Reconciling Control and Dataflow Reactivity in Embedded Systems with Céu

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ABSTRACT

Céu is a Esterel-based reactive language that targets constrained embedded platforms. Relying on a deterministic semantics, it provides safe shared-memory concurrency among lines of execution. Céu 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 I/O devices (e.g. buttons, timers, transceivers). 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 [9]), 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-system 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 address this motivation. In this work, we focus on the fundamental differences between Céu and Esterel that enable new programming functionalities:

- A deterministic execution semantics for memory operations allows programs to safely share memory.
- A stack-based execution policy for internal events provides new advanced control mechanisms, such as exception handling, and dataflow programming.

We discuss in detail the differences between Céu and Esterel, 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 source code size in comparison to the state-of-the-art [8]. Céu has a small memory footprint, using less than 5 Kbytes of ROM and 100 bytes of RAM for a program with sixteen (simple) lines of execution.

The rest of the paper is organized as follows: Section 2 gives an overview of Céu and Esterel, exposing the fundamental similarities and differences between the two. Section 3 shows how to build some advanced control-flow mechanisms on top of Céu's internal events. Section 4 presents a formal semantics for the control primitives of Céu. Section 5 compares Céu to existing synchronous languages targeting embedded systems. Section 6 concludes the paper and makes final remarks.

```
// ESTEREL
loop
   abort
      [
         await A
      ||
         await B
      ];
      emit O
   when R
end
```

```
1   // CEU
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
```

Figure 1: The same specification in Esterel and Céu.

2. OVERVIEW OF CÉU AND ESTEREL

Céu is a synchronous reactive language based on Esterel [5] with support for multiple concurrent lines of execution known as *trails*. 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 the implementations in Esterel and Céu side-by-side for 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 translated almost identically in the two implementations (lines 3-8), with a small syntactic mismatch between the '||' and `par/and` constructs. For the second phrase with the reset behavior, the Esterel version uses a `abort-when`, which 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 in parallel and restarts the `loop`.

Esterel and Céu 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. Programs advance in discrete and subsequent reactions to external *signals* (or *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 hypothesis [13]. The `await` statements are the only that halt a running reaction and allow a program to advance in this notion of time. To ensure that reactions run in bounded time and programs always progress, loops are required to contain at least one `await` statement in all possible paths [14, 4].

In the following sections, we show the three basic differences from Céu to Esterel: deterministic execution for side-effect operations (Section 2.1), hierarchical abortion for lines of execution (Section 2.2), and stack-based execution for internal events (Section 2.3). They are fundamental to enable advanced control mechanism in Céu.

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 handled sequentially and uninterruptedly by the program. Note that even with the single-event rule of Céu, there is still concurrency given that multiple lines of execution may react to the same event.

Another difference between Esterel and Céu is regarding their definitions 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, as in "`call f1() || call f2()`", the execution 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). 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 seen 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 synchronous languages can abort awaiting lines of execution without tweaking them with synchronization primitives. In contrast, it is known that traditional (asynchronous) multi-threaded languages cannot express thread termination safely [3].

The code fragments of Figure 2 show corner cases for thread abortion in Esterel and Céu. For instance, it is not clear in the leftmost example in Esterel if the call to `f` should execute or not (after `A`), given that the body and abortion events are the same. For this reason, Esterel provides *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 `par/hor` compositions (standing for *hierarchical-or*) which schedules both sides before terminating. 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 of the sides terminates, but also allows the other side to run before.

```
// ESTEREL
abort
    await A;
    call f();
when A;
```

```
// CEU (or)
par/or do
    await A;
with
    await A;
    _f();
end
```

```
// CEU (hor)
par/hor do
    await A;
    _g();
with
    await A;
    _f();
end
```

Figure 2: Thread abortion in Esterel and Céu.

```
// ESTEREL
input A;
signal B;
[[
    await A;
    emit B;
    call printf("2");
||
    await B;
    call printf("1");
]]
```

```
1   // CEU
2   input void A;
3   event void b;
4   par/and do
5       await A;
6       emit b;
7       _printf("2");
8   with
9       await b;
10      _printf("1");
11  end
```

Figure 3: Internal signals (events) in Esterel and Céu.

