

Reconciling Control and Dataflow Reactivity in Embedded Systems

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ABSTRACT

CÉU is a Esterel-based reactive language that targets constrained embedded platforms. Relying on a deterministic semantics, CÉU provides safe shared memory for concurrent lines of execution. CÉU also introduces a stack-based execution policy for internal events which enables advanced control mechanisms considering the context of embedded systems, such as exception handling and dataflow programming. The conjunction of shared-memory concurrency with internal events allows programs to express dependency among variables reliably, reconciling the control and dataflow reactive styles in a single language.

Categories and Subject Descriptors

D.3.1 [Programming Languages]: Formal Definitions and Theory; D.3.3 [Programming Languages]: Language Constructs and Features

General Terms

Design, Languages

Keywords

Concurrency, Dataflow, Determinism, Embedded Systems, Esterel, Synchronous, Reactivity

1. INTRODUCTION

Embedded systems are essentially reactive and interact permanently with the surrounding environment through input and output devices (e.g. buttons, timers, transceivers, etc.). An established alternative to *C* in the field of safety-critical embedded systems is the family of reactive synchronous languages [2]. Two major styles of synchronous languages have evolved: in the *control-imperative* style (e.g. Esterel [5]), programs are structured with control flow primitives, such as parallelism, repetition, and preemption; in the *dataflow-declarative* style (e.g. Lustre [10]), programs can be seen as graphs of values, in which a change to a value is propagated through its dependencies without explicit programming.

We believe that embedded systems programming can benefit from a new language that reconciles both reactive synchronous styles, while preserving typical *C* features that programmers are familiarized, such as shared memory concurrency. CÉU [14] is a Esterel-based programming language targeting embedded systems aiming to XXX this YYY. In this work, we focus on the differences from CÉU to Esterel that enable new programming functionalities:

- The execution order for memory operations rely on a deterministic semantics, allowing programs to safely share memory.
- Internal events follow a stack-based execution policy, providing new advanced control mechanisms, such as exception handling, and dataflow programming.

We discuss in detail each of these features and, in particular, how they avoid *glitches* and *cyclic dependencies* in dataflow programming [1]. We also present a formal semantics for the control primitives of CÉU.

CÉU shares the same limitations with Esterel and synchronous languages in general: computations that run in unbounded time (e.g., cryptography, image processing) do not fit the zero-delay hypothesis [13], and cannot be elegantly implemented.

Nonetheless, previous work focusing on Wireless Sensor Networks [14] shows that the expressiveness of CÉU is sufficient for implementing a wide range of applications (e.g. network protocols and a radio driver), with a considerable reduction in code complexity in comparison to the state-of-the-art [9]. CÉU has a small memory footprint, using less than 5 Kbytes of ROM and 100 bytes of RAM for a simple program with sixteen lines of execution.

TODO The rest of the paper is organized as follows: Section 2 describes the main differences between CÉU and Esterel. Section 3 shows how to implement some advanced control-flow mechanisms on top of CÉU internal events. Section 4 shows the semantics... Section 5 compares CÉU to existing synchronous and asynchronous languages for embedded systems. Section 6 concludes the paper and makes final remarks.

2. OVERVIEW OF CÉU AND ESTEREL

CÉU is a synchronous reactive language based on Esterel [6] with support for multiple lines of execution known as *trails*.

<pre> 1 // ESTEREL 2 loop 3 [4 await A 5 6 await B 7]; 8 emit O 9 each R </pre>	<pre> 1 // CÉU 2 loop do 3 par/or do 4 par/and do 5 await A; 6 with 7 await B; 8 end 9 emit O; 10 with 11 await R; 12 end 13 end </pre>
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Figure 1: The “ABRO” specification in Esterel and Céu.

By reactive, we mean that programs are stimulated by the environment through input events that are broadcast to all awaiting trails. By synchronous, we mean that any trail at any given time is either reacting to the current event or is awaiting another event; in other words, trails are always synchronized at the current (and single) event.

