An Approach to the Implementation of Overlapping Rules in Standard ML

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Abstract. We describe an approach to programming rule-based systems in Standard ML, with a focus on so-called overlapping rules, that is rules that can still be active when other rules are fired. Such rules are useful when implementing rule-based reactive systems, and to that effect we show a simple implementation of Loyall’s Active Behavior Trees, used to control goal-directed agents in the Oz virtual environment. We discuss an implementation of our framework using a reactive library geared towards implementing those kind of systems.

1 Introduction

Rule-based systems have had a long history in AI and powerful implementations have been developed. The most problematic aspect of this work has always been that of integrating the rule-based approach to a general-purpose language for application support. As an example along those lines, in Crawford et al describe R++, a rule-based extension to C++ completely integrated with the object-oriented features of the language, implemented as a rewrite of R++ into C++ code.

One common use of rules, and indeed the primary motivation for this work, is to help write rule-based reactive systems, reactive in the sense of having the system react to changes in the environment. A change in the environment should enable a certain number of appropriate rules that can be fired to react to the environment change, possibly effecting new changes to the environment that will enable other rules.

One aspect of rule-based reactive systems we focus on is that of long-acting overlapping rules. In most rule-based systems, a single rule is active at any given time: when the system determines that a rule is enable, the rule is fired, the environment is updated, and a new rule can be selected. This is not so great is some of the rules are computationally intensive: when such a rule is fired, it will take time to execute and if the system relies on other rules to ensure say responsiveness of the interface, the system will not respond to the user until the rule has finished executing. In general one, may want rules that span multiple other rules firing. For example, one may pre-fire a rule when certain conditions are met, perhaps pre-computing some values, and get ready for the “real” firing once the “real” conditions are in place. Or one may want a rule that when fired

\[1\] In this paper, we focus exclusively on production rule systems. Related systems, such as those based on a notion of term rewrite rule, have not been considered at this point.
will perform a given action at every subsequent rule firing until maybe a condition occurs that stops this behavior. It is of course possible to achieve these effects in certain rule-based systems, by a process of chaining rules (at the end of one rule, setting up the firing conditions of the next rule), along with a suitable notion of concurrently fired rules.

In this paper, we describe an approach to the integration of rule-based programming in Standard ML (SML) [9], with a strong focus on overlapping rules to achieve the effects described above. The resulting framework is suitable for the design of domain-specific abstractions for various rule systems. In contrast with other work, we do not worry about efficiency issues in this paper, but rather concentrate on expressiveness and applicability of the framework. We assume throughout the paper a basic knowledge of SML, as described in various introductory material such as [10,12].

After reviewing the basic notions of rule-based programming in Section 2, we discuss the framework in Sections 3-4. We give an application of the flexibility of the framework in Section 5, where we design domain-specific abstractions for controlling a goal-directed agent. Section 6 focuses on implementation details, including a reference implementation in terms of an existing reactive library for programming reactive systems in SML, introduced in [11], and based on the reactive approach of Boussinot [2,3].

2 OPS-style production rules

In this section, we establish the terminology and the model of rules we are interested in, namely OPS-style production rules [5]. The production-system model of computation is a paradigm on the same footing as the procedural paradigm, the functional paradigm or the object-oriented paradigm: it is a view of what a computation ought to be to best achieve a given goal.

A production-system program is an unordered collection of basic units of computation called production rules (henceforth simply called rules). Each rule has a condition part and an action part. An inference engine is used to execute the rules: it determines which rules are enabled by checking which conditions are true, and select rules to execute or fire from the enable rules. A rule is fired by executing its action part, which typically will have a side effect of performing input and output or computing a value and updating some date in memory. Thus rule-based systems fundamentally based on the notion of side effects.

Many mechanisms can be used to select which enabled rule to fire. In the literature, the term conflict set is often used to name the set of rules which are enabled, reflecting the intuition that somehow these rules can be conflicting, that is update the store in different incompatible ways. To ensure such problems do not occur, production systems will typically select a single rule to fire, by methods involving various notions such as priority or probabilities, along with notions such as the best matching of the conditions and so on.

