A Deterministic and Terminating Semantics for the Synchronous Programming Language Céu

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Abstract

Céu is a synchronous programming language for embedded soft real-time systems. It focus on control-flow safety features, such as safe shared-memory concurrency and safe abortion of lines of execution, while enforcing memory-bounded, deterministic, and terminating reactions to the environment. In this work, we present a small-step structural operational semantics for Céu and a proof that reactions have the properties enumerated above: that for a given arbitrary timeline of input events, multiple executions of the same program always react in bounded time and arrive at the same final finite memory state.

CCS Concepts • **Theory of computation → Operational semantics**; • **Software and its engineering → Concurrent programming languages**; • **Computer systems organization** → *Embedded software*;

Keywords Operational semantics, Céu, Synchronous languages

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1 Introduction

Céu [19, 21] is a Esterel-based [9] programming language for embedded soft real-time systems that aims to offer a concurrent, safe, and expressive alternative to C with the characteristics that follow:

Reactive: code only executes in reactions to events.
Structured: programs use structured control mechanisms, such as `await` (to suspend a line of execution), and `par` (to combine multiple lines of execution).
Synchronous: reactions run atomically and to completion on each line of execution, i.e., there's no implicit preemption or real parallelism.

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Structured reactive programming lets developers write code in direct style, recovering from the inversion of control imposed by event-driven execution [1, 16, 18]. Synchronous languages offer a simple run-to-completion execution model that enables deterministic execution and make formal reasoning tractable. For this reason, it has been successfully adopted in safety-critical real-time embedded systems [3].

Previous work in the context of embedded sensor networks evaluates the expressiveness of Céu in comparison to event-driven code in C and attests a reduction in source code size (around 25%) with a small increase in memory usage (around 5–10% for *text* and *data*) [21]. Céu has also been used in the context of multimedia systems [22] and games [20].

Céu inherits the synchronous and imperative mindset of Esterel but adopts a simpler semantics with fine-grained execution control [19]. The list that follows summarizes the semantic peculiarities of Céu:

- Fine-grained, intra-reaction deterministic execution, which makes Céu fully deterministic.
- Stack-based execution for internal events, which provides a limited but memory-bounded form of subroutines.
- Finalization mechanism for lines of execution, which makes abortion safe with regards to external resources.

In this work, we present a formal semantics for a subset of Céu that focus on its peculiarities in comparison to other synchronous languages.

- qual a abordagem / operational semantics / dois passos
- quais os resultados / provas
- quais os desafios e limitações
- **Guilherme**: TODO

Francisco: Descrever seções.

2 Céu

Céu is a synchronous reactive language in which programs advance in a sequence of discrete reactions to external events. It is designed for control-intensive applications, supporting concurrent lines of execution, known as *trails*, and instantaneous broadcast communication through events. Computations within a reaction (such as expressions, assignments, and system calls) are also instantaneous considering the synchronous hypothesis [10]. Céu provides an `await` statement that blocks the current running trail allowing the program to advance its other trails; when all trails are blocked, the reaction terminates and control returns to the environment.

In Céu, every execution path within loops must contain at least one `await` statement to an external input event [6, 21]. This restriction, which is statically checked by the compiler, ensures that every reaction runs in bounded time, eventually terminating with all trails blocked in `await` statements. Céu has an additional restriction, which it shares with Esterel and synchronous languages in general [4]: computations that take a non-negligible time to run (e.g., cryptography or image processing algorithms) violate the zero-delay hypothesis, and thus cannot be directly implemented.

Listing 1 shows a compact reference of Céu:

```
// Declarations
input ⟨type⟩ ⟨id⟩;          // declares an external input event
event ⟨type⟩ ⟨id⟩;          // declares an internal event
var   ⟨type⟩ ⟨id⟩;          // declares a variable

// Event handling
⟨id⟩ = await ⟨id⟩;          // awaits an event and assigns the received value
emit ⟨id⟩(⟨exp⟩);           // emits an event passing a value

// Control flow
⟨stmt⟩ ; ⟨stmt⟩                                  // sequence
if ⟨exp⟩ then ⟨stmts⟩ else ⟨stmts⟩ end           // conditional
loop do ⟨stmts⟩ end                              // repetition
every ⟨id⟩ in ⟨id⟩ do ⟨stmts⟩ end                // event iteration
finalize [⟨stmts⟩] with ⟨stmts⟩ end              // finalization

// Logical parallelism
par/or  do ⟨stmts⟩ with ⟨stmts⟩ end  // aborts when any side ends
par/and do ⟨stmts⟩ with ⟨stmts⟩ end  // terminates when all sides ends
par     do ⟨stmts⟩ with ⟨stmts⟩ end  // never terminates

// Assignment & Integration with C
⟨id⟩ = ⟨exp⟩;               // assigns a value to a variable
_⟨id⟩(⟨exps⟩)               // calls a C function (id starts with '_')
```

Listing 1. The concrete syntax of Céu.