Figure 1 shows side-by-side the implementations in Esterel and Céu for the “ABRO” example with the following specification [4]: “Emit an output *O* as soon as two inputs *A* and *B* have occurred. Reset this behavior each time the input *R* occurs”. The first phrase of the specification is almost identical in the two implementations, with a small syntactic mismatch between the ‘||’ and `par/and` constructs (lines 3-8 in Esterel, and 4-9 in Céu). The reset behavior of Esterel uses a `loop-each` syntactic sugar, which expands to the more primitive `abort-when` and serves the same purpose of Céu’s `par/or` (to be discussed in Section 2.2). In both cases, the occurrence of event *R* aborts the awaiting statements and restarts the loop.

Céu and Esterel have a strong imperative flavor, with explicit control flow through sequences, loops, and also assignments. Being designed for control-intensive applications, they provide additional support for concurrent lines of execution and broadcast communication through events. Esterel and Céu also rely on a *multiform notion of time*, in which programs advance in discrete and subsequent reactions to external *signals* (*events* in Céu). Internal computations within a reaction (e.g. expressions, assignments, and native calls) are considered to take no time in accordance with the synchronous (or *zero-delay*) hypothesis [13]. The `await` statements are the only that halt a running reaction and allow a program to advance in this definition of time. To ensure that reactions run in bounded time and programs always progress, loops must contain at least one `await` statement in all possible paths [14, 4].

2.1 External reactions and determinism

In Esterel, an external reaction can carry simultaneous signals, while in Céu, a single event defines a reaction. The notion of time in Esterel is similar to that of digital circuits, in which multiple wires (signals) can be queried for their status (*present* or *absent*) on each clock tick. Céu more closely reflects event-driven programming, in which occurring events are sequentially and uninterruptedly handled by the program [?, ?]. Note that even with the single-event rule

there is still concurrency in Céu given that multiple lines of execution may react to the same event.

Another difference between Esterel and Céu is on their definition for determinism: Esterel is deterministic with respect to reactive control, i.e., “the same sequence of inputs always produces the same sequence of outputs” [4]. However, the order of execution for side-effect operations within a reaction is non-deterministic: “if there is no control dependency and no signal dependency, as in “`call f1() || call f2()`”, the order is unspecified and it would be an error to rely on it” [4]. In Céu, when multiple trails are active at a time, as in “`par/and do _f1() with _f2() end`”, they are scheduled in the order they appear in the program text (i.e. `_f1` executes first)¹. This way, Céu is deterministic also with respect to the order of execution of side effects within a reaction.

On the one hand, enforcing an execution order for concurrent operations may seem arbitrary and also precludes true parallelism. On the other hand, it provides a priority scheme for trails (discussed in Section 2.2), and ensures a reproducible execution for shared-memory programs. For software development, we believe that deterministic shared-memory concurrency is beneficial, specially considering embedded systems which make extensive use of memory mapped ports for I/O.

2.2 Thread abortion

The introductory example of Figure 1 illustrates how awaiting lines of execution can be aborted from enclosing code without being tweaked with synchronization primitives. It is known that traditional (asynchronous) multi-threaded languages cannot express thread termination safely [3, 12].

The code fragments of Figure 2 illustrate thread abortion in Esterel and Céu. Note that it is not clear in the leftmost example in Esterel if the call to `f` should execute or not, given that the body and abortion event are the same. For this reason, Esterel provides the *weak* and *strong* variations for the `abort` statement. With *strong* abortion (the default), the body is aborted immediately and the call does not execute. In Céu, given the deterministic scheduling rules, strong and weak abortions can be chosen by reordering trails inside a `par/or`, e.g., in the example in the middle, the second trail is strongly aborted and the call to `_f` never executes.

Céu also supports a `par/hor` composition (standing for *hierarchical-or*) which schedules both sides on termination. This way, in the rightmost example of Figure 2, both `_g` and `_f` (in this order) will execute in reaction to `S`. Hierarchical traversal is fundamental for dataflow programming, as we discuss in Section 3.2. Note that in contrast with a `par/and`, a `par/hor` rejoins on the same reaction one side terminates, but it also schedules the other side to run.