In a rule-based system, control is data-driven, that is the data determines which part of the program will execute — furthermore, communication between different units is done solely through the use of data. There is no concept of a subroutine call to another
rule, or anything of that sort. Rule-based systems allow a cleaner separation of knowledge (in the form of rules) from the control (encapsulated in the inference engine). This makes rule-based systems well-suited to program expert systems for analysis problems, and for programs for which the exact flow of control is not known. In this paper, we will make the further refined point that with the appropriate extensions, rule-based systems are well-suited for the compositional development of reactive systems.

3 A framework for rule-based programming

We begin by considering a general framework for the handling of simple OPS-style rules in SML, where actions are executed atomically and terminate before a new rule can be fired. We discuss the framework abstractly, that is in terms its interface.

The first notion of importance is that of a set of rules, as an abstract type with a single basic operation that creates an empty set of rules. The reason for keeping the set of rules abstract is to allow for different implementations, some possibly aimed at optimizing the evaluation of the conditions.

```
type rule_set
val newSet : unit -> rule_set
```

A rule is simply defined as a pair of a condition and an action, as in OPS. Since we want the condition to be dynamically evaluated, it is implemented as a function (the standard way to delay evaluation in an eager language such as SML). A condition evaluates to a positive integer (a word), which we call the fitness of the condition, indicating the degree to which the condition is satisfied. There is no a priori semantics or range associated with those, they are left to the discretion of the programmer. The only restriction is that a fitness of zero is used to indicate that a rule is not enabled. One can implement simple boolean conditions as values 0 and 1, if need be. The only operation on rules is to add them to rule sets. Note that because functions are first-class in SML, rules become first-class as well. That is, they can be passed as argument to functions, and returned from functions.

```
type rule = {cond : unit -> word,
            action : unit -> unit}
val addRule : rule * rule_set -> rule_set
val mkSet : rule list -> rule_set
```

The final ingredient of the system is the inference engine, that selects which of the rules will be fired. At this point, the issue of when the rules should be fired must be addressed. Many systems tie the firing of the rules, or at least the evaluation of the conditions, to a change to variables that affect the conditions. We choose a much more fundamental approach using an explicit call that monitors the conditions, from which we can derive a change-of-state trigger. While inefficient, this approach has the advantage of being general. The other issue this does not address is that of conflict resolution, which rules to fire of all those that are enabled. We provide a selection of conflict resolution strategies. A function monitor is used to select rules to fire in a given set of rules. It takes as argument a conflict resolution flag determining the resolution strategy to use:
AllBest fires all the rules that qualify as the best rule to apply, sorted according to fitness. RandBest randomly picks one of the rules that qualify as the best rule. AllDownTo and RandDownTo perform similarly, but consider all the rules whose fitness is at least the given value. One can easily extend the framework to allow for custom conflict resolution, which we do not pursue in this paper for simplicity.

Our notion of fitness is general. As we noted, we can imagine a binary fitness (0-1) for boolean firing, but also a fitness based on how close the conditions are to being completely satisfied, or even as far as how many conditions are actually satisfied (if we allow firing based on partially satisfied conditions). An easy extension to the framework would be to pass information from the condition to the action. We can mimic this easily by using a reference cell which can also be hidden in a closure of the rule, as follows:

```ml
let val r = ref 0
    in {cond = fn () => if (!r1) > (!r2) then 1 else 0,
        action = fn () => r1 := (!r1) - (!r2)}
```

In striking difference with other systems, rules are not persistent in this framework: once a rule fires and executes, it is removed from the rule set. To make a rule persistent, we can use the function persistent. This allows us to dispense with a function to remove rules from rule sets. Moreover, persistent comes for free given our extension for managing overlapping rules, as we will see in the next section.

val persistent : rule -> rule

As an example of how to use the framework, consider a simple rule-based program to compute the greatest common divisor of two integers, the classic Euclid’s algorithm. The example is artificial (it is easily implemented in SML without rules), but serves well to illustrate the basics. A more complete example is presented in Section 5. The program can be expressed as follows in Dijkstra’s language of guarded commands:

```ml
do X > Y → X := X − Y | Y > X → Y := Y − X od
```

The corresponding code in our framework is more verbose, but essentially similar:

```ml
fun gcd (x,y) = let
    val rx = ref x
    val ry = ref y
    fun r (r1,r2) = persistent
        {cond = fn () => if (!r1) > (!r2) then 1 else 0,
         action = fn () => r1 := (!r1) - (!r2)}

    val rs = mkSet [r (rx,ry), r (ry,rx)]
    fun loop () = if ((rx) = (ry)) then (!rx)
        else (monitor AllBest rs; loop ())

    in
        loop {}
end
```
The above example is interesting because it shows how the fact that rules are first-class in the framework allow for parametrized rules: the rule \( r \) in the above code is parametrized over the reference cells containing the two arguments, parameterization which nicely showcases the symmetry of the rules.