2.3 Internal events

Esterel makes no semantic distinctions between internal and external signals, both having only the notion of either presence or absence during the entire reaction [3]. In Céu, however, internal events follow a stack-based execution policy, similar to 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 after `A`. For the version in Céu, the occurrence of `A` makes the program behave as follows (with the stack in emphasis):

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

Internal events bring support for a limited form of subroutines, as depicted in Figure 4. The subroutine `inc` is defined as a loop (lines 3-6) that continuously awaits its identifying event (line 4), incrementing 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` (line 10). Given the stacked execution for internal events, the calling trail pauses, the subroutine awakes (line 4), runs its body (yielding `v=2`), loops, and awaits the next "call" (line 4, again). Only after this sequence that the calling trail resumes and passes the assertion test.

In contrast with *C* functions, this form of subroutines can be combined with the other primitives of Céu, such as parallel compositions. Furthermore, it can `await`, keeping context information such as locals and the program counter (like coroutines). In Section 3.1 we show how to implement exceptions on top of it.

```
1   event int* inc; // subroutine '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.

```
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.

On the one hand, this form of subroutines has a significant limitation that it cannot express recursive calls: an `emit` to itself will always be ignored, given that a running body cannot be awaiting itself. On the other hand, this very same limitation bring some important safety properties to subroutines: they are guaranteed to react in bounded time; memory for locals is also bounded, not requiring runtime stacks. In Section 3.2, we take advantage of the lack of recursion 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, showing 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 mechanisms on top of internal events. In the example of Figure 5, an external entity periodically writes to a file and notifies the program through the event `ENTRY` carrying the number of available characters. The application reacts to every `ENTRY` in a loop (lines 8-13), invoking the `read` subroutine (line 11), and then using the filled buffer (line 12). Because this code does not handle failures, it is straight to the point and easy to follow.

Figure 6 defines the `read` subroutine which performs the actual low-level `_read` system call and may fail. The code is placed in parallel so that it can be invoked by the normal application flow. The subroutine awaits requests in a loop (lines 5-10) and may emit exceptions through event `excpt` (lines 7-9).

```
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; // throws exception
9        end
10    end
11 end
```

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

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

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

To handle read exceptions, we use an additional trail in Figure 7 that *strongly* aborts the normal flow on exceptions (line 3). For instance, if the application tries to read an entry and fails, it will behave 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 3 of Figure 7) and terminates the `par/or`, aborting the normal behavior and terminating the program.
   stack: []

The exception handler (line 3 of Figure 7) is placed in parallel with the normal behavior (line 5), and can 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` (line 3 of Figure 7). For instance, the new handler of Figure 8 catches exceptions in a loop (lines 3-6) and fallbacks to a default string (line 5). The program now 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 (line 6).
   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 (lines 9-13) remains unchanged, with all machinery

```
1  <...>       // DECLARATIONS
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  with
10    <...>    // READ subroutine (throw exceptions)
11 end
```

Figure 8: Exception handling with resumption.

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

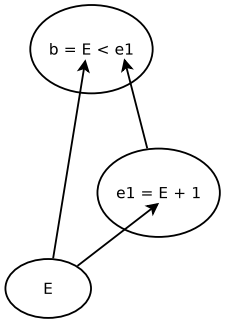
Reactive dataflow programming provides a declarative style to express dependency relationships among data. Céu can express data dependency relying on `par/hor` compositions and internal events to address two common subtleties in this context: *glitches* and *cyclic dependencies* [1].

A glitch is a situation in which a dependency graph is updated in an inconsistent order. It is usually avoided by traversing the graph in topological order [6, 1]. Figure 9 shows a graph for the expression `E < E+1`, which should always yield *true*. In a glitch-free implementation, when `E` changes, `e1` should be updated before `b` (because `b` also depends on `e1`) to avoid yielding `false`. The code in the right of the graph implements this "reactive expression" in Céu. The first trail (lines 4-13) updates and signals `b` whenever either `E` or `e1` changes. The second trail (lines 15-19) updates and signals `e1` whenever `E` changes. The `par/hor` (lines 6-11) ensures that `b` is only updated (in line 12) after `e1` and `E` (in lines 8 and 10). Follows the program behavior for a reaction to `E=>1` (which should awake lines 8 and 17):