2.3 Internal events

Esterel makes no semantic distinction between internal and external signals, both having only the notion of presence or absence during the entire reaction [3]. In Céu, however, internal and external events behave differently:

¹Céu calls native functions by prefixing names with an underscore.

<pre>// ESTEREL abort await S; call f(); when S;</pre>	<pre>// CEU (or) par/or do await S; with await S; _f(); end</pre>	<pre>// CEU (hor) par/hor do await S; _g(); with await S; _f(); end</pre>
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Figure 2: Thread abortion in Esterel and Céu.

<pre>// ESTEREL input START; signal A, B; [[await START; emit A; call printf("3");]] await A; emit B; call printf("2"); await B; call printf("1");]]</pre>	<pre>1 // CEU 2 input void START; 3 event void a, b; 4 par/and do 5 await START; 6 emit a; 7 _printf("3"); 8 with 9 await a; 10 emit b; 11 _printf("2"); 12 with 13 await b; 14 _printf("1"); 15 end</pre>
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Figure 3: Internal signals (events) in Esterel and Céu.

- External events can be emitted only by the environment, while internal events only by the program.
- A single external event can be active at a time, while multiple internal events can coexist within a reaction.
- External events are handled in a queue, while internal events follow a stacked execution policy (like subroutine calls in typical programming languages).

Figure 3 illustrates the use of internal signals (events) in Esterel and Céu. For the version in Esterel, given that there is no control dependency between the calls to `printf`, they may execute in any order on `START`. For the version in Céu, the occurrence of `START` makes the program behave as follows (with the stack in emphasis):

1. 1st trail awakes (line 5), emits `a`, and pauses.
stack: [1st]
2. 2nd trail awakes (line 9), emits `b`, and pauses.
stack: [1st, 2nd]
3. 3rd trail awakes (line 13), prints 1, and terminates.
stack: [1st, 2nd]
4. 2nd trail (on top of the stack) resumes, prints 2, and terminates.
stack: [1st]
5. 1st trail resumes, prints 3, and terminates.
stack: []
6. All trails have terminated, so the `par/and` rejoins, and the program also terminates;

Internal events bring support for a limited form of subroutines, as illustrated in Figure 4. The subroutine `inc` is defined as a loop (lines 3-6) that continuously awaits its identifying event (line 4) and increments the value passed as reference (line 5). A trail in parallel (lines 8-11) invokes the subroutine in reaction to event `A` through an `emit`. Given the stacked execution for internal events, the calling trail pauses

```
1 event int* inc; // function 'inc'
2 par/or do
3   loop do // definitions are loops
4     var int* p = await inc;
5     *p = *p + 1;
6   end
7 with
8   var int v = 1;
9   await A;
10  emit inc => &v; // call 'inc'
11  _assert(v==2); // after return
12 end
```

Figure 4: The subroutine `inc` is defined in a loop, in parallel with the caller.

(line 10) and the subroutine awakes (line 4). Only after the subroutine “returns” (after the next `await` in line 4) that the calling trail resumes and passes the assertion test.

This form of subroutines has some significant limitations:

- Single instance:** Calls to a running subroutine have no effect. For instance, if the subroutine in the example waits for another event before the loop, it cannot serve new requests.
- Single calling:** Further calls to a subroutine in a reaction also have no effect. To avoid unbounded execution, an `await` statement in Céu must be awaiting before a reaction starts.
- No recursion:** Recursive calls to a subroutine also have no effect, i.e., a trail cannot be awaiting itself while it is running.
- No concurrency:** If two trails in parallel try to call the same subroutine, only the first trail takes effect (based on deterministic scheduling). The second call fails on the *single calling* property.