Listing 2 shows a complete example in Céu that toggles a LED whenever a radio packet is received, terminating with a button press always with the LED off. The implementation first declares the `BUTTON` and `RADIO_RECV` as input events (ln. 1–2). Then, it uses a `par/or` composition to run two activities in parallel: a single statement that waits for a button press before terminating (ln. 4), and an endless loop that toggles the LED on and off on radio receives (ln. 9–14). The `finalize` clause (ln. 6–8) ensures that, no matter how its enclosing trail terminates, the LED will be unconditionally turned off (ln. 7).

The `par/or` composition, which stands for a *parallel-or*, provides an orthogonal abortion mechanism [4] in which its composed trails do not know when and how they are aborted (i.e., abortion is external to them). The finalization mechanism extends orthogonal abortion to also work with activities that use stateful resources from the environment (such as files and network handlers), as we discuss in Section 2.3.

```
1  input void BUTTON;
2  input void RADIO_RECV;
3  par/or do
4      await BUTTON;
5  with
6      finalize with
7          _led(0);
8      end
9      loop do
10         _led(1);
11         await RADIO_RECV;
12         _led(0);
13         await RADIO_RECV;
14     end
15 end
```

Listing 2. A program in Céu that toggles a LED on every radio receive, terminating on a button press in a consistent state.

In Céu, any identifier prefixed with an underscore (e.g., `_led`) is passed unchanged to the underlying C compiler. Therefore, access to C is straightforward and syntactically traceable. To ensure that programs operate under the synchronous hypothesis, the compiler environment should only provide access to C operations that can be assumed to be instantaneous, such as non-blocking I/O and simple accesses to data structures.

2.1 External and Internal Events

Céu defines time as a discrete sequence of reactions to unique external input events. External input events are received from the environment, and each delimits a new logical unit of time that triggers an associated reaction. The life-cycle of a program in Céu can be summarized as follows [21]:

i The program initiates a "boot reaction" in a single trail (parallel constructs may create new trails).
ii Active trails execute until they await or terminate, one after another. This step is called a *reaction chain*, and always runs in bounded time.
iii When all trails are blocked, the program goes idle and the environment takes control.
iv On the occurrence of a new external input event, the environment awakes *all* trails awaiting that event, and the program goes back to step (ii).

A program must react to an event completely before handling the next one. By the synchronous hypothesis, the time the program spends in step (ii) is conceptually zero (in practice, negligible). Hence, from the point of view of the environment, the program is always idle on step (iii). In practice, if a new external input event occurs while a reaction executes, the event is saved on a queue, which effectively schedules it to be processed in a subsequent reaction.

External events and discrete time

The sequential processing of external input events induces a discrete notion of time in Céu, as illustrated in Figure 1. The continuous timeline shows an absolute reference clock with "physical timestamps" for the event occurrences (e.g., event `C` occurs at $17ms521us$). The discrete timeline shows how the same occurring events fit in the logical notion of time of Céu. The boot reaction `boot-0` happens before any input, at program startup. Event `A` "physically" occurs during `boot-0` but, because time is discrete, its corresponding reaction only executes afterwards, at logical instant `A-1`. Similarly, event `B` occurs during `A-1` and its reaction is postponed to execute at `B-2`. Event `C` also occurs during `A-1` but its reaction must also wait for `B-2` to execute and so it is postponed to execute at `C-3`. Event `D` occurs during an idle period and can start immediately at `D-4`. Finally, two instances of event `E` occur during `D-4`; they are handled in the subsequent reactions `E-5` and `E-6`.

Unique input events imply mutually exclusive reactions, which execute atomically and never overlap. Automatic mutual exclusion is a prerequisite for deterministic reactions as we discuss in Section 3.

