Article

A model for interactive media authoring

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Abstract: A single paragraph of about 200 words maximum. For research articles, abstracts should give a pertinent overview of the work. We strongly encourage authors to use the following style of structured abstracts, but without headings: 1) Background: Place the question addressed in a broad context and highlight the purpose of the study; 2) Methods: Describe briefly the main methods or treatments applied; 3) Results: Summarize the article's main findings; and 4) Conclusion: Indicate the main conclusions or interpretations. The abstract should be an objective representation of the article, it must not contain results which are not presented and substantiated in the main text and should not exaggerate the main conclusions.

Keywords: interactive scores; intermedia; dataflow; patcher; i-score

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1. Introduction

Many music software fit in one of three categories: sequencers, patchers, and textual programming environments. Sequencers are used to describe temporal behaviours: an audio clip plays after another, while an automation curve changes an audio filter. Patchers are more commonly used to describe invariants: for instance specific audio filters, or compositional patterns.

We propose in this paper a method that combines the sequencer and the patcher paradigm in a live system.

The general approach is as follows: we first introduce a minimal model of the data we are operating on: namely, remote software or hardware such as OSC peripherals and sound cards. Then, two structures are presented: the first is a temporal structure, which allows to position events and processes relatively to each other, hierarchically, and in a timely fashion. The second is a graph structure akin to dataflows. This graph uses special connection types to take into account the fact that nodes of the graph might not always be active at the same time. Both structures are then combined: the state of the temporal processes is bound to the dataflow nodes. This combination is then expanded with specific implicit cases that are relevant in computer music workflows. These cases are described using structures wrapping the temporal and dataflow graphs.

We compare the various models in the context of music creation: what entails using only the temporal structure, only the graph structure, and the combination of both.

The latter model is shown to have enough expressive power to allow for recreation of common audio software logic within it: for instance traditional or looping audio sequencers. Additionnally, its use is presented in sample compositions: the first one is an example of audio editing, the second an interactive musical installation.

1.1. State of the art

There is a long-standing interest in the handling of time in programming languages, which is intrinsically linked to how the language handles dynamicity.

PEARL90[1][1] provides temporal primitives allowing for instance to perform loops at a given rate for a given amount of time. More recently, Céu has been introduced as a synchronous language with temporal operators, and applications to multimedia[2].

OpenMusic is a visual environment which allows to write music by functional composition. It has been recently extended with timed sequences allowing to specify evolutions of parameters in time[3].

Likewise, the Bach library for Max [**?**] allows to define temporal variations of parameters during the playing of a note by with the mechanism of slots. The processes controlled by such parameters are then available to use in the Max patch.

The Max for Live extension to Ableton Live allows to embed Max patches in the Ableton Live sequencer. Through the API provided, one can control the execution of various elements of the sequencer in Max; automations in Live can also be used to send data to Max patches at a given time.

A method for dynamic patching of Max abstractions based on CommonLisp has been proposed by Thomas Hummel[**?**] to reduce resource usage by enabling and disabling sub-patches at different points in the execution of a program. This has the advantage of saving computing power for the active elements of the score.

Dataflows and especially synchronous dataflows have seen tremendous usage in the music and signal processing community. A list of patterns commonly used when developing dataflow-based music software is presented in [4]. Formal semantics are given in [5]. Specific implementation aspects of dataflow systems are discussed in the Handbook of Signal Processing Systems[**?**].

Dynamicity in dataflows is generally separated in two independent aspects: dynamicity of the data, and of the topology. The first relates to the variability on the streams of tokens, while the second is about changes to the structure of the graph. Boolean parametric dataflows[6] have been proposed to solve dynamicity of topology, by introducing conditionals at the edges.

base: max, pd, séquenceurs: cubase/protools , live/bitwig...

openmusic

antescofo

inscore

1.2. Context of this research

This paper follows existing research on interactive scores, as part of the i-score project. Previous research focused on operational semantics for interactive scores, based on time automatas[7] or Petri nets[8], mainly for software verification purposes. In contrast, we give here domain-centered functional semantics which models the current C++ implementation of the software.

We first define the temporal model, then extend it with a distinct data model which reads and produces the various inputs & outputs of the system. Then, we introduce implicit operations and defaults in the context of a GUI software to create, modify, and playback such scores. These operations allow to simplify the usage of the paradigm for composers. Real-world examples are provided and discussed.

