s and emits the result on a signal r.

```ml
let process stamp s r asco =
  loop
    await s;
    emit r (date asco)
  end
val stamp:
  (unit, unit) event -> (delay, delay) event ->
  (unit, unit) event -> unit process
```

The function date returns a date relative to the tempo. It corresponds to the elapsed delay since the beginning of the performance. Therefore the process stamp is responsive to the execution speed. Then, the following process emits a signal sync each time the last values emitted on signals r1 and r2 are approximately equal, i.e., whenever the difference between the two values is less than a constant eps.

```ml
let process spy r1 r2 sync eps =
  loop
    await (r1 \ r2);
    let t1 = last ?r1
    and t2 = last ?r2 in
    if abs_float (t1 -. t2) < eps then
      emit sync ()
  end
val spy:
  (float, float) event -> (float, float) event ->
  (unit, unit) event -> float -> unit process
```

The construct await (r1 \ r2) awaits for one of the two signals r1 or r2 to be emitted. The expression last ?r1 evaluates to the last value emitted on signal r1.

![Figure 6. The melodic figure of Steve Reich’s Piano Phase](image)
Finally we can combine the previous processes to achieve the desired behavior.

```ocaml
let process compare s1 s2 sync eps =
  signal r1 default -.eps gather (fun x y -> x) in
  signal r2 default -.eps gather (fun x y -> x) in
  run (stamp s1 r1) ||
  run (stamp s2 r2) ||
  run (spy r1 r2 sync eps)
val compare:
  (unit, unit) event -> (unit, unit) event ->
  (unit, unit) event -> float -> unit process
```

This process, associates a date to each emission of signals s1 and s2 respectively. Then, in parallel, we launch the process of emission of very unlikely since the entire sequence is played between two conflicts. Indeed, if a signal has never been emitted, the last value playing together. It accelerates. It corresponds to the behavior of actual musicians.

```
let process piano_phase k =
  run (piano_phase ((k + 1) mod 12))
in
let piano_phase sync desync first_note kth_note =
  let rec process piano_phase x =
    let ev = last_event asco in
    run (melody ev 4 0.25 first_note);
    emit desync ();
    do
      let ev = last_event asco in
      run (melody (ev+1) 16 0.246 first_note) ||
      run (track k kth_note) ||
      run (compare first_note kth_note sync 0.05) until sync done;
    run (piano_phase ((k + 1) mod 12))
  in
  piano_phase 1
val piano_phase: (unit, unit) event -> (unit, unit) event ->
  (unit, unit) event -> (unit, unit) event -> unit process
```

First, we play the sequence four times with the duration of the notes set to 0.25 (a sixteenth note) i.e., synchronously with the pianist. During this phase, the loop is linked to the last detected instrumental event: last_event asco. Then we emit the signal desync and start to play the sequence slightly faster with the next instrumental event (the duration of the notes is set to 0.246). In parallel, we compare emissions of signals first_note and kth_note. When they are close enough (here eps is set to 0.05), the signal sync is emitted. Then we increment k and restart the whole process. The number of iterations in the desynchronized mode is set to 16. After that, if the two pianists have not resynchronized, the electronic part stops.

### 5.2 Synchronous Observer

In ReactiveML, signals are broadcast communication channels. Therefore, one can easily write synchronous observers [11], i.e., processes that listen to the inputs and outputs of a process without altering its behavior. For instance, it is relatively easy to program a graphical interface for the previous example. This section is simply a proof of concept. We do not claim that this interface is especially aesthetic.

Let us start with a very simple process that draws a rectangle at a given position. Left, Right or Full, each time a signal s is emitted.

```ocaml
let process draw_sig s pos color =
  loop
  await s;
  draw_rect pos color;
  run (wait asco 0.2);
  Graphics.clear_graph ()
end
val draw_sig:
  (unit, unit) event -> position -> color ->
  unit process
```

The process wait waits for a duration specified relative to the tempo of the environment. Thus, the interface is responsive to the speed of the performance.

Then, we can write a graphic observer that reacts to the emission of two signals s1 and s2 by alternating between two modes triggered by the signals m1 and m2.

```
let process graphic_observer s1 s2 m1 m2 =
  loop
    do
      Graphics.clear_graph ();
      run (draw_sig s1 Full Graphics.green) until m1 done;
    do
      Graphics.clear_graph ();
      begin
        run (draw_sig s1 Left Graphics.blue) ||
        run (draw_sig s2 Right Graphics.red)
      end
    until m2 done
end
val graphic_observer:
  (unit, unit) event -> (unit, unit) event ->
  (unit, unit) event -> (unit, unit) event ->
  unit process
```

In the first mode, we draw a green rectangle on the entire graphic window each time the signal s1 is emitted. When an emission of signal m1 occurs, we switch to the second mode. Then, we draw a blue rectangle on the left side of the window each time the signal s1 is emitted, and a red rectangle on the right side if the signal s2 is emitted. Then, we restart the whole process when the signal m2 is emitted.