In practice, the synchronous hypothesis for Céu holds if reactions execute faster than the rate of incoming input events. Otherwise, the program would continuously accumulate delays between physical occurrences and actual reactions for the input events. Considering the context soft real-time systems, such delays and postponed reactions might be tolerated as long as they are infrequent and the application does not take too long to catch up with real time. Note that the synchronous semantics is the norm in typical event-driven systems, such as event dispatching in UI toolkits, game loops in game engines, and clock ticks in embedded systems.

Internal events as subroutines

In Céu, queue-based processing of events applies only to external input events, i.e., events submitted to the program by the environment. Internal events, which are events generated internally by the program via `emit` statements, are processed in a stack-based manner. Internal events provide a fine-grained execution control, and, because of their stack-based processing, can be used to implement a limited form of subroutines, as illustrated in Listing 3:

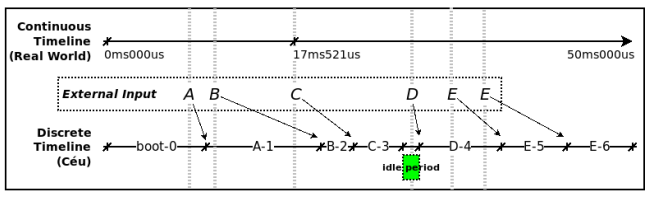

Figure 1. The discrete notion of time in Céu.

```
1  event int* inc;          // declares subroutine "inc"
2  par/or do
3      var int* p;
4      every p in inc do    // implements "inc" through an event iterator
5          *p = *p + 1;
6      end
7  with
8      var int v = 1;
9      emit inc(&v);        // calls "inc"
10     emit inc(&v);        // calls "inc"
11     _assert(v==3);       // asserts result after the two returns
12 end
```

Listing 3. A Céu program with a "subroutine".

In the example, the "subroutine" `inc` is defined as an event iterator (ln. 4–6) that continuously awaits its identifying event (ln. 4), and increments the value passed by reference (ln. 5). A trail in parallel (ln. 8–11) invokes the subroutine through two consecutive `emit` statements (ln. 9–10). Given the stack-based execution for internal events, as the first emit executes, the calling trail pauses (ln. 9), the subroutine awakes (ln. 4), runs its body (yielding `v=2`), iterates, and awaits the next "call" (ln. 4, again). Only after this sequence does the calling trail resumes (ln. 9), makes a new invocation (ln. 10), and passes the assertion test (ln. 11).

Céu also supports nested `emit` invocations, e.g., the body of the subroutine `inc` (ln. 5) could `emit` an event targeting another subroutine, creating a new level in the stack. We can think of the stack as a record of the nested, fine-grained internal reactions that happen inside the same outer reaction to a single external event.

This form of subroutines has a significant limitation though: it cannot express recursion, since an `emit` to itself is always ignored as a running trail cannot be waiting on itself. That being said, it is this very limitation that brings important safety properties to subroutines. First, they are guaranteed to react in bounded time. Second, memory for locals is also bounded, not requiring data stacks.

At first sight, event iteration such as in "`every e do <...> end`" seems to be equivalent to "`loop do await e; <...> end`". However, the `loop` variation would not compile because it does not contain a path to an external input `await` (`e` is an internal event). However, event iterators enforce syntactic restrictions and cannot contain `await` or `break` statements. The absence of `break` guarantees that an iterator never terminates from itself, essentially behaving as a safe blocking point in the program. For this reason, the restriction that execution paths within loops must contain at least one external `await` is extended to alternatively contain an `every` statement.

2.2 Shared-Memory Concurrency

Embedded applications make extensive use of global memory and shared resources, such as through memory-mapped

registers and system calls to device drivers. Hence, an important goal of Céu is to ensure a reliable behavior for programs with concurrent lines of execution sharing memory and interacting with the environment.

```
input void A;
input void B;
var int x = 1;
par/and do
    await A;
    x = x + 1;
with
    await B;
    x = x * 2;
end
```

[a] Accesses to x are never concurrent.

```
1  input void A;
2  // (empty line)
3  var int y = 1;
4  par/and do
5      await A;
6      y = y + 1;
7  with
8      await A;
9      y = y * 2;
10 end
```

[b] Accesses to y are concurrent but deterministic.

Figure 2. Shared-memory concurrency in Céu: example [a] is safe because the trails access x atomically in different reactions; example [b] is unsafe because both trails access y in the same reaction.

In Céu, when multiple trails are active during the same reaction, they are scheduled in lexical order, i.e., in the order they appear in the program source code. For instance, consider the two examples in Figure 2, both defining shared variables (ln. 3), and assigning to them in parallel trails (ln. 6, 9).