[**?**]

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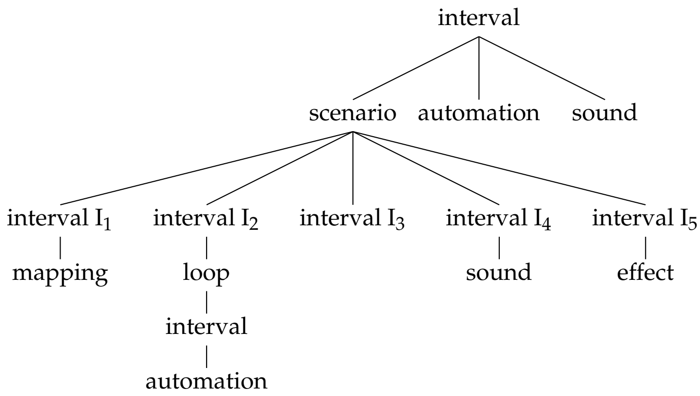
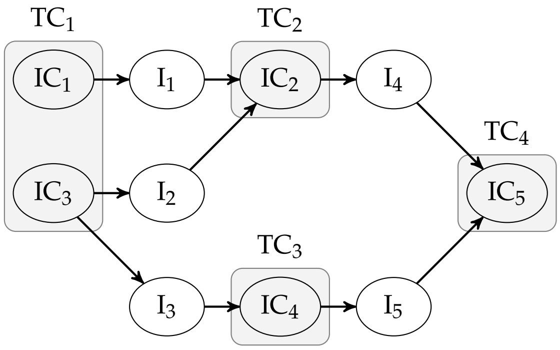
[1] Not to be mistaken with the Perl language commonly used for text processing



(a) Hierarchical tree



(b) Temporal DAG

2. Proposed sequencer behaviour

We give here an overview of the whole system ; the choices and ideas proposed will be explained in detail in the following sections.

The overall goal is to associate traditional dataflow graphs with temporal semantics. In terms of model, two structures are present: the dataflow graph which will generate and process musical data, and the control graph which will specify when and how the dataflow graph runs.

For the dataflow graph, the traditional musical programming patterns of and are used.

cite control-signal separation

cite audio processing in buffers

The temporal graph allows three things :

- Embedding interaction choices in the time-line.
- Arbitrary hierarchy.
- Merging of loop-based and timeline-based control: we show in section10.1 that this is enough to allow both time-based and loop-based behaviors to co-exist in a single structure and user interface, unlike existing approaches which splits those in two mostly distinct domains ; this enables a large array of possible intermediary behaviors.

Then, at each tick, the temporal graph runs as described in section 4. This produces tokens in the dataflow graph nodes. Once tokens have been produced for every temporal structure, the data graph runs.

To accomodate for the tempoarl semantics, special connection types

For the sake of simplicity, the user interface merges the two graphs; section **??** presents in detail some automatic set-up and enforced assumptions done by the software.

3. Orchestrated data

We first define the data we operate on. External devices are modeled as a tree of optional parameters.

Value parameters can have values of common data types such as integer, float, etc. Audio parameters are arrays that contain either the current input audio buffers of the sound card or the buffers that will be written to the sound card's output.

The tree of nodes is akin to the methods and containers described in the OSC specification.

$$\begin{aligned}
\textbf{Value} &= \text{Float} \mid \text{Int} \mid \text{Bool} \mid \text{String} \mid \ldots \\
\textbf{ValueParameter} &= \text{Value} \times \text{Protocol} \\
\textbf{AudioParameter} &= \text{Float}[\,][\,] \times \text{Protocol} \\
\textbf{Parameter} &= \text{ValueParameter} \mid \text{AudioParameter} \\
\textbf{Node} &= \text{String} \times \text{Maybe Parameter} \times \text{Node}[\,]
\end{aligned}$$

Parameters and nodes bear additional metadata which is not relevant to describe here: textual description, tags, etc.

The parameters's associated values match the state of an external device: synthesizer, etc. Multiple protocols are implemented to allow this: for instance OSC, MIDI, etc.