1. Line 8 awakes and assigns `v1=1`. (The `par/hor` cannot rejoin yet, allowing other trails to react.)
2. Line 17 awakes, emits `e1=>2`, and pauses.
3. Line 10 awakes and assigns `v2=2`. (The `par/hor` still hangs until the program blocks.)
4. Line 18 resumes, loops, and awaits the next occurrence of `E`.
5. Now that the program cannot advance, the `par/hor` rejoins and correctly emits `b=>1` (i.e. `v1=1 < v2=2`).

Note that the described behavior does not depend on the order the trails are defined in the source code. The `par/hor` is fundamental to avoid the composition abortion, which would result in missing the update to `e1` in line 10.

Mutual dependency is another known issue in dataflow languages, usually requiring the explicit placement of a specific delay operator to avoid runtime cycles [6, 15]. However, an explicit delay is somewhat *ad hoc* because it splits an internal dependency problem across two reactions to the environment. Céu relies on the stack-based execution for internal events to avoid runtime cycles. As an example, the program in Figure 10 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




```
1   input int E;
2   event int b, e1;
3   par/or do
4     // b = E < E + 1
5     loop do
6       var int v1=0,v2=1;
7       par/hor do
8         v1 = await E;
9       with
10        v2 = await e1;
11      end
12      emit b => v1 < v2;
13    end
14  with
15    // s1 = s + 1
16    loop do
17      var int v = await E;
18      emit e1 => v + 1;
19    end
20  end
```

Figure 9: Glitch avoidance in Céu with a `par/hor`.

```
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      <...>                   // 3rd trail
14      emit tc => 0;
15  end
```

Figure 10: A dataflow program with mutual dependency.

update the temperatures (lines 3-6 and 8-11). The third trail (lines 13-14) signals a temperature change and the program behaves as follows (with the stack in emphasis):

1. 3rd trail signals `tc=>0` (line 14) and pauses.
   stack: [3rd]
2. 1st trail awakes (line 4), signals `tf=>32` (line 5), and pauses.
   stack: [3rd,1st]
3. 2nd trail awakes (line 9), signals `tc=>0` (line 10), and pauses.
   stack: [3rd,1st,2nd]
4. no trails are awaiting `tc` (1st trail is paused at line 5, breaking the cycle), so 2nd trail (on top of the stack) resumes, loops, and awaits `tf` again.
   stack: [3rd,1st]
5. 1st trail resumes, loops, and awaits `tc` again (line 4).
   stack: [3rd]
6. 3rd trail resumes with all dependencies resolved and terminates the program.
   stack: []

As seen in step 4, the second `emit tc=>0` (line 10) is ignored by the 1st trail which is stacked in the reaction to the first `emit tc=>0` (line 14). This way, the stack-based execution for internal events can unambiguously express mutual dependencies. An actual application would run the dependency code in 1st and 2nd trails in parallel and invoke `await` and `emit` on the events `tc` and `tf` (as exemplified in lines 13-14).

4. THE SEMANTICS OF CÉU

We present a formal semantics of Céu focusing on the control aspects of the language, with a reduced syntax as follows:

```
                          // primary expressions
p ::= mem(id)             (any memory access to 'id')
    | await(id)           (await event 'id')
    | emit(id)            (emit event 'id')
    | break               (loop escape)
                          // compound expressions
    | mem(id) ? p : p     (conditional)
    | p ; p               (sequence)
    | loop p              (repetition)
    | p and p             (par/and)
    | p or p              (par/or)
    | p hor p             (par/hor)
                          // derived by semantic rules
    | awaiting(id,n)      (awaiting 'id' since seqno 'n')
    | emitting(n)         (emitting on stack level 'n')
    | p @ loop p          (unwinded loop)
```

The $mem(id)$ primitive represents all accesses, assignments, and C function calls that affect a memory location identified by id. As the challenging parts of Céu reside on its control structures, we are not concerned here with a precise semantics for side effects, but only with their occurrences in programs. The special notation nop is used to represent an innocuous mem expression (it can be though as a synonym for $mem(\epsilon)$, where ϵ is an unused identifier). All other expressions map to their counterparts in the concrete language.