In the example [a], the two assignments to x can only execute in reactions to different events A and B, which cannot occur simultaneously by definition (Section 2.1). Hence, for the sequence of events A->B, x becomes 4 ((1+1)*2), while for B->A, x becomes 3 ((1*2)+1).

In the example [b], the two assignments to y are simultaneous because they execute in reaction to the same event A. Since Céu employs lexical order for intra-reaction statements, the execution is still deterministic, and y always becomes 4 ((1+1)*2). However, note that an apparently innocuous change in the order of trails modifies the behavior of the program. To mitigate this threat, Céu performs concurrency checks at compile time to detect conflicting accesses to shared variables: if a variable is written in a trail segment, then a concurrent trail segment cannot read or write to that variable [21]. Nonetheless, the static checks are optional and are not a prerequisite for the deterministic semantics of the language.

2.3 Abortion and Finalization

The par/or of Céu is an orthogonal abortion mechanism because the two sides in the composition need not be tweaked with synchronization primitives or state variables in order to affect each other. In addition, abortion is *immediate* in the sense that it executes atomically in the current micro reaction.

```
par/or do
   var _msg_t msg;
   <...> // prepare msg
   finalize
      _send(&msg);
   with
      _cancel(&msg);
   end
   await SEND_ACK;
with
   <...>
end
//
```

[a] Local resource finalization

```
1  par/or do
2     var _FILE* f;
3     finalize
4        f = _fopen(...);
5     with
6        _fclose(f);
7     end
8     _fwrite(..., f);
9     await A;
10    _fwrite(..., f);
11 with
12    <...>
13 end
```

[b] External resource finalization

Figure 3. Céu enforces the use of finalization to prevent *dangling pointers* for local resources and *memory leaks* for external resources.

Immediate orthogonal abortion is a distinctive feature of synchronous languages and cannot be expressed effectively in traditional (asynchronous) multi-threaded languages [4, 17].

However, aborting lines of execution that deal with external resources may lead to inconsistencies. For this reason, Céu provides a finalize construct to unconditionally execute a series of statements even if the enclosing block is externally aborted.

Céu also enforces the use of finalize for system calls that deal with pointers representing resources, as illustrated in the two examples of Figure 3:

- If Céu **passes** a pointer to a system call (ln. [a]:5), the pointer represents a **local** resource (ln. [a]:2) that requires finalization (ln. [a]:7).
- If Céu **receives** a pointer from a system call return (ln. [b]:4), the pointer represents an **external** resource (ln. [b]:2) that requires finalization (ln. [b]:6).

Céu tracks the interaction of system calls with pointers and requires finalization clauses to accompany them. In the example in Figure 3.a, the local variable msg (ln. 2) is an internal resource passed as a pointer to _send (ln. 5), which is an asynchronous call that transmits the buffer in the background. If the block aborts (ln. 11) before receiving an acknowledge from the environment (ln. 9), the local msg goes out of scope and the external transmission now holds a *dangling pointer*. The finalization ensures that the transmission also aborts (ln. 7). In the example in Figure 3.b, the call to _fopen (ln. 4) returns an external file resource as a pointer. If the block aborts (ln. 12) during the await A (ln. 9), the file remains open as a *memory leak*. The finalization ensures that the

file closes properly (ln. 6). In both cases, the code does not compile without the `finalize` construct.[1]

The finalization mechanism of Céu is fundamental to preserve the orthogonality of the `par/or` construct since the clean up code is encapsulated in the aborted trail itself.

3 Formal Semantics

In this section, we introduce a reduced syntax for Céu and propose an operational semantics to formally describe the language. We describe a small synchronous kernel highlighting the peculiarities of Céu, in particular, the stack-based execution for internal events. For the sake of simplicity, we focus on the control aspects of the language, leaving out side-effects and system calls (which behave like in conventional imperative languages).