We can run the process graphic_observer with signals first_note, kth_note, desync and sync in parallel with the process piano_phase to obtain a simple graphical visualization of Piano Phase. During the synchronous phase, green flashes indicate that Alice, i.e., the electronic part, is playing the first note of the sequence. During the desynchronization, we can see red flashes on the right each time Bob, i.e., the actual pianist, is playing the k-th note, and blue ones on the left each time the accompaniment part is playing the first note.

### 6. Related Work

**Comparison with the actual Antescofo language** We focused here on a subset of the actual language of Antescofo. However, constructs that we left aside can be easily encoded using our library. For instance, an original control structure was added to the
language recently [8]. The construct whenever pred seq triggers the sequence seq whenever the predicate pred is true. The predicate may depend on variables, in this case, its value is re-evaluated each time one of the variables is updated. Adding this feature to our library was relatively easy as we now show.

First, variables become ReactiveML signals. Thus, it is possible to react when a variable is updated.

```ml
let make_var value =
    signal x default value gather (fun x y -> x)
```

The function make_var value creates a variable initialized with the value value.

Then, we can easily define classic functions to set and access the value of a variable.

```ml
let set x v = emit x v
let get x = last ?x
```

To set the value of a variable x, one need only to emit the desired value v on the corresponding signal. We can access the current value of a variable thanks to the function last ? (see Section 5.1).

Then, the following process waits for one of the variables contained in the list vars to be updated.

```ml
let await_vars vars =
    signal moved default () gather (fun x y -> ()) in
    let rec await_par vars =
        match l with
        | [] -> ()
        | x :: l ->
            run (await_par l) ||
            (await x; emit moved ())
        in
    do run (await_par vars) until moved done
```

The recursive process await_par waits in parallel for an update of any variable. Whenever an update occurs, the signal moved is emitted. Thanks to the preemptive construct do/until, this emission stops the execution of the process await_par.

Finally the whenever construct can be implemented as follows.

```ml
let rec process whenever pred vars p =
    run (await_vars vars);
    begin
    if pred (List.map get vars) then run p ||
    run (whenever pred vars p)
    end
```

Whenever a variable contained in vars is updated, we re-evaluate the predicate pred with the new values of the variables. If the predicate is true we launch the process p, meanwhile we start another instance of the process whenever. Thus, if the predicate is true again while p is still running, we execute another process p in parallel. Here a predicate is a function applied to a list of variables.

Thus, our approach shows that ReactiveML is well suited for prototyping new features of the language.

**Functional music** The idea of composing music in a functional framework is not new. One can cite the Haskore library [14], for instance, which allows the expression and combination of musical structures in Haskell. More recently, Haskore and HasSound (a library for audio processing in Haskell) merged into a single embedded language: Euterpea [13]. Thus, this language handles both high-level music representation and low-level audio processing.

We took a similar approach: embedding a domain-specific language inside a functional language. Yet, our approach is not the same as we embed a reactive language in a more expressive reactive language. The major advantage, with respect to the embedding in a general purpose functional language is that we can rely on the temporal expressiveness, static analysis and runtime of ReactiveML.

Note that, we focused here on the control of a musical performance. Audio synthesis is left to an audio environment such as Max/MSP [20] or its open source counterpart PureData [21]. An interesting development would be to couple our work with a functional language dedicated to audio synthesis like the language Faust [19] or Euterpea.

**Live coding** There are several languages dedicated to musical live coding. One can for instance cite Chuck [22] and SuperCollider [18]. These languages allow live interactions with an audio environment.

Our approach is completely different. Instead of creating an entire domain specific language, we chose to embed it in a general purpose one that already offers most of the features we need: higher order, recursion, inductive data types... This choice enabled us to implement our library in only a few hundred lines of code. Yet we can already use it to specify relatively complex behavior.

**Composing Mixed Music** The Iscore project [7] proposes a tool to compose interactive scores by specifying temporal constraints between musical objects. Musical structures can be bound to external events such as those occurring during a live performance. In this approach, relations are computed statically before the performance.

Besides, there exist programming languages dedicated to electronic music. For instance, Max/MSP and PureData are graphical languages that handle both the control treatment and signal processing.

However, in both cases it is relatively difficult to program dynamically changing behavior which evolves with parameters instantiated at performance time. For instance, the whenever construct described above would be difficult to simulate. Moreover, these languages are not functional.

### 7. Conclusion

In this paper we showed that a reactive functional language like ReactiveML is well suited to the specification of reactive processes such as a performance of mixed music. We believe that this embedding is a powerful tool for programming mixed music scores as well as prototyping new features for the Antescofo language.

Here, the link with a live performance is realized through the listening machine of the Antescofo system. However, this is not a real limitation. It could be interesting to adapt our framework to other sensors like a gesture follower [3], a speech recognition system or even combine these different input systems. Such an application with multiple sensors and actuators fits into the kind of systems for which synchronous languages like ReactiveML have been designed.

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**References**