The core of our semantics is a relation that, given a sequence number n identifying the current reaction chain, maps a program p and a stack of events S in a single step to a modified program and stack:

$$\langle S, p\rangle \xrightarrow[n]{} \langle S', p'\rangle$$

where

$$\begin{aligned} S, S' &\in id^* && (sequence\ of\ event\ identifiers : [id_{top}, ..., id_1]) \\ p, p' &\in P && (as\ described\ in\ the\ syntax\ above) \\ n &\in \mathbb{N} && (univocally\ identifies\ a\ reaction\ chain) \end{aligned}$$

At the beginning of a reaction chain, the stack is initialized with the special η event and the occurring external event ext ($S = [\eta, ext]$), but $emit$ expressions may push new events on top of it (we discuss how they are popped further). The event η is used as a special marker to check for and resume pending hor expressions before terminating the reaction.

We describe this relation with a set of *small-step* structural semantics rules, which are built in such a way that at most one transition is possible at any time, resulting in deterministic reaction chains. Figure 11 shows the transitions rules for the complete semantics of Céu.

An $await$ is simply transformed into an $awaiting$ that remembers the current external sequence number n (rule **await**). An $awaiting$ can only transit to a nop (rule **awaiting**) if its referred event id matches the top of the stack and its sequence number is smaller than the current one ($m < n$). An $emit$ transits to an $emitting$ holding the current stack

level ($|S|$ stands for the stack length), and pushing the referred event on the stack (in rule **emit**). With the new stack level $|S|+1$, the $emitting(|S|)$ itself cannot transit, as rule **emitting** expects its parameter to match the current stack level. This trick provides the desired stack-based semantics for internal events.

Proceeding to compound expressions, the rules for conditionals and sequences are straightforward. Given that our semantics focuses on control, rules **if-true** and **if-false** are the only to query *mem* expressions. The "magical" function *val* receives the memory identifier and current reaction sequence number, returning the current memory value. Although the value is arbitrary, it is unique in a reaction chain, because a given expression can execute only once within it (remember that *loops* must contain *awaits* which, from rule **await**, cannot awake in the same reaction they are reached).

The rules for loops are analogous to sequences, but use **'@'** as separators to properly bind breaks to their enclosing loops. 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 they reach a $mem(id)$. 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 them). The rules **par-adv1** and **par-adv2** force the transitions on the left branch p to occur before transitions on the right branch q. The deterministic behavior of the semantics relies on the *isBlocked* predicate, defined in Figure 12 and used in rule **and-adv2**, requiring the left branch p to be blocked in order to allow the right transition from q to q'. An expression becomes blocked when all of its trails in parallel hang in *awaiting* and *emitting* expressions.

The rules **par-brk1** and **par-brk2** deal with a *break* in each of the parallel sides. A *break* terminates the whole composition to escape the innermost loop (*aborting* the other side).

The difference betwen 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 terminates, the composition is simply substituted by the other side, as both sides are required to terminate (rules **and-nop1** and **and-nop2**). For a parallel *or*, reaching a *nop* in either of the sides should immediatelly 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 still 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 only allowing transitions with η at the top of the stack, when the program is guaranteed to be blocked. For the second condition, we check if there is a pending nested *hor*, forcing it to transit before (via rules **par-adv1** or **par-adv2**).

$$\langle S,\ await(id)\rangle \xrightarrow[n]{} \langle S,\ awaiting(id,n)\rangle \quad \textbf{(await)}$$

$$\langle id : S,\ awaiting(id,m)\rangle \xrightarrow[n]{} \langle id : S,\ nop\rangle,\ \ m < n \quad \textbf{(awaiting)}$$

$$\langle S,\ emit(id)\rangle \xrightarrow[n]{} \langle id : S,\ emitting(|S|)\rangle \quad \textbf{(emit)}$$

$$\langle S,\ emitting(|S|)\rangle \xrightarrow[n]{} \langle S,\ nop\rangle \quad \textbf{(emitting)}$$