As a final remark, we note that the rules as we have presented them in this section are simpler than they are in the actual framework. The rules in the implemented framework contain an extra field generically called \( \text{data} \) whose type is a parameter to the structure implementing the rules (in effect, the library is implemented as a functor). The monitoring function takes as an extra argument a function to compute a fitness both from the result of the evaluation of the condition and the data (which for example can contain notions such as rule priority and so on). Since describing this explicitly would require us to go into the details of both the module system and the type system of SML, we punt on these issues in this paper.

4 Managing overlapping rules

The main point of this work was to introduce overlapping rules, that is rules that can span multiple invocations and be performed in parallel with other rules. From an interface point of view, the framework only requires the addition of a single primitive, which we call \( \text{wait} \), to add the desired functionality:

\[
\text{val wait : (unit \rightarrow \text{word}) option} \rightarrow \text{unit}
\]

The semantics of \( \text{wait} \) is simple. Fundamentally, \( \text{wait} \) interrupts the action of the current rule, as if the rule was finished executing, except that at the next time the monitoring function is invoked to fire a rule, the rules that were interrupted are allowed to resume while the new rule fires. Hence the term overlapping. In fact, the \( \text{wait} \) primitive takes two forms. The form \( \text{wait} (\text{NONE}) \) behaves as an unconditional interruption. Execution continues the next time the monitoring function is invoked. The form \( \text{wait} (\text{SOME} (f)) \) with \( f \) as a condition (that is, a \( \text{unit} \rightarrow \text{word} \) function) also interrupts, but only resumes the rule the next time the monitoring function is invoked with the condition \( f \) being satisfied. In effect, \( \text{wait} (\text{SOME} (f)) \) interrupts the rule and conceptually replaces it with a new rule containing the remainder of the interrupted rule, with a condition \( f \).

As we mentioned in the previous section, rules are not persistent: once they are fired and execute, they are removed from the rule set. We can implement the persistent function using \( \text{wait} \):

\[
\text{fun persistent (cond,action) =}
\begin{align*}
& \text{cond} = \text{cond} , \\
& \text{action} = \text{let}
\begin{align*}
& \text{fun loop ()} = (\text{action}() ) ; \\
& \text{wait (SOME (cond))} ; \\
& \text{loop ()}
\end{align*}
\end{align*}
\text{loop ()}
\end{align*}
\]

This nicely shows the power of first-class rules.

\footnote{a primitive SML type defined as \textbf{datatype} ‘a option = \textbf{NONE} | \textbf{SOME} ‘a.}
5   An application: goal-directed agent control

We describe in this section one of the motivating applications for the development of the framework in the first place, that of controlling goal-directed agents. The architecture we have in mind is inspired by Hap, a reactive, goal-driven architecture for controlling agents in the Oz virtual environment [8]. The main structure in Hap is an active behavior tree (ABT), which represents all the goals and behaviors an agent is pursuing at any given point [4]. An agent chooses the next step to perform by selecting one of the leaves of its ABT. Three types of actions can be performed depending on the type of the node selected.

1. **Primitive physical action**: an action sent to the action server, which can either succeed or fail depending on the state of the world.
2. **Primitive mental action**: an action that simply performs a computation (possibly with side effects) and which always succeeds.
3. **Subgoal**: an action corresponding to a new subgoal; an appropriate behavior is selected that matches that subgoal, and the ABT is expanded by adding the steps specified by the behavior to the tree as children of the subgoal selected.