3.1 Abstract Syntax

The grammar below defines the syntax of a subset of Céu that is sufficient to describe all semantic peculiarities of the language.

p ::=	$\texttt{mem}(id)$	*any memory access to "id"*
	$\texttt{await}_{ext}(id)$	*await external event "id"*
	$\texttt{await}_{int}(id)$	*await internal event "id"*
	$\texttt{emit}_{int}(id)$	*emit internal event "id"*
	`break`	*loop escape*
	`if` b `then` p_1 `else` p_2	*conditional*
	$p1$ `;` $p2$	*sequence*
	`loop` p_1	*repetition*
	`every` id p_1	*event iteration*
	p_1 `and` p_2	*par/and*
	p_2 `or` p_2	*par/or*
	`fin` p	*finalization*
	p_1 `@loop` p_2	*unwinded loop*
	p_1 `@and` p_2	*unwinded par/and*
	p_1 `@or` p_2	*unwinded par/or*
	`@canrun`(n)	*can run on stack level n*
	`@nop`	*terminated program*

The $\texttt{mem}(id)$ primitive represents all accesses, assignments, and system calls that affect a memory location identified by id. According to the synchronous hypothesis of Céu, `mem` expressions are considered to be atomic and instantaneous. 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.

We assume that `mem`, $\texttt{await}_{ext}$, and $\texttt{await}_{int}$ and $\texttt{emit}_{int}$ expressions do not share identifiers: any identifier is either a variable, an external event, or an internal event.

Most expressions in the abstract language are mapped to their counterparts in the concrete language. The exceptions are the finalization block `fin` p and the `@`-expressions, which are internal expressions that result from the expansion of awaits, emits, and loops by the transition rules to be discussed.

Regarding other mismatches between the concrete and abstract languages, the concrete `await` and `emit` primitives support communication of values between them, e.g., an "`emit a(10)`" awakes a "`v=await a`" setting variable `v` to 10. To reproduce this functionality in the formal semantics, we can use a shared variable to hold the value of an $\texttt{emit}_{int}$ and access it after the corresponding $\texttt{await}_{int}$. Also, a "`finalize` A `with` B `end;` C" in the concrete language is equivalent to "A; ((`fin` B) `or` C)" in the abstract language. In the concrete language, A and C execute in sequence, and the finalization code B is implicitly suspended waiting for C termination. In the abstract language, "`fin` B" suspends forever when reached (it is an awaiting expression that never awakes). Hence, we need an explicit `or` to execute C in parallel, whose termination aborts "`fin` B", which finally causes B to execute (by the semantic rules to be discussed).

3.2 Operational Semantics

The core of our semantics describes how a program reacts to a single external input event, i.e., starting from an input event, how the program behaves and becomes idle again to proceed to a subsequent reaction. We use a set of small-step operational rules, which are built in such a way that at most one transition is possible at any time, resulting in deterministic reactions. The transition rules map a triple with a program p, a stack level n, and an emitted event e to a modified triple as follows:

$$\langle p, n, e\rangle \longrightarrow \langle p', n', e'\rangle\,,$$

where $p, p' \in \mathbf{P}$ are abstract-language programs, $n, n' \in \mathbf{N}$ are nonnegative integers representing the current stack level, and $e, e' \in \mathbf{E} \cup \{\varepsilon\}$ are the events emitted before and after the transition (both possibly the empty event ε).

We will refer to the triples on the left-hand and right-hand sides of symbol $\longrightarrow$ as *descriptions* (denoted δ). The triple on the left-hand side of symbol $\longrightarrow$ is called the *input description*, and the triple on its right-hand side is called the *output description*.

At the beginning of a reaction to an input event id, the input description is initialized with stack level 0 ($n = 0$) and with the emitted event ($e = id$). At the end of a reaction, after an arbitrary but finite number of transitions, the last output description will block with a (possibly) modified program p', at stack level 0, and with no event emitted (ε):

$$\langle p, 0, e\rangle \xrightarrow{*} \langle p', 0, \varepsilon\rangle\,.$$

We distinguish between two types of transition rules: *outermost* transitions $\xrightarrow[out]{}$ and *nested* transitions $\xrightarrow[nst]{}$.

[1] The compiler only forces the programmer to write the finalization clause, but cannot check if it actually handles the resource properly.

Outermost transitions

The $\xrightarrow[out]{}$ rules **push** and **pop** are non-recursive definitions that only apply to the program as a whole and manipulate the stack level:

$$\frac{e \neq \varepsilon}{\langle p, n, e\rangle \xrightarrow[out]{} \langle bcast(p, e), n+1, \varepsilon\rangle} \quad \textbf{(push)}$$

$$\frac{n > 0 \qquad p = \texttt{@nop} \vee isblocked(p, n)}{\langle p, n, \varepsilon\rangle \xrightarrow[out]{} \langle p, n-1, \varepsilon\rangle} \quad \textbf{(pop)}$$

Rule **push** matches whenever there is an emitted event in the input description, and instantly broadcasts the event to the program, which means (a) awaking active $\texttt{await}_{ext}$ or $\texttt{await}_{int}$ expressions altogether (see function *bcast* in Figure 4), (b) creating a nested reaction by increasing the stack level, and, at the same time, and (c) consuming the event (e becomes ε). Rule **push** is the only rule in the semantics that matches an emitted event and also immediately consumes it.