We define two core operations on parameters:

$$\begin{aligned}
\textbf{pull} &: \text{Parameter} \rightarrow \text{Parameter} \\
&\quad (v, p) \mapsto (v', p) \text{ where v' is the last known value in the remote device} \\
\textbf{push} &: \text{Parameter} \times \text{Value} \rightarrow \text{Parameter} \\
&\quad (v, p), v' \mapsto (v', p) \text{ and v' is sent to the remote device}
\end{aligned}$$

4. Temporal model

The temporal model is twofold: it is a hierarchical tree of processes, whose durations and execution times are directed by intervals organized in a Directed Acyclic Graph (DAG). The beginning and end of the intervals is subjected to various conditions that will be presented ; these conditions allow for various interactive behaviours. In particular, specific dispositions of intervals and conditions are implemented as processes themselves, scenario and loop, which allows for hierarchy.

We note: TC for temporal conditions, IC for instantaneous conditions, I for intervals, P for processes. First, these elements are defined, then the semantics imposed on them by the scenario and the loop are presented. These semantics allow both serial and parallel execution of musical processes.

4.1. Data types

4.1.1. Conditions and expressions

We first define the conditional operations we want to be able to express. We restrain ourselves to simple propositional logic operands: **and**, **or**, **not**.

Expressions operate on addresses and values of the device tree presented in 3.

Formally, expressions are defined as a tree: Let **Comparator** be an identifier for standard value comparison operations: $<, \leq, >, \geq, =, \neq$ and **Operator** standard logical operators **and** & **or**.

```
type subexpr = Var of string | Value of value;;
type expression =
| Greater   of subexpr*subexpr
| GreaterEq of subexpr*subexpr
| Lower     of subexpr*subexpr
| LowerEq   of subexpr*subexpr
```

```
| Equal     of subexpr*subexpr
| Different of subexpr*subexpr
| Negation  of expression
| And       of expression*expression
| Or        of expression*expression
| Impulse   of impulseId*string
;;
```

Two operations are defined on expressions and the data types that compose them:

- An atom is a comparison between two parameters, a parameter and a value, or two values.
- Negations and compositions are the traditional propositional calculus building blocks.
- We introduce a specific operator, "impulse", which allows to decide whether a message was received for a given variable.

4.1.2. Temporal processes

Temporal processes are executed by intervals at each tick. The actual processes will be defined in sections , 4.2, 4.3, 5.

A process is a type P associated with the following operations:

$$\begin{aligned}\textbf{start} &: \mathrm{P} \rightarrow \mathrm{P}\\ \textbf{stop} &: \mathrm{P} \rightarrow \mathrm{P}\\ \textbf{tick} &: \mathrm{P} * \mathbb{Z} * \mathbb{Z} * \mathbb{R} \rightarrow P\\ \textbf{Process} &: \mathrm{Scenario} \mid \mathrm{Loop} \mid \ldots\end{aligned}$$

4.1.3. Interval

We want to be able to express the passing of time, for a given duration. This duration may or may not be finite.

A duration is defined as a positive integer. An interval is at its core a set of durations: a min, an optional max, and the current position. The lack of max means infinity. An interval is said to be fixed when its min equals its max. It may be enabled or disabled.

```
type interval = {
  itvId: intervalId;
  itvNode: nodeId;
  minDuration: duration;
  maxDuration : duration option;
  nominalDuration : duration;
  speed: float;
  processes: process list
}
```

The time scale is not specified by the system: for instance, when working with audio data it may be better to use the audio sample as a base unit of time. But many applications don't use the audio rate: when working purely with visuals it may be better to use the screen refresh rate as time base in order not to waste computer resources and energy.

4.1.4. Instantaneous condition

Then, we want to be able to enable or disable events and intervals according to a condition, given in the expression language seen in **??**. An instantaneous condition is defined as follows:

```
type condition = {
  icId: instCondId;
  condExpr: expression;
  previousItv: intervalId list;
  nextItv: intervalId list;
}
```

It is preceded and followed by a set of intervals.

Expressions are disabled either when they are false or when they are preceded by a non-null number of intervals, all of them already disabled through other conditions. This propagates recursiveley to the following intervals and conditions.

4.1.5. Temporal condition

A temporal condition is used to synchronize starts and ends of intervals, while allowing to implement behaviours such as : "start the chorus when the fader is at 0".