Céu provides no support for standard functions for a number of reasons:

- The interaction with other Céu control primitives is not obvious (e.g., executing an `await` or a `par/or` inside a function).
- They would still be restricted in some ways given the embedded context (e.g. no recursion or closures).
- Programs can always recur to *C* functions for low-level operations.

In Section 3.2, we take advantage of non-recursive subroutines to properly describe mutual dependency among trails in parallel.

3. ADVANCED CONTROL MECHANISMS

In this section, we explore the stacked execution for internal events in Céu, demonstrating how it enables to derive support for *exceptions* and *dataflow programming* without requiring specific primitives.

3.1 Exception handling

Céu can naturally express different forms of exception handling on top of internal events without a specific construct. In the illustrative example in Figure 5, an external entity pe-

```

1 // DECLARATIONS
2 input int ENTRY;
3 var _FILE* f = <...>; // file handler
4 var char[10] buf; // current entry
5 event int read;
6 event void excpt;
7
8 // NORMAL FLOW
9 loop do
10     var int n = await ENTRY;
11     emit read => n; // calls 'read'
12     _printf("line: %s\n", buf);
13 end

```

Figure 5: Normal flow to read file entries.

```

1 <...> // DECLARATIONS (previous code)
2 par/or do
3     <...> // NORMAL FLOW (previous code)
4 with
5     loop do // READ subroutine
6         var int n = await read;
7         if _read(f,buf,n) != n then
8             emit excpt; // throw exception
9         end
10    end
11 end

```

Figure 6: Low-level read operation is placed in parallel with the normal flow.

periodically writes to a file and notifies the program through the event `ENTRY` carrying the number of available characters (defined in line 2). The expected behavior for the application is to react to every `ENTRY` in a loop (lines 8-13), invoking the `read` operation (line 11), and then using the filled buffer (line 12). Note that the file operation `read` is defined as an internal event working as a subroutine, which is expected to fill the variable `buf` with the entry contents. Because this code does not handle failures, it is straight to the point and easy to follow.

Figure 6 defines the subroutine that performs the actual low-level `_read` system call, which is placed in parallel with the normal flow. The subroutine awaits requests in a loop (lines 5-10) and may emit exceptions through event `excpt` on any error (lines 7-9).

To handle read exceptions, we use an additional `par/or` in Figure 7 that *strongly* aborts the normal flow on any exception. For instance, suppose that the normal flow tries to read a string and fails. The program behaves as follows (with the stack in emphasis):

1. Normal flow invokes the read operation (line 11 of Figure 5) and pauses.
stack: [norm]
2. Read operation awakes (line 6 of Figure 6), throws an exception (line 8), and pauses.
stack: [norm, read]
3. Exception handler awakes (line 4 of Figure 7) and terminates the `par/or`, aborting the normal behavior and terminating the program.
stack: []

The exception handler (lines 3-7 of Figure 7) was placed

```

1 <...> // DECLARATIONS
2 par/or do
3     par/or do
4         await excpt; // catch exceptions
5     with
6         <...> // NORMAL FLOW
7     end
8 with
9     <...> // READ (throw exceptions)
10 end

```

Figure 7: Exceptions are caught with a `par/or` that strongly aborts the normal flow.

```

1 ...
2     par/or do
3         loop do
4             await excpt; // catch exceptions
5             buf = <...>; // assigns a default
6         end
7     with
8         <...> // NORMAL FLOW
9     end
10 ...

```

Figure 8: Exception handling with resumption.

around the normal behavior (line 6), but could effectively abort its execution to avoid the unsafe use of `buf` (line 12 of Figure 5).

This mechanism can also support resumption if the exception handler does not terminate its surrounding `par/or` (lines 3-7 of Figure 7). For instance, the new handler of Figure 8 catch exceptions in a loop and fallbacks to a default string. The program behaves as follows (steps 1-2 are the same):

3. Exception handler awakes (line 4 of Figure 8), assigns a default string to `buf` (line 5), and awaits the next exception (line 4).
stack: [norm, read]
4. Read subroutine resumes (line 8 of Figure 6), and awaits the next call.
stack: [norm]
5. Read call resumes (line 11 of Figure 5), and uses `buf` normally (line 12), as if no exceptions had occurred.
stack: []

Note that throughout the example, the normal flow of Figure 5 remains unchanged, with all machinery to handle exceptions placed around it. With some syntactic sugar these exception mechanisms could be exposed in a higher level to developers.