Rule **pop** only decreases the stack level, not affecting the program, and only applies if the program is blocked (see function *isblocked* in Figure 4). This condition ensures that an $\texttt{emit}_{int}$ only resumes after its internal reaction completes and blocks, as discussed in Section 2.1.

At the beginning of the reaction, an external event is emitted, which will trigger rule **push**, which will immediately raise the stack level to 1. At the end of the reaction, the program will block or terminate and successive applications of rule **pop** will eventually lead to a description containing this same program at stack level 0. (Rule **pop** is the only rule that decreases the stack level.)

Nested transitions

The $\xrightarrow[nst]{}$ rules are recursive definitions with the following general format:

$$\langle p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle .$$

Nested transitions do not affect the stack level and never have an emitted event as a precondition. The distinction between $\xrightarrow[out]{}$ and $\xrightarrow[nst]{}$ prevents rules **push** and **pop** from matching and, consequently, from inadvertently modifying the current stack level before the nested reaction is complete.

A complete reaction consists of the following series of transitions:

$$\langle p, 0, e_{ext}\rangle \xrightarrow[out]{push} \langle p_1, 1, \varepsilon\rangle \left[\xrightarrow[nst]{}^{*} \xrightarrow[out]{} \right]^{*} \xrightarrow[nst]{}^{*} \xrightarrow[out]{pop} \langle p', 0, \varepsilon\rangle .$$

First, a $\xrightarrow[out]{push}$ starts a nested reaction at level 1. Then, a series of alternations between zero or more $\xrightarrow[nst]{}$ transitions (nested reactions) and a single $\xrightarrow[out]{}$ transition (stack operation) takes place. Finally, a last $\xrightarrow[out]{pop}$ transition decrements the stack level to 0 and terminates the reaction.

The $\xrightarrow[nst]{}$ transition rules for atomic expressions are defined as follows:

$$\langle \texttt{mem}(id), n, \varepsilon\rangle \xrightarrow[nst]{} \langle \texttt{@nop}, n, \varepsilon\rangle \quad \textbf{(mem)}$$

$$\langle \texttt{emit}_{int}(id), n, \varepsilon\rangle \xrightarrow[nst]{} \langle \texttt{@canrun}(n), n, id\rangle \quad \textbf{(emit-int)}$$

$$\langle \texttt{@canrun}(n), n, \varepsilon\rangle \xrightarrow[nst]{} \langle \texttt{@nop}, n, \varepsilon\rangle \quad \textbf{(can-run)}$$

A `mem` operation becomes a `@nop` which indicates the memory access (rule **mem**). An $\texttt{emit}_{int}(id)$ generates an event id and transits to a $\texttt{@canrun}(n)$ which can only resume at level n (rule **emit-int**). Since all $\xrightarrow[nst]{}$ rules can only transit with $e = \varepsilon$, an $\texttt{emit}_{int}$ causes rule **push** to execute at the outer level, creating a new level $n+1$ on the stack. Also, with the new stack level, the resulting $\texttt{@canrun}(n)$ itself cannot transit (rule **can-run**), providing the desired stack-based semantics for internal events.

Proceeding to compound expressions, the rules for conditionals and sequences are straightforward:

$$\frac{eval(\texttt{mem}(id))}{\langle \texttt{if mem}(id)\ \texttt{then}\ p\ \texttt{else}\ q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p, n, \varepsilon\rangle} \quad \textbf{(if-true)}$$

$$\frac{\neg\ eval(\texttt{mem}(id))}{\langle \texttt{if mem}(id)\ \texttt{then}\ p\ \texttt{else}\ q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle q, n, \varepsilon\rangle} \quad \textbf{(if-false)}$$

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

$$\langle \texttt{@nop};\ q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle q, n, \varepsilon\rangle \quad \textbf{(seq-nop)}$$

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

Given that our semantics focuses on control, rules **if-true** and **if-false** are the only to query `mem` expressions. Function *eval* evaluates a given `mem` expression.