Temporal conditions carry instantaneous conditions, which will be evaluated at the moment where the temporal condition becomes true.

```
type temporalCondition = {
  tcId: tempCondId;
  syncExpr: expression;
  conds: condition list
}
```

4.1.6. Execution

Execution operates as follows:

```
let tick_interval (itv:interval) t offset (state:score_state) =
  let cur_date = (get_date itv state.itv_dates) in
  let new_date = (cur_date + (truncate (ceil (float t) *. itv.speed))) in
  let new_pos = (float new_date /. float itv.nominalDuration) in
  let tp = tick_process cur_date new_date new_pos offset in
  let rec exec_processes procs funs state =
    match procs with
    | [] -> (funs, state)
    | proc::t -> let (nf, ns) = tp state proc in
                 exec_processes t (funs@[nf]) ns
  in
  let (funs, state) = exec_processes itv.processes [] state in
  ({ state with itv_dates = (set_date itv new_date state.itv_dates) },
   (funs @ [ add_tick_to_node itv.itvNode (make_token new_date new_pos offset) ]))
```

processes:

```
let tick_process cur_date new_date new_pos offset state p  =
   match p.impl with
    | Scenario s -> tick_scenario p.procId s cur_date new_date new_pos offset state
    | Loop l -> tick_loop l cur_date new_date new_pos offset state
    | DefaultProcess -> (add_tick_to_node p.procNode (make_token new_date new_pos offset), state)
```

4.2. Temporal graph: scenario

Execution of a TC

```

and scenario_process_TC scenario tc (state:score_state) =
  let minDurReached ic (state:score_state) =
    ...
  in
  let maxDurReached ic (state:score_state) =
    ...
  in

  let execute_ic scenario (state:score_state) ic =
    ...
  in
  let execute_tc scenario tc (state:score_state) =
    let rec execute_all_ics ics (state:score_state) started_itvs ended_itvs happened_ics =
      match ics with
      | [] -> (state, started_itvs, ended_itvs, happened_ics)
      | cond::t -> let (newStatus, started, stopped) = execute_ic scenario state cond in
                   execute_all_ics
                    t
                    (* update the statuses of the ICs with new values *)
                    { state with ic_statuses = (list_assoc_replace state.ic_statuses cond.icId newStatus) }
                    (started@started_itvs)
```

```
                    (stopped@ended_itvs)
                    (if newStatus = Happened then cond::happened_ics else happened_ics)
    in
    let (state, started_itv_ids, ended_itv_ids, happened_ics) = execute_all_ics tc.conds state [] [] [] in

    let rec start_all_intervals itvs (state:score_state) funs =
      ...
    in
    let (state, funs) =
        start_all_intervals (get_intervals started_itv_ids scenario) state [] in

    (state, List.flatten funs, happened_ics)
  in


  let rec mark_IC_min conds state =
    ..
  in
  let state = mark_IC_min tc.conds state in

  let tcMaxDurReached =
    List.exists
      (fun ic -> ((List.assoc ic.icId state.ic_statuses) = Pending) && (maxDurReached ic state))
      tc.conds
  in

  let is_pending_or_disposed ic =
    let cur_st = (List.assoc ic.icId state.ic_statuses) in
    cur_st = Pending || cur_st = Disposed
  in

  if (not (List.for_all is_pending_or_disposed tc.conds))
  then
    ((state, [ ], [ ]), false)
  else
    if ((tc.syncExpr <> true_expression) && (not tcMaxDurReached))
    then
      let state = { state with listeners = register_listeners tc.syncExpr state.listeners } in
      if (not (evaluate tc.syncExpr state.scoreEnv state.listeners))
      then
        ((state, [ ], [ ]), false)
      else
        let state = { state with listeners = unregister_listeners tc.syncExpr state.listeners } in
        (execute_tc scenario tc state, true)
    else
     (execute_tc scenario tc state, true)
```