$$\frac{val(id,n) \neq 0}{\langle S, (mem(id)\ ?\ p\ :\ q)\rangle \xrightarrow[n]{} \langle S,p\rangle} \quad \textbf{(if-true)}$$

$$\frac{val(id,n) = 0}{\langle S, (mem(id)\ ?\ p\ :\ q)\rangle \xrightarrow[n]{} \langle S,q\rangle} \quad \textbf{(if-false)}$$

$$\frac{\langle S,p\rangle \xrightarrow[n]{} \langle S',p'\rangle}{\langle S, (p\ ;\ q)\rangle \xrightarrow[n]{} \langle S', (p'\ ;\ q)\rangle} \quad \textbf{(seq-adv)}$$

$$\langle S, (mem(id)\ ;\ q)\rangle \xrightarrow[n]{} \langle S,q\rangle \quad \textbf{(seq-nop)}$$

$$\langle S, (break\ ;\ q)\rangle \xrightarrow[n]{} \langle S, break\rangle \quad \textbf{(seq-brk)}$$

$$\langle S, (loop\ p)\rangle \xrightarrow[n]{} \langle S, (p\ @\ loop\ p)\rangle \quad \textbf{(loop-expd)}$$

$$\frac{\langle S,p\rangle \xrightarrow[n]{} \langle S',p'\rangle}{\langle S, (p\ @\ loop\ q)\rangle \xrightarrow[n]{} \langle S', (p'\ @\ loop\ q)\rangle} \quad \textbf{(loop-adv)}$$

$$\langle S, (mem(id)\ @\ loop\ p)\rangle \xrightarrow[n]{} \langle S, loop\ p\rangle \quad \textbf{(loop-nop)}$$

$$\langle S, (break\ @\ loop\ p)\rangle \xrightarrow[n]{} \langle S, nop\rangle \quad \textbf{(loop-brk)}$$

$$\frac{\langle S,p\rangle \xrightarrow[n]{} \langle S',p'\rangle}{\langle S, (p\ par\ q)\rangle \xrightarrow[n]{} \langle S', (p'\ par\ q)\rangle} \quad \textbf{(par-adv1)}$$

$$\frac{isBlocked(n,S,p)\ ,\ \ \langle S,q\rangle \xrightarrow[n]{} \langle S',q'\rangle}{\langle S, (p\ par\ q)\rangle \xrightarrow[n]{} \langle S', (p\ par\ q')\rangle} \quad \textbf{(par-adv2)}$$

$$\langle S, (break\ par\ q)\rangle \xrightarrow[n]{} \langle S, (clear(q)\ ;\ break)\rangle \quad \textbf{(par-brk1)}$$

$$\frac{isBlocked(n,S,p)}{\langle S, (p\ par\ break)\rangle \xrightarrow[n]{} \langle S, (clear(p)\ ;\ break)\rangle} \quad \textbf{(par-brk2)}$$

$$\langle S, (mem(id)\ and\ q)\rangle \xrightarrow[n]{} \langle S,q\rangle \quad \textbf{(and-nop1)}$$

$$\langle S, (p\ and\ mem(id))\rangle \xrightarrow[n]{} \langle S,p\rangle \quad \textbf{(and-nop2)}$$

$$\langle S, (mem(id)\ or\ q)\rangle \xrightarrow[n]{} \langle S, clear(q)\rangle \quad \textbf{(or-nop1)}$$

$$\frac{isBlocked(n,S,p)}{\langle S, (p\ or\ mem(id))\rangle \xrightarrow[n]{} \langle S, clear(p)\rangle} \quad \textbf{(or-nop2)}$$

$$\frac{q \neq (a\ hor\ b)\ \vee\ (a \neq nop\ \wedge\ b \neq nop)}{\langle [\eta], (nop\ hor\ q)\rangle \xrightarrow[n]{} \langle [\eta], nop\rangle} \quad \textbf{(hor-nop1)}$$

$$\frac{p \neq (a\ hor\ b)\ \vee\ (a \neq nop\ \wedge\ b \neq nop)}{\langle [\eta], (p\ hor\ nop)\rangle \xrightarrow[n]{} \langle [\eta], nop\rangle} \quad \textbf{(hor-nop2)}$$