(For our purposes, we drop the distinction between mental and physical actions, since we can model mental actions as physical actions that always succeed). Programming an agent reduces to programming behaviors for various goals. Goals have no intrinsic meaning, they are simply names on top of which the programmer can attach any semantics she desires. Behaviors are defined by specifying to which goal they apply, a pre-condition for the application of that behavior (simply a predicate over the state of the world), and the steps that the behavior prescribes (physical actions, mental actions, subgoals). At this point, many details enter the description, to provide control over managing goals and behaviors. There are three kind of behaviors:

1. **Sequential**: the steps are performed in order, and failure of any step signifies the failure of the corresponding goal to which the behavior is attached; success of the last step signifies success of the corresponding goal.
2. **Concurrent**: the steps are performed in any order, but again failure of any step signifies the failure of the corresponding goal.
3. **Collection**: the steps are performed in any order, but success or failure of the steps are irrelevant. When all steps have succeeded or failed, the corresponding goal succeeds.

Subgoals steps in behaviors can moreover be annotated as *persistent*, that is when they succeed or fail, they are not removed, but rather persist as a continuing goal. Typically, top-level goals are persistent. Conversely, subgoals can be annotated with a *success test*, a predicate over the state of the world, which gets tested every time the ABT is activated. If the success test of a subgoal is true, the subgoal automatically succeeds.

Choosing a step to perform is by default done at random over all the applicable steps in an ABT, that is all the leaves that can be either executed right away or subgoals that can be expanded because a behavior applies (no behavior may apply because either none has been defined or no pre-condition is satisfied). Similarly, choosing a behavior
to perform once a subgoal step has been chosen is by default done at random over all applicable behaviors. One can modify this default by assigning priorities to various subgoals.

All of this is meant to evoke the kind of structure we would like to express in our framework. Since Hap revolves around the notion of goals, we abstractly provide a notion of goal to the framework of the previous sections, where goals are for simplicity represented as strings.

```plaintext
datatype goal_status = Success | Failure |
| Active | Available |
| NoSuch

val goalSet : string -> unit
val goalSucceed : string -> unit
val goalFail : string -> unit
val goalStatus : string -> goal_status
val goalClear : string -> unit
```

where `goalSet` enables the given goal, such that it is to be pursued by the agent (it becomes available). The functions `goalSucceed` and `goalFail` are used to record that a goal has succeeded or failed. The function `goalStatus` returns the status of the given goal. The status of a goal is either `Success` or `Failure` if the goal has been recorded as such, or `Active` if a behavior is actively pursuing the goal, but is not done with it yet. A status of `Available` indicates that the goal is enabled, but that no behavior is pursuing it, while a status of `NoSuch` indicates that no such goal exists. The function `goalClear` removes a goal from the active list of goals. We define the boolean-valued helper functions `isAvailable` and `isDone` to check the status of a goal to be respectively `Available` or `Success/Failure`.

We interpret an ABT behavior as a rule, triggered both by the pre-condition of the behavior (if present) and the apparition as `Available` of the goal the behavior is meant to pursue. We do not worry about either sequential, collection or concurrent annotations, choosing rather to let the programmer manage the steps of the behavior explicitly. Patterns quickly emerge. For instance, a behavior for goal `g` triggered by a condition `c` and sequentially performing subgoal `g1`, action `a` and subgoal `g2` can be interpreted as a rule:

```plaintext
val beh1 = (cond = fn () => if isAvailable (g) andalso c
            then 1 else 0,
          action = fn () =>
            (goalSet (g1);
             wait (SOME (fn () => isDone (g1)));
             case (goalStatus (g1))
               of Success => (goalClear (g1);
                             a;
                             wait (NONE);
                             goalSet (g2);
                             wait (SOME (fn () => isDone (g2)));
                             case (goalStatus (g2))
                               of Success => (goalClear (g2);
                                               goalSucceed (g));
                               _ => (goalClear (g2);
                                   goalFail (g))
                           _ => (goalClear (g1);
                             goalFail (g))));
```

Similarly, the previous behavior can be implemented concurrently by setting all the goals at once and waiting for all the goals to be done.
val beh2 = 
  {cond = fn () => if isAvailable (g) andalso c then 1 else 0, 
   action = fn () => 
     (goalSet (g1); 
      goalSet (g2); 
      wait {SOME (fn () => isDone (g1) andalso isDone (g2))}; 
     case (goalStatus (g1),goalStatus (g2)) 
     of (Success,Success) => (goalClear (g1); 
      goalClear (g2); 
      goalSucceed (g)) 
     | (_,_) => (goalClear (g1); 
      goalClear (g2); 
      goalFail (g))}

By virtue of the andalso in the first waiting condition of beh2, the conditions must all be true for the system to proceed at that point. Although it does sequentializes the testing of the conditions, this is not an issue given our current framework since the rule is resumed when all the conditions are satisfied. It may however become an issue if we attempt to optimize the satisfaction of the conditions. Persistence of goals can be implemented by clearing them and setting them again, while goal success tests can be wrapped inside the wait condition for that goal.