3.2 Dataflow programming

Reactive dataflow programming provides a declarative style to express dependency relationships among data [1]. Two issues

Mutual dependency is a known issue in dataflow languages, requiring the explicit placement of a specific delay operator to avoid runtime cycles [7, 15]. This solution is somewhat *ad hoc* and splits an internal dependency problem across two reactions to the environment. CÉU can safely express cyclic dependencies, given that reactions are guaranteed to

```

1  event int tc, tf;
2  par/or do
3    loop do // 1st trail
4      var int v = await tc;
5      emit tf => (9 * v / 5 + 32);
6    end
7  with
8    loop do // 2nd trail
9      var int v = await tf;
10     emit tc => (5 * (v-32) / 9);
11   end
12 with
13   var int v = await tf; // 3rd trail
14   <...>
15 with
16   <...> // 4th trail
17   emit tc => 0;
18 end

```

Figure 9: A dataflow program with mutual dependency.

terminate.

As an example, the program in Figure 9 applies the temperature conversion formula between Celsius and Fahrenheit, so that whenever the value in one unit is set, the other is automatically recalculated (a problem proposed in [1]).

We first define the *tc* and *tf* events to signal temperature changes (line 1). Then, we create the 1st and 2nd trails to await for changes and mutually update the temperatures (lines 3-6 and 8-11). The third and fourth trails respectively react to (lines 13-14) and signal temperature changes (lines 16-17). The program behaves as follows (with the stack in emphasis):

1. 4th trail signals *tc*=>0 and pauses.
stack: [4th]
2. 1st trail awakes, signals *tf*=>32, and pauses.
stack: [4th, 1st]
3. 2nd trail awakes, signals *tc*=>0, and pauses.
stack: [3rd, 1st, 2nd]
4. no trails are awaiting *tc* (1st trail is paused), so 2nd trail (on top of the stack) resumes, loops, and awaits *tf* again.
stack: [3rd, 1st]
5. 3rd trail also awakes from *tf*=>32, uses the updated value, and eventually halts.
stack: [3rd, 1st]
6. 1st trail resumes, loops, and awaits *tc* again.
stack: [3rd]
7. 3rd trail resumes with all dependencies resolved and terminates the program.
stack: []

The stack-based execution for internal events can unambiguously express mutual dependencies, as seen in step 4, when the *emit tc*=>0 of line 10 is ignored by the 1st trail which is already reacting to the first *emit tc*=>0 of line 17. The stack also ensures that an *emit* that triggers nested dependencies only resumes after the relationships are completely updated.

```

event int b, s, s1; par/or do loop do var int v = await s; emit
s1 => v + 1; end with loop do var int v1=0, v2=1; par/hor
do v1 = await s; with v2 = await s1; end emit b => v2 >
v1; end end

```

4. THE SEMANTICS OF CÉU

We present a formal semantics of CÉU focusing on the control aspects of the language. The syntax for a subset of CÉU that is sufficient to describe all semantic peculiarities of the language is as follows:

// primary statements	// description
<i>nop</i> (v)	(constant value)
<i>mem</i>	(any memory access)
<i>await</i> (e)	(await event 'e')
<i>emit</i> (e,v)	(emit event 'e' passing 'v')
<i>break</i>	(loop escape)
// compound statements	
<i>mem</i> ? <i>p</i> : <i>q</i>	(conditional)
<i>p</i> ; <i>q</i>	(sequence)
<i>loop</i> <i>p</i>	(repetition)
<i>p</i> and <i>q</i>	(par/and)
<i>p</i> or <i>q</i>	(par/or)
<i>p</i> hor <i>q</i>	(par/hor)
// derived by semantic rules	
<i>awaiting</i> (e,m)	(awaiting 'e' since seqno 'm')
<i>emitting</i> (t)	(emitting on stack level 't')
<i>p</i> @ <i>loop</i> <i>p</i>	(unwinded loop)