Figure 11: The semantics of Céu.

$$
\begin{aligned}
isBlocked(n, a : S, awaiting(b, m)) &= (a \neq b \ \vee \ m = n) \\
isBlocked(n, S, emitting(s)) &= (|S| \neq s) \\
isBlocked(n, S, (p \ ; \ q)) &= isBlocked(n, S, p) \\
isBlocked(n, S, (p \ @ \ loop \ q)) &= isBlocked(n, S, p) \\
isBlocked(n, S, (p \ and \ q)) &= isBlocked(n, S, p) \ \wedge \\
&\quad\ isBlocked(n, S, q) \\
isBlocked(n, S, (p \ or \ q)) &= isBlocked(n, S, p) \ \wedge \\
&\quad\ isBlocked(n, S, q) \\
isBlocked(n, S, \_) &= false \ \ (mem, await, \\
&\quad\ emit, break, if, loop)
\end{aligned}
$$

Figure 12: The recursive predicate *isBlocked*.

A reaction chain eventually blocks in *awaiting* and *emitting* expressions in parallel trails. If all trails hangs only in *awaiting* expressions, it means that the program cannot advance in the current reaction chain. However, *emitting* expressions should resume in the ongoing reaction, when their lower stack indexes are restored (see rule **emit**). Therefore, we define another relation to pop the stack if the program becomes blocked (behaving as the previous relation, otherwise):

$$
\frac{\langle S, p\rangle \ \xrightarrow[n]{} \ \langle S', p'\rangle}{\langle S, p\rangle \xRightarrow[n]{} \langle S', p'\rangle} \qquad\qquad \frac{isBlocked(n, \ s : S, \ p)}{\langle s : S, p\rangle \xRightarrow[n]{} \langle S, p\rangle}
$$

To describe a *reaction chain* in Céu, i.e., how a program behaves in reaction to a single external event, we use the reflexive transitive closure of this relation:

$$\langle S, p\rangle \xRightarrow[n]{*} \langle S', p'\rangle$$

Finally, to describe the complete execution of a program, we need multiple "invocations" of reaction chains, incrementing the sequence number:

$$
\begin{aligned}
\langle [\eta, e1], p\rangle &\xRightarrow[1]{*} \langle [], p'\rangle \\
\langle [\eta, e2], p'\rangle &\xRightarrow[2]{*} \langle [], p''\rangle \\
&\ldots
\end{aligned}
$$

Each invocation starts with an 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.

5. RELATED WORK

With respect to control-based languages for embedded systems, the emerging area of Wireless Sensor Networks produced a number of synchronous alternatives to low-level event-driven systems [7, 10, 11]. Some offer predictable and lightweight multi-threading [7] with shared-memory concurrency, but lack thread composition and abortion (as described in Section 2.2). They also do not provide first-class events or a powerful broadcast mechanism, limiting their control mechanisms. OSM [11] provides parallel state machines with a formal and mature synchronous model, with (equivalent) support to thread composition and abortion. However, although machines can share memory, the execution order for operations among them is non-deterministic. Also, describing sequential code across reactions is not straightforward with state machines [11] (in comparison to Céu's `await` statement). Another Esterel-based language for constrained systems [10] made similar design decisions to ours, handling a single external event at a time, and relying on a deterministic scheduler for safe memory sharing.

Functional Reactive Programming (FRP) adapts modern functional languages to the reactive dataflow style [16]. In particular, Flask [12] shows that dataflow languages can also target constrained systems. Céu borrows some ideas from an FRP implementation [6], such as a push-driven evaluation and glitch prevention. However, dataflow in Céu is less abstract in comparison to FRP, and limited to static relationships only.

6. CONCLUSION

As a descendant of Esterel, Céu achieves a high degree of reliability for embedded systems, while also embracing practical aspects, such as shared-memory concurrency, and advanced control-flow mechanisms. Céu introduces a stack-based execution policy for internal events, expanding its expressiveness, such as for describing exceptions and dataflow programming without dedicated primitives. As far as we know, Céu is the first language to reconcile the control and dataflow reactive styles.

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