One difficulty of this approach, immediately noticeable from the above code, is that it is very error-prone, even if it is much more flexible than ABTs. In effect, we have to implement the handling of the goals explicitly, for every single behavior. However, the flexibility of first-class rules and first-class functions allows us to easily generate such rules from a declarative description of the intended behavior. Consider a type behavior that describes a behavior declaratively:

```plaintext
type behavior = {goal : string, 
  precond : (unit -> bool) option, 
  kind : behavior_kind, 
  steps : behavior_step list} 
```

```plaintext
datatype behavior_kind = Sequential | Concurrent 

datatype behavior_step = Subgoal of string 
  | Action of unit -> bool 
```

(For simplicity, we drop the collective kind of behavior, its handling similar enough to the concurrent one to not cause a problem). We can describe the previous two behaviors beh1 and beh2 as follow (this time using behavior parameterization!):

```plaintext
fun beh (k) = 
  {goal = g, 
   precond = SOME (fn () => c), 
   kind = k, 
   steps = [Subgoal (g1), 
     Action (fn () => a), 
     Subgoal (g2)]} 

val beh1 = beh (Sequential) 
val beh2 = beh (Concurrent) 
```

We can then interpret such descriptions in our framework, by a function behavior-Rule, which takes a description of type behavior and returns a rule of type rule. The implementation of behaviorRule is simply a question of writing a rule whose action is an interpreter for lists of behavior_step. For the truly interested, the code for behavior-Rule is given in Figure 1.
fun behaviorRule {goal,precond,kind,steps} = let
  fun split [] = ([],[])
  | split (x::xs) = let
    val (sg,acts) = split (xs)
    in
      case x of
        Subgoal (g) => (g::sg,acts)
      | Action (a) => (sg,a::acts)
    end
  end

  fun cond () = if isAvailable (goal) andalso
    (case precond of NONE => true
     | SOME (pc) => pc ()
     )
    then 1 else 0
  in
    case kind of
      Sequential => let
        fun perform_steps [] = goalSucceed (goal)
        | perform_steps (Action (a)::r) = (a (); wait (NONE);
          perform_steps (r))
        | perform_steps (Subgoal (g)::r) = (goalSet (g);
          wait (SOME (fn () => isDone (g)));
          case (goalStatus (g)) of
            Success => (goalClear (g);
            perform_steps (r))
          | _ => (goalClear (g);
            goalFail (goal))
        )
      end
    | Concurrent => let
        val (subgoals,actions) = split (steps)
        in
          app goalSet subgoals;
          app (fn a => a ()) actions;
          wait (SOME (fn () => List.all (fn x => x)
            (map isDone subgoals)));
          if (List.all (fn g => case (goalStatus (g))
            of Success => true
          | _ => false)
            subgoals)
          then (app goalClear subgoals;
            goalSucceed (goal))
          else (app goalClear subgoals;
            goalFail (goal))
        end
    end
end

Fig. 1. Code for behaviorRule
6 Implementation

The framework we have described has been implemented for the Standard ML of New Jersey compiler \([1]\) using the reactive library described in \([11]\). One advantage of this approach is that the semantics of the system is easily derivable from the one in \([11]\).

Before discussing the implementation, let us give an overview of the reactive library.