A *nop* represents a terminated computation associated with a constant value. The *mem* primitive represents all memory accesses, assignments, and *C* function calls. The semantic rules generate three statements that the programmer cannot write: the *awaiting* avoids that an *await* awakes during the same reaction it is reached; the *emitting* represents the continuation of an *emit* and enables the desired stacked behavior for internal events; a *loop* is expanded with the special '@' separator (instead of ';') to properly bind *break* statements inside *p* to the enclosing loop.

We use a *small-step* structural operational semantics to formally describe a *reaction chain* in CÉU, i.e., how a program behaves in reaction to a single external event. The semantics require an explicit stack to properly nest the emission of internal events. A complete reaction chain in CÉU is formalized as follows:

$$\langle S, s, p \rangle \xrightarrow[n]{*} \text{pop}(p, \langle S', s', p' \rangle)$$

At a given external sequence *n*, a program *p* with a stack of events *S* with top *s* continuously progress until no transitions are possible. After every transition, the top of the stack is popped if the program becomes blocked.

At the beginning of each reaction, the external sequence number *n* is incremented and the stack is initialized with the new external event, i.e., *s* = 1 and *S* = {1 ↦ *ext*}. The top of the stack represents the single event being handled at a time: it is initialized to the external event, but *emit* statements can push new events on top of it. When no transitions are possible in the current level, the stack is popped and the previous event is reactivated. The reaction chain terminates when the level 0 is popped from the stack, signaling that the original external event has been completely handled and no trails are pending.

To describe the full execution of a program with reaction chains in sequence, we need multiple “invocations” of the

operational semantics, i.e.:

$$\begin{aligned} \langle \{1 \mapsto e1\}, 1, p \rangle &\xRightarrow{1} \langle \{\}, -1, p' \rangle \\ \langle \{1 \mapsto e2\}, 1, p' \rangle &\xRightarrow{2} \langle \{\}, -1, p'' \rangle \\ &\dots \end{aligned}$$

Each invocation starts with the external event at the top of the stack and finishes with a modified program and an empty stack. After each invocation, the sequence number is incremented.

Figure 10 shows the transitions rules for the complete semantics of CÉU. At any time, at most one transition is possible. This way, there is a single order of execution for side effects (represented by **mem** operations), and reaction chains are always deterministic.

A *mem* reduces to a *nop* in a single step (rule **mem**), representing the (bounded) execution of a side-effect operation. Although we opted not to formalize side effects, the actual values yielded by *mem* operations are required in conditionals (e.g., the value of a variable or the result of a *C* function call). (In the rules that an yielded *nop* cannot appear in a conditional, we omit its generated value, i.e., we use *nop* instead of *nop(v)*.)

An *await* is simply transformed into an *awaiting* that remembers the current external sequence number *n* (rule **a**). An *awaiting* can only transit to a *nop* (rule **awaiting**) if its referred event matches the top of the stack (*S(s)*) and its sequence number is smaller than the current one (*m < n*). An *emit* transits to an *emitting* and stacks its referred event (rule **emit**). With the new stack level *s + 1*, the *emitting(s)* cannot transit, as rule **emitting** expects its parameter to match the current stack level. This trick enforces the desired stack-based semantics for internal events.

The function *pop* (called after every transition) removes the top of the stack when the rules cannot make a transition, allowing that previously stacked *emitting* operations progress:

$$\text{pop}(p, \langle S, s, p' \rangle) = \begin{cases} \langle S, s-1, p' \rangle, & p = p' \\ \langle S, s, p' \rangle, & p \neq p' \end{cases}$$

The rules for conditionals and sequences are straightforward (**if-*** and **seq-***). Given that the semantics focus on control, note that rules **if-true** and **if-false** are the only to query *nop(v)* values.