Scenario tick

```
let tick_scenario pid scenario olddate newdate pos offset (state:score_state) =
  let dur = newdate - olddate in
  let rec process_root_tempConds scenario tc_list state funs =
     ...
  in

  let rec process_tempConds scenario tc_list (state:score_state) funs happened_ics =
     ...
  in

  let rec process_intervals scenario itv_list overticks funs dur offset end_TCs state =
     ...
  in

  let (state, funcs) =
    process_root_tempConds
        scenario
        (get_rootTempConds pid scenario state)
        state [] in

  let running_intervals = (List.filter (is_interval_running scenario state.ic_statuses) scenario.intervals) in
  let (state, overticks, end_TCs, funcs) =
    process_intervals scenario running_intervals [] funcs dur offset [] state in
  let (state, funcs, conds) = process_tempConds scenario end_TCs state funcs [] in

  let rec finish_tick scenario overticks conds funcs dur offset end_TCs state =
    match conds with
```

```
    | [ ] ->
      (match end_TCs with
       | [ ] -> (state , funcs)
       | _ -> let (state , new_funs , conds) =
                process_tempConds scenario end_TCs state [] [] in
            finish_tick scenario overticks conds (funcs@new_funs) dur offset [ ] state)

    | (cond:condition) :: remaining ->
      match (List.assoc_opt (find_parent_TC cond scenario).tcId overticks) with
      | None -> finish_tick scenario overticks remaining funcs dur offset end_TCs state
      | Some (min_t, max_t) ->
        let (state , overticks , end_TCs, funcs) =
            process_intervals
              scenario
              (following_intervals cond scenario)
              overticks funcs
              max_t
              (offset + dur - max_t)
              end_TCs
              state
        in
        finish_tick scenario overticks remaining funcs dur offset end_TCs state
  in

  let (state , funcs) = finish_tick scenario overticks conds funcs dur offset end_TCs state in
  (list_fun_combine funcs , state)
;;
```

4.3. Loop

Pbq: not introducing cycles in the temporal graph

5. Data model

=> set date => set offset pour offset audio (p-ê pas nécessaire si on fait comme LAStream)

6. Data graph

6.1. Structures

```
type edgeId = EdgeId of int;;
type nodeId = NodeId of int;;
type portId = PortId of int;;
type edgeType =
    Glutton
  | Strict
  | DelayedGlutton of value list
  | DelayedStrict of value list
;;
type edge = {
    edgeId: edgeId;
    source: portId;
    sink: portId;
    edgeType: edgeType;
};;
type port = {
    portId: portId;
    portAddr: string option;
    portEdges: edgeId list;
};;
type token_request = {
  token_date: duration;
  position: position;
  offset: duration;
};;
type dataNode =
    Automation of automation
  | Mapping of mapping
  | Sound of sound
  | Passthrough of passthrough;;
type grNode = {
```

```
    nodeId: nodeId;
    data: dataNode;
};;
type graph = {
    nodes: grNode list;
    edges: edge list;
};;
type grNodeState = {
  executed: bool;
  prev_date: duration;
  tokens: token_request list
};;
type graph_state = {
    node_state: (nodeId * grNodeState) list;
    port_state: (portId * value option) list
};;
```

6.2. Operations

Input mix on each port

```
let init_port (p:port) g gs (e:environment) =
  match p.portEdges with
  | [] -> let pv = match p.portAddr with
               | None -> None
               | Some str -> Some (pull str e)
               in
       replace_value p gs pv
  | _ -> replace_value p gs (List.fold_left (aggregate_data g gs) None (get_edges p.portEdges g) )
  ;;

let init_node n g gs (e:environment) =
  match n.data with
    | Automation (op, curve)  -> clear_port op gs;
    | Mapping (ip, op, curve) -> let gs = clear_port op gs in
                                 init_port ip g gs e
    | Sound (op, audio)       -> clear_port op gs;
    | Passthrough (ip, op)    -> let gs = clear_port op gs in
                                 init_port ip g gs e
;;

let write_port p (g:graph) (gs:graph_state) (e:environment) =
  let has_targets = (p.portEdges = []) in
  let all_targets_disabled =
    has_targets &&
    List.for_all (fun x -> in_port_disabled x g gs) p.portEdges in
  if(not has_targets || all_targets_disabled) then
    (gs, write_port_env p gs e)
  else
    (write_port_edges p gs, e)
;;

let teardown_node n g gs e =
  match n.data with
  | Automation (op, _)      -> write_port op g gs e;
  | Sound (op, _)           -> write_port op g gs e;
  | Mapping (ip, op, curve) -> let (gs, e) = write_port op g gs e in
                               (clear_port ip gs, e);
  | Passthrough (ip, op)    -> let (gs, e) = write_port op g gs e in
                               (clear_port ip gs, e);
;;
```