The library defines a type \(\text{rexp}\) of reactive expressions, which are expressions that define control points. A reactive expression is created through a function \(\text{rexp}\) that expects a \(\text{unit} \rightarrow \text{unit}\) function as argument. The argument function calls the function \(\text{stop}\) to define a control point. The function \(\text{react}\) is used to take a reactive expression and to evaluate the code starting from the last control point reached until the next control point is reached. This is called \(\text{activating}\) a reactive expression. When a reactive expression evaluates to a value without reaching a control point, it is said to \(\text{terminate}\). Interesting combinators can be defined to take reactive expressions and combining them. The most important of such combinators is the \(\text{merge}\) combinator, which takes two reactive expression \(e_1\) and \(e_2\) and creates a new reactive expression \(e\) that behaves as follows: when \(e\) is activated, \(e_1\) and \(e_2\) are activated, one after the other. In effect, this interleaves the execution of \(e_1\) and \(e_2\). The combinator \(\text{loop}\) takes a reactive expressions \(e_1\) and creates a new reactive expression \(e\) that behaves as follows: when \(e\) is activated, \(e_1\) is activated. If \(e_1\) terminates, it is reset (the reactive expression is re-instantiated) and activated again. The reactive expression \(\text{nothing}\) simply terminates immediately.

A more fine-grained notion of control point is also available. A reactive expression can call \(\text{suspend}\) to suspend its current execution. A \(\text{suspend}\) acts as a \(\text{stop}\), except that a special combinator \(\text{close}\) is available. Given a reactive expression \(e_1\), \(\text{close}\) returns a new reactive expression which behaves as follows: when \(e\) is activated, it repeatedly activates \(e_1\) until all its reactive subexpressions have reached stop-defined control points. This allows finer control over the order of execution of the reactive subexpressions, an example of which we will see in this section.

It is clear, given this description, how the library may be useful to implement the details of overlapping rules. For brevity, we assume the reactive library has been bound to a structure \(R\). The implementation of the framework is rather simple, although it is complicated by technical details and some mismatches with the underlying reactive library. We define a rule set as a reactive expression, a \(\text{merge}\) of all the relevant rules.

\[
\begin{align*}
\text{type rule_set} &= \text{R.rexp} \\
\text{fun newSet} () &= \text{R.nothing}
\end{align*}
\]

A rule is defined as before, while adding a rule to a set of rules consists of merging the reactive expression corresponding to the rule in the merge of the rule set.

\[
\begin{align*}
\text{type rule} &= \{ \text{cond} : \text{unit} \rightarrow \text{word}, \\
&\quad \text{action} : \text{unit} \rightarrow \text{unit} \} \\
\text{fun addRule} \ (rs \ (\text{cond}, \text{action})) &= \text{let} \\
&\quad \text{val r} = \text{R.exp} (\text{fn} () \Rightarrow \{ \text{condition} \ (\text{cond}); \\
&\quad \quad \text{action} () \}) \\
&\quad \text{in} \\
&\quad \text{R.merge} \ (rs, r) \\
&\quad \text{end} \\
\text{val mkSet} &= \text{foldr} \ \text{addRule} \ \text{newSet} ()
\end{align*}
\]

The function \(\text{condition}\) terminates immediately if monitoring determines that it should be fired (according to the fitness of the condition), otherwise it stops to wait
for another instant where the condition is deemed fit. To bypass a limitation of the current reactive library, which is more geared towards locally determining whether a given reactive expression is allowed to continue rather than being selected through a global check, we introduce a global variable to hold a list of all computed fitnesses and allow the system to select the ones that will execute.

```ml
val globalFitnesses = ref ([]) : (unit ref * word) list ref
```

We uniquely tag each condition being computed using a value of type `unit ref`, a trick commonly used in SML to get unique identifiers that can be quickly compared for identity. When the function `condition` is encountered, the current fitness is computed and stored along with a unique identifier for the condition. The reactive expression is then suspended (not stopped). This gives the other reactive expressions running in parallel a chance to evaluate their conditions. Upon resumption of the suspension, each condition checks if it is allowed to continue by seeing if it is listed in a list of allowed-to-continue conditions, stored in the previous `globalFitnesses` variable.

```ml
fun condition (f) = let
  val r = ref ()
  fun loop () = (globalFitnesses := (r,f)::(!globalFitnesses)
                   suspend ();
    if (List.exists (fn (r',_) => r=r') (!globalFitnesses))
      then ()
    else (stop (); loop ())
  in
  loop ()
end
```

The function `wait` that implements an interruption of the execution of the rule is simple:

```ml
fun wait (NONE) = (stop (); suspend ())
| wait (SOME (f)) = (stop (); condition (f))
```

(The suspend in `wait (NONE)` is a technicality, needed to prevent the firing of stopped rules with no conditions until all the conditions of the other rules have been checked).