The rules for loops are analogous to sequences, but use '@' as separators to properly bind a break to its enclosing loop. When a program first encounters a *loop*, it first expands its body in sequence with itself (rule **loop-expd**). Rules **loop-adv** and **loop-nop** are similar to rules **seq-adv** and **seq-nop**, advancing the loop until it reaches a *nop*. However, what follows the loop is the loop itself (rule **loop-nop**). Note that if we used ';' as a separator in loops, rules **loop-brk** and **seq-brk** would conflict. Rule **loop-brk** escapes the enclosing loop, transforming everything into a *nop*.

The rules with the **par** prefix are valid for all *and/or/hor* compositions (substituting the *par* in the rules for each of

$$\begin{aligned} \langle S, s, \text{mem} \rangle &\xrightarrow{n} \langle S, s, \text{nop}(v) \rangle, v \in \mathbb{N} & (\text{mem}) \\ \langle S, s, \text{await}(e) \rangle &\xrightarrow{n} \langle S, s, \text{awaiting}(e, n) \rangle & (\text{await}) \\ \langle S, s, \text{awaiting}(S(s), m) \rangle &\xrightarrow{n} \langle S, s, \text{nop} \rangle, m < n & (\text{awaiting}) \\ \langle S, s, \text{emit}(e, v) \rangle &\xrightarrow{n} \langle S \uplus \{(s+1) \mapsto e\}, \\ &\quad s+1, \text{emitting}(s) \rangle & (\text{emit}) \\ \langle S, s, \text{emitting}(s) \rangle &\xrightarrow{n} \langle S, s, \text{nop} \rangle & (\text{emitting}) \\ \\ \frac{m \xrightarrow{n} m'}{\langle S, s, (m ? p : q) \rangle \xrightarrow{n} \langle S, s, (m' ? p : q) \rangle} & (\text{if-adv}) \\ \langle S, s, (\text{nop}(v) ? p : q) \rangle &\xrightarrow{n} \langle S, s, p \rangle, (v \neq 0) & (\text{if-true}) \\ \langle S, s, (\text{nop}(0) ? p : q) \rangle &\xrightarrow{n} \langle S, s, q \rangle & (\text{if-false}) \\ \\ \frac{p \xrightarrow{n} p'}{\langle S, s, (p ; q) \rangle \xrightarrow{n} \langle S, s, (p' ; q) \rangle} & (\text{seq-adv}) \\ \langle S, s, (\text{nop} ; q) \rangle &\xrightarrow{n} \langle S, s, q \rangle & (\text{seq-nop}) \\ \langle S, s, (\text{break} ; q) \rangle &\xrightarrow{n} \langle S, s, \text{break} \rangle & (\text{seq-brk}) \\ \langle S, s, (\text{loop } p) \rangle &\xrightarrow{n} \langle S, s, (p @ \text{loop } p) \rangle & (\text{loop-expd}) \\ \\ \frac{p \xrightarrow{n} p'}{\langle S, s, (p @ \text{loop } q) \rangle \xrightarrow{n} \langle S, s, (p' @ \text{loop } q) \rangle} & (\text{loop-adv}) \\ \langle S, s, (\text{nop} @ \text{loop } p) \rangle &\xrightarrow{n} \langle S, s, \text{loop } p \rangle & (\text{loop-nop}) \\ \langle S, s, (\text{break} @ \text{loop } p) \rangle &\xrightarrow{n} \langle S, s, \text{nop} \rangle & (\text{loop-brk}) \\ \\ \frac{p \xrightarrow{n} p'}{\langle S, s, (p \text{ par } q) \rangle \xrightarrow{n} \langle S, s, (p' \text{ par } q) \rangle} & (\text{par-adv1}) \\ \frac{\text{isBlocked}(p) \wedge q \xrightarrow{n} q'}{\langle S, s, (p \text{ par } q) \rangle \xrightarrow{n} \langle S, s, (p \text{ par } q') \rangle} & (\text{par-adv2}) \\ \langle S, s, (\text{break par } q) \rangle &\xrightarrow{n} \langle S, s, \text{break} \rangle & (\text{par-brk1}) \\ \frac{\text{isBlocked}(p)}{\langle S, s, (p \text{ par break}) \rangle \xrightarrow{n} \langle S, s, \text{break} \rangle} & (\text{par-brk2}) \\ \langle S, s, (\text{nop and } q) \rangle &\xrightarrow{n} \langle S, s, q \rangle & (\text{and-nop1}) \\ \langle S, s, (p \text{ and } \text{nop}) \rangle &\xrightarrow{n} \langle S, s, p \rangle & (\text{and-nop2}) \\ \langle S, s, (\text{nop or } q) \rangle &\xrightarrow{n} \langle S, s, \text{nop} \rangle & (\text{or-nop1}) \\ \frac{\text{isBlocked}(p)}{\langle S, s, (p \text{ or } \text{nop}) \rangle \xrightarrow{n} \langle S, s, \text{nop} \rangle} & (\text{or-nop2}) \\ \frac{q \neq (a \text{ hor } b) \vee (a \neq \text{nop} \wedge b \neq \text{nop})}{\langle S, 0, (\text{nop hor } q) \rangle \xrightarrow{n} \langle S, 1, \text{nop} \rangle} & (\text{hor-nop1}) \\ \frac{p \neq (a \text{ hor } b) \vee (a \neq \text{nop} \wedge b \neq \text{nop})}{\langle S, 0, (p \text{ hor } \text{nop}) \rangle \xrightarrow{n} \langle S, 1, \text{nop} \rangle} & (\text{hor-nop2}) \end{aligned}$$