The rules for loops are analogous to sequences, but use "`@`" as separators to properly bind breaks to their enclosing loops:

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

$$\frac{\langle p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle}{\langle p\ \texttt{@loop}\ p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p'\ \texttt{@loop}\ p, n, e\rangle} \quad \textbf{(loop-adv)}$$

$$\langle \texttt{@nop @loop}\ p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \texttt{loop}\ p, n, \varepsilon\rangle \quad \textbf{(loop-nop)}$$

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

When a program 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 a `@nop` is reached. 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 semantic rules for `and` and `or` compositions force transitions on their left branches p to occur before their

right branches q:

$$\langle p \texttt{ and } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p \texttt{ and } (\texttt{@canrun}(n); q), n, \varepsilon\rangle \quad \textbf{(and-expd)}$$

$$\frac{\langle p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle}{\langle p \texttt{ @and } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p' \texttt{ @and } q, n, e\rangle} \quad \textbf{(and-adv1)}$$

$$\frac{\mathit{isblocked}(p, n) \qquad \langle q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle q', n, e\rangle}{\langle p \texttt{ @and } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p \texttt{ @and } q', n, e\rangle} \quad \textbf{(and-adv2)}$$

$$\langle p \texttt{ or } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p \texttt{ or } (\texttt{@canrun}(n); q), n, \varepsilon\rangle \quad \textbf{(or-expd)}$$

$$\frac{\langle p, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle}{\langle p \texttt{ @or } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p' \texttt{ @or } q, n, e\rangle} \quad \textbf{(or-adv1)}$$

$$\frac{\mathit{isblocked}(p, n) \qquad \langle q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle q', n, e\rangle}{\langle p \texttt{ @or } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p \texttt{ @or } q', n, e\rangle} \quad \textbf{(or-adv2)}$$

Rules **and-expd** and **or-expd** insert a $\texttt{@canrun}(n)$ at the beginning of the right branch. This ensures that any $\texttt{emit}_{int}$ on the left branch, which transits to a $\texttt{@canrun}(n)$, still resumes before the right branch starts. The deterministic behavior of the semantics relies on the *isblocked* predicate (see Figure 4) which appears in rules **and-adv2** and **or-adv2**. These rules require the left branch p to be blocked for the right branch to transition from q to q'.

In a parallel `@and`, if one of the sides terminates, the composition is simply substituted by the other side (rules **and-nop1** and **and-nop2** below). In a parallel `@or`, however, if one of the sides terminates, the whole composition terminates and function *clear* is used to properly finalize the aborted side (rules **or-nop1** and **or-nop2**).

$$\langle \texttt{@nop @and } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle q, n, \varepsilon\rangle \quad \textbf{(and-nop1)}$$

$$\frac{\mathit{isblocked}(p, n)}{\langle p \texttt{ @and @nop}, n, \varepsilon\rangle \xrightarrow[nst]{} \langle p, n, \varepsilon\rangle} \quad \textbf{(and-nop2)}$$

$$\langle \texttt{@nop @or } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(q), n, \varepsilon\rangle \quad \textbf{(or-nop1)}$$

$$\frac{\mathit{isblocked}(p, n)}{\langle p \texttt{ @or @nop}, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(p), n, \varepsilon\rangle} \quad \textbf{(or-nop2)}$$

The *clear* function (see Figure 4) concatenates all active `fin` bodies of the side being aborted, so that they execute before the composition rejoins. Note that there are no transition rules for `fin` expressions. This is because once reached, a `fin` expression halts and will only execute when it is aborted by a parallel trail and is expanded by the *clear* function. Note also that there is a syntactic restriction that postulates that `fin` bodies cannot contain awaiting expressions ($\texttt{await}_{ext}$, $\texttt{await}_{int}$, `every`, or `fin`), i.e., the result of a *clear* call is guaranteed to execute entirely within a reaction.