The core of the work is done in `monitor`, which is in charge of activating the reactive expression corresponding to the rule set, gather the results, compute which conditions are satisfied, and resume the suspensions.

```ml
fun monitor c rs = let
  val clearVar = R.loop (R.rexp (fn () => (globalFitnesses := [];
                                  stop ()))))
  val r = R.loop (R.rexp (fn () => (computeEnabled (c);
                                  stop ()))))
  in
  R.react (R.close (R.merge (clearVar,R.merge (rs,r))))
end
```

The above code encompasses the control flow of the monitoring process, and relies heavily on the fact that merges are deterministic. A non-deterministic implementation could play with `suspend` calls to achieve the right order of execution: we need to make sure at every instant that `clearVar` is executed first, and `computeEnabled` is activated after all suspensions. The actual rule selection is performed by `computeEnabled`.

3 This does make the library non-reentrant. This could be corrected by an appropriate change to the reactive library (implementing reaction-specific data, for instance), or by including a notion of execution context to bind the use of the variable to a given context.
fun computeEnabled (AllBest) = let
    fun max (curr,[]) = curr
    | max (curr,(_,x)::xs) = if x>curr then max (x,xs) else max (curr,xs)
    val bestVal = max (1,globalFitnesses)
    val lst = List.filter (fn (_,a) => a=bestVal) (globalFitnesses)
in
    globalFitnesses := lst
end
| computeEnabled (RandBest) = (as AllBest, but return random element)
| computeEnabled (AllDownTo (v)) = let
    val lst = List.filter (fn (_,a) => a>=v) (globalFitnesses)
in
    globalFitnesses := lst
end
| computeEnable (RandDownTo (v)) = (as AllDownTo, but return random element)

7 Conclusion

So what have we done? We have developed a general framework for rule-based pro-
gramming in SML, flexible enough to handle standard OPS-style rules, as well as over-
lapping rules. The fact that rules are first-class in the framework gave us enough flex-
ibility to express Loyall’s active behavior trees through an interpreter of declarative
behaviors.

We have not worried about the efficiency of the framework. Some rather standard
optimizations as found in modern rule-based systems can easily be applied, although
optimizations of the conditions may require them to be lifted into a more structured
type, such as for example

    datatype condition = Basic of unit -> word
    | And of condition list
    | Or of condition list
    | Not of condition
    | ...

in order to allow for such things as caching of condition evaluations and so on. On
another note, evaluating a condition is only required if the references the condition
refers to have been changed, so an optimized framework should maintain a list of the
references used by conditions and record changes accordingly.

The tradeoff between generality and conciseness is not new. If we are willing to
restrict flexibility, we can design an appropriate surface language which we can trans-
late into this framework for execution. This is what we did for the implementation of
behaviors in Section 5. This makes our framework a target language for the interpreta-
tion of domain-specific rule-based languages. In a similar way, the reactive library of
[11] was designed as a target language for the interpretation of domain-specific reactive
languages, which is the way it is being used in this paper.

Using the SugarCubes framework described in [4], we could move most of the
framework to Java, but SML has distinct advantages, at least at first brush: we have seen
how first-class rules and first-class functions helped design suitable domain-specific ab-
stractions; the module system, although not used in this paper, plays a crucial role in
the generalization of the framework to general rules that can carry arbitrary data (not
only conditions and actions). The whole approach is also helped by the fact that SML
already implements state-based programming through the use of explicit references. It will be interesting to see how much of this can be carried over to Java.

This frameworks, one of the first implemented using the library in [11], also points to some conclusions about the reactive approach. If the order in which parallel reactive expressions are activated is important, then we need to be careful, appropriately using suspend calls to get the order right; this makes the resulting system brittle and the code hard to see correct. A better approach may be to allow one to explicitly control the order of execution of the branches of a merge. On a related note, the reactive library is geared towards determining reactive expression activation locally, while we have encountered in this paper a reasonable instance where the activation decision is taken on a global level. It would be interesting to find an extension of the reactive library to do that cleanly, without resorting to a list of unique identifiers indicating which expression is allowed to resume.

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