6.3. Tick description

General flow:
disable strict nodes
sort remaining nodes according to the custom order chosen (default, temporal, custom)
priority: * explicit cables * local or global address
do a tick:

```
let rec sub_tick graph gs nodes (e:environment) =
 match nodes with
 | [ ] -> (gs, e);
 | _ ->
   let next_nodes = List.filter can_execute nodes in
   let next_nodes = List.sort (nodes_sort next_nodes) next_nodes in
   match next_nodes with
   | [ ] -> (gs, e) ;
   | cur_node::q ->
     let gs = init_node cur_node graph gs e in
     let rec run_ticks_for_node g gs n tokens =
       match tokens with
       | [] -> gs
       | token::t -> let gs = exec_node g gs n (List.assoc n.nodeId gs.node_state) token
                     in run_ticks_for_node g gs n t
     in
     let gs = run_ticks_for_node graph gs cur_node
                                (List.assoc cur_node.nodeId gs.node_state).tokens in
     let (gs, e) = teardown_node cur_node graph gs e in

     sub_tick graph gs (remove_node next_nodes cur_node.nodeId) e;;
```

6.4. Data nodes

Say that in the C++ code, the port kinds are statically checked : no way to mistake input from output.

```
type curve = float -> float;;
type automation = port * curve;;
type mapping = port * port * curve;;
type sound = port * float array array;;
type passthrough = port * port;;
```

6.4.1. Passthrough

-> used for scenario and interval -> mixing at the input

- Automation: start point + set of (segment * breakpoint)

  curve + message output port $x \in [0;1]$ -> in the nominal duration of the parent time interval.
- Mapping: message input port + curve + message output port
- Javascript: n message input port + curve + n message output port
- Piano roll: notes + midi output port
- Sound file: sound data + midi output port
- Passthrough:
- Buffer: Used to keep audio input in memory
- Metronome:
- Constant: writes a value at each tick Why isn't the delay cable not enough ? can't go backwards. pb: pauser au milieu: coupure. cas dans les boucles: on réécrit par dessus (buffer vidé sur start).
- Shader

7. Combined model

-> on ajoute node aux tc

-> nodeprocess fait le lien entre graphnode et time process, permet de faire l'activation et l'écoulement du temps

-> offset nécessaire pour tc pour gérer l'audio (mais pourrait être ajouté dans le modèle de base. Ou bien passer une paire de pointeurs.. ?)

7.1. Combined tick and general flow

Exécution complète d'un tick: Copy audio buffers and input data, execute the temporal tick, apply the function to the graph state, execute the graph tick, copy the output audio buffer and apply the produced state by pushing the values.

Pour être propre, il faudrait faire un "pull" général au début...

```
let add_tick_to_node nodeId token (gs:graph_state) =
  let cur_state = (find_node_state gs nodeId) in
  replace_node_state gs nodeId { cur_state with
      tokens = cur_state.tokens @ [ token ];
  }
;;
```

Multiple possibilities for a tradeoff between accuracy and performance:

- Use the requested ticks. This allows to have a better the performance - latency ratio at the expense of sample-accuracy for the control data.
- Use the requested ticks and tick all the nodes at the smallest granularity: given two nodes A, B, with tokens at $t = 10$, $t = 25$ for A and $t = 17$ for B, tick all the nodes at 10, 17, 25.
- Maximal accuracy : tick with a granularity of one sample every time.

```
let main_loop root graph duration granularity
                          (state:score_state) ext_events ext_modifications =
 let total_dur = duration in
 let rec main_loop_rec root graph
                       remaining old_remaining granularity
                       (state:score_state) (gs:graph_state) funs =
   if remaining > 0
   then
     (
     let elapsed = total_dur - remaining in
     let old_elapsed = total_dur - old_remaining in
     let (root,graph,state) =
        ext_modifications root graph state old_elapsed elapsed  in
     let (state, new_funs)  =
        tick_interval root granularity 0 state in
     let gs = add_missing graph gs in
     let (gs, e)              =
        tick_graph_topo graph (update_graph (funs@new_funs) gs) state.scoreEnv in
     let state =
     { state with
       scoreEnv =
         (update (commit e) ext_events old_elapsed elapsed);
       listeners =
         (update_listeners state.listeners e.local ext_events old_elapsed elapsed)
     } in
     main_loop_rec root graph (remaining - granularity) old_remaining
         granularity state gs []
     )
   else
     (root, graph, state)
 in
 let (state, funs) = start_interval root state in
 let gs = { node_state = [] ; port_state = [] } in
 main_loop_rec root graph duration duration granularity state gs funs
;;
```

Détailler l'approche réactive

7.2. Details

Conditions et cie: The most common case for an expression is to be true.