Figure 10: The semantics of Céu.

them). The transitions on the left branch p are forced to occur before transitions on the right branch q (rules **par-adv1** and **par-adv2**). The deterministic behavior of the semantics relies on the *isBlocked* recursive predicate, which is only true if all branches in parallel are hanged in *awaiting* or *emitting* operations that cannot transit:

$$\begin{aligned} isBlocked(n, S, s, awaiting(e, m)) &= (e \neq S(s) \vee m = n) \\ isBlocked(n, S, s, emitting(t)) &= (t \neq s) \\ isBlocked(n, S, s, (p ; q)) &= isBlocked(n, S, s, p) \\ isBlocked(n, S, s, (p @ loop q)) &= isBlocked(n, S, s, p) \\ isBlocked(n, S, s, (p par q)) &= isBlocked(n, S, s, p) \wedge \\ &\quad isBlocked(n, S, s, q) \\ isBlocked(n, S, s, *) &= false \text{ (all others)} \end{aligned}$$

For instance, rule **par-adv2** requires the left branch p to be blocked in order to allow the right transition from q to q' . The rules **par-brk1** and **par-brk2** deal with a *break* in each of the parallel sides, which terminates the whole composition to escape the innermost loop (strongly aborting the other side).

The difference among the three parallel compositions consists in how to deal with one of the sides terminating with a *nop*. For an *and* composition, if one of the sides terminate, the composition is simply substituted by the other side (rules **and-nop1** and **and-nop2**), as both sides are required to terminate. For a parallel *or*, reaching a *nop* in either of the sides should immediately terminate the composition (rules **or-nop1** and **or-nop2**). However, for a parallel *hor* it is not enough that one of the sides reaches a *nop*, as the other should also be allowed to react. The rules **hor-nop1** and **hor-nop2** ensure, first, that a composition rejoins only after no transitions are possible in either sides, and second, that rejoins happen from inside out, i.e., that nested compositions rejoin before outer compositions. The first condition is achieved by allowing transitions with $s = 0$ only, when the program is guaranteed to be blocked. For the second condition, we check if a nested *hor* is also pending, forcing that composition to transit first (via rules **par-adv1** or **par-adv2**).

5. RELATED WORK

6. CONCLUSION

7. REFERENCES

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