UI: création automatique de liens implicites des enfants vers les parents si demandé (propriété de l'ui "propagate"). N'a de sens que pour l'audio de par la nature homogène de ces flux. => "cable créé par défaut" quand on rajoute un processus dont on marque l'entrée

=> pour toute contrainte, pour tout scénario, créer noeud qui fait le mixage => création d'objets récursivement, etc

- Problème des states dans scénario ? => states du scénario: comment interviennent-ils ? faire un scénario fantôme

- Mettre l'accent sur la recréation de la sémantique de i-score à partir du graphe: => messages: actuellement "peu" typés ; rajouter type de l'unité ?

=> pbq du multicanal: pour l'instant non traitée, on ne gère que les cas mono / stereo pour le upmix / downmix Choix pour multicanal: faire comme jamoma avec objets tilde => sliders et dispatching de canaux ? => cables: rubberband ? il faut mettre un rubberband dès qu'on a une entrée et une sortie qui n'ont pas la même vitesse relative. Dire que pour les automations ça interpole de manière naturelle avec le ralentissement et l'accélération (on sépare vitesse et granularité)

- Dire qu'on pourrait affiner en combinant plus précisément les "sous-ticks" temporels et de données pour que par exemple la production d'un état dans un scénario entraîne une condition dans un autre scénario -> tout réduire à un tick

8. Audio behaviour

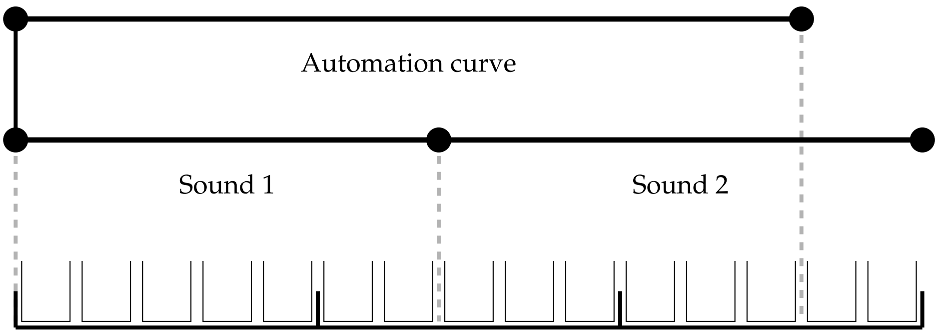


Figure 2. A scenario. The small bins represent individual audio samples ; the bigger bins represent the tick rate of the sound card. For the sake of the example, one can assume that the automation curve is used to control the output volume of the englobing scenario, not represented here.

Table 1. Value of token requests for the scenario 2. In each cell, (a, b, c) stands for previous date, current date, offset.

	Tick 0	Tick 1	Tick 2	Tick 3
Automation	$(0,0,0)$			
Sound 1	$(0,0,0)$	$(0,5,0)$	$(5,7,0)$	
Sound 2			$(0,3,2)$	$(3,8,0)$
Scenario	$(0,0,0)$	$(0,5,0)$	$(5,10,0)$	$(10,15,0)$

Expliquer tick avec données, offset, etc.

Cas complexe:

dernier tick d'une boucle qui a un enfant fichier son + automation

9. Mapping from visual language

All the objects in the visual language correspond to the objects presented earlier, at the exception of the states.

States : intervals with a duration equal to zero. IC / TC / interval / processes : no change edges : between processes

10. Applications and examples

10.1. Reconstructing existing paradigms

In this part we give example of reconstruction of standard audio software behaviours with the given model.

10.1.1. Audio sequencer

Notable software in this category includes Steinberg Cubase, Avid Pro Tools, ...

The common metaphor for audio sequencers is the track, inspired from mixing desks and tape recorders. We will take the example of audio and midi tracks. Such an audio sequencer can be modeled by :

- A root: an infinite interval.
- This interval contains two processes: a scenario and an effect bus. The sound output of the scenario goes to the input of the effect bus.
- The scenario contains the actual tracks.
- These tracks are also modeled by infinite constraints.

We divide the tracks in two categories. Audio tracks are built with :

- A scenario with a single sequence of intervals, some of which may bear sound file processes and others being empty.
- An effect bus process. The output of the scenario goes to the input of the effect bus. Generally, this effect bus would end by channel operations such as panning and volume adjustment, in a similar fashion to mixing desks.

Midi tracks are built with :

- A scenario with a single sequence of intervals, some of which may bear MIDI notes processes and others being empty.
- An instrument process, which takes MIDI data and outputs sound.
- Like before, an effect bus applied to the instrument's output.

This can easily be extended with further features: sends, automations, etc.

10.1.2. Looping audio sequencer

More recently, a different kind of sequencer has emerged: the looping, non-linear sequencer. The prime example of this is Ableton Live. We give the example for a simplified model of live-looping without quantization.

These sequencers are also organized in tracks ; however, within a track, the musician can choose a single loop that is currently playing, and regularly switch the current loop.

Hence, the general organization stays the same than for the audio sequencer: most importantly, the way effect buses are applied does not change.

- Each clip of a track is given an index.
- Each track also has a parameter which is the next clip to play, next_clip. These parameters can be introduced as variables in the device tree.
- We replace the scenarios containing the actual sound files or midi notes by loop processes.
- The loops processes are defined with and ending temporal condition.
- Inside the loop pattern, there is a single scenario process. This scenario process has a set of parallel intervals, each with one sound file. Every interval begins with an instantaneous condition that compares the next_clip parameter to the current clip's index. Hence, at most one clip is playing at the same time in each track. If the next_clip does not change the track keeps looping on the sound file.

Extension: par ex. dans une boucle on peut mettre un autre scénario. Pb : tic qui manque. On peut y remédier en exécutant le trigger "en avance".

10.1.3. Patcher

10.2. Musical examples

10.2.1. Audio compositing

-> on utilise un scénario qui lit des parties d'une entrée son dans différents bus d'effets. L'effet peut se déclencher en retard.

Org:

Intervalle racine

Process 1: Audio input Process 2 : Scenario -> Trois itv ; entrée reliée strict à sortie de audio input ; sortie dans parent

Process 3 : FX Process 4 : scenario Audio Input -> itv 1,2,3 -> scenario -> fx -> scenario

10.2.2. Musical carousel

We present here a real-world interactive music example: the musical carousel. Each seat on the carousel has different instrument-like input devices: reactive pads, motion sensors, etc. A run in the carousel generally operates as follows:

- The first few seconds, the rules of the carousel are explained to the participants.
- The song starts: the passengers can start interacting with their instruments. An overall music is generated from their interpretation. Played notes stay in predefinite scales which may vary over time; pre-recorded parts can also be layered on top. The overall song structure can vary according to the intensity of the played music: for instance, if everyone plays *piano*, different instruments may become available in the next section of the song, a part may be shorter or longer, etc. Such variations are written by the composer for each song.
- At the end of the song, the participants hear a summarized version of the song they just played. This version also has additional corrections and adjustments applied algorithmically.

- Réutilisation des données d'entrée: scores sur certaines parties ; réutilisation de certaines notes et des pics d'intensité -> nécessite d/dx - Gammes: filtrage global du MIDI In

10.3. Notes on implementation

=> "third gen" audio sequencer. first gen: cubase, etc second gen: non-linear: ableton, bitwig third gen: entirely interactive: i-score, iannix. what else ?

reproducibilité: code source dispo

11. Evaluation and Discussion

Enforcing graph constraints: mostly done through UI. For instance: ic are created on tc, etc. No "going back" which would break DAG-ness.

Faire parenthèse sur domain driven design sur logiciels de musique qui fournit de meilleurs résultats que application directe de modèles existants (petri, etc). Peut-être donner un méta-modèle qui correspond à nos structures ?

Dire pourquoi un tic est introduit lors d'une interaction (notamment, permet de ne pas avoir de "boucle infinie" si on a une boucle de durée 0 avec deux triggers vrais) ; est aussi plus cohérent pour les utilisateurs pour qui une interaction doit être manifeste.

Avantage: manipulation uniforme des processus, que ce soit des automations, des groupes, des fichiers sons, etc.

12. Conclusion

missing: quantification

missing: sound speed

Supplementary Materials: The following are available online at www.mdpi.com/link, Figure S1: title, Table S1: title, Video S1: title.

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Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "X.X. and Y.Y. conceived and designed the experiments; X.X. performed the experiments; X.X. and Y.Y. analyzed the data; W.W. contributed reagents/materials/analysis tools; Y.Y. wrote the paper." Authorship must be limited to those who have contributed substantially to the work reported.

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