Finally, a `break` in one of the sides in parallel escapes the closest enclosing `loop`, properly aborting the other side by applying the *clear* function:

$$\langle \texttt{break @and } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(q); \texttt{break}, n, \varepsilon\rangle \quad \textbf{(and-brk1)}$$

$$\frac{\mathit{isblocked}(p, n)}{\langle p \texttt{ @and break}, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(p); \texttt{break}, n, \varepsilon\rangle} \quad \textbf{(and-brk2)}$$

$$\langle \texttt{break @or } q, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(q); \texttt{break}, n, \varepsilon\rangle \quad \textbf{(or-brk1)}$$

$$\frac{\mathit{isblocked}(p, n)}{\langle p \texttt{ @or break}, n, \varepsilon\rangle \xrightarrow[nst]{} \langle \mathit{clear}(p); \texttt{break}, n, \varepsilon\rangle} \quad \textbf{(or-brk2)}$$

A reaction eventually blocks in $\texttt{await}_{ext}$, $\texttt{await}_{int}$, `every`, `fin`, and `@canrun` expressions in parallel trails. If no trails are blocked in `@canrun` expressions, it means that the program cannot advance in the current reaction. However, `@canrun` expressions can still resume in lower stack indexes and will eventually resume in the current reaction (see rule **pop**).

3.3 Determinism, Termination, and Memory Bounds

- informal discussion

Determinism

The proof for determinism relies on the fact all semantic rules are mutually exclusive, i.e., their preconditions are unique in the set of rules. This can be verified by direct inspection of rules.

Rule **push** is the only one with $e \neq \epsilon$ as a precondition, and is trivially mutually exclusive with all other rules.

Rule **pop** either has $p = @nop$ or $\mathit{isblocked}(n, p)$ as preconditions. Note that rule **pop** only applies syntactically to top-level transitions. For instance, it can never match $\xrightarrow[nst]{}$ rules for subprograms as in rule **seq-adv**. Hence, for the first case, rule **pop** only applies, and is the only one to apply, to *nop* as the whole program (i.e., a *nop* not surrounded by other expressions, such as in rule **seq-nop**). For the second case, we need to show that given $\langle p, n, \epsilon\rangle$, no $\xrightarrow[nst]{}$ transitions apply with $\mathit{isblocked}(n, p)$ and vice versa. Except for *@canrun*, there are no $\xrightarrow[nst]{}$ transitions for the other blocking expressions ($\mathit{awaitExt}$, $\mathit{awaitInt}$, *every*, and fin). However, considering the precondition $\langle p, n, \epsilon\rangle$, $\mathit{isblocked}(n, @canrun(n))$ is false. Hence, given the preconditions for rule **pop**, no $\xrightarrow[nst]{}$ transitions can occur. Conversely, if a $\xrightarrow[nst]{}$ transition is possible, then $\mathit{isblocked}(n, p)$ must be false. Again, except for *@canrun*, all other transitions do not involve blocking expressions, hence, for these transitions, $\mathit{isblocked}(n, p)$ must be false. For rule **canrun**, a transition can only occur if the current stack level matches $@canrun(n)$. In this case, $\mathit{isblocked}(n, @canrun(n))$ is false.

Finally, we need to show that $\xrightarrow[nst]{}$ transitions are mutually exclusive among themselves. Note that most rules have unique syntactic prefixes, e.g., $(@nop\ @and\ q)$ (rule **and-nop1**) is trivially mutually exclusive with $(@nop\ @loop\ p)$

(i) Function *bcast*:

$$
\begin{aligned}
bcast(\texttt{await}_{ext}(e), e) &= \texttt{@nop} \\
bcast(\texttt{await}_{int}(e), e) &= \texttt{@nop} \\
bcast(\texttt{every}\ e\ p, e) &= p;\ \texttt{every}\ e\ p \\
bcast(\texttt{@canrun}(n), e) &= \texttt{@canrun}(n) \\
bcast(\texttt{fin}\ p, e) &= \texttt{fin}\ p \\
bcast(p;\ q) &= bcast(p, e);\ q \\
bcast(p\ \texttt{@loop}\ q, e) &= bcast(p, e)\ \texttt{@loop}\ q \\
bcast(p\ \texttt{@and}\ q, e) &= bcast(p, e)\ \texttt{@and}\ bcast(q, e) \\
bcast(p\ \texttt{@or}\ q, e) &= bcast(p, e)\ \texttt{@or}\ bcast(q, e) \\
bcast(\_, e) &= \bot\ (\texttt{mem}, \texttt{emit}_{int}, \texttt{break}, \\
&\qquad \texttt{if then else}, \texttt{loop}, \texttt{and}, \texttt{or}, \texttt{@nop})
\end{aligned}
$$

(ii) Predicate *isblocked*:

$$
\begin{aligned}
isblocked(\texttt{await}_{ext}(e), n) &= true \\
isblocked(\texttt{await}_{int}(e), n) &= true \\
isblocked(\texttt{every}\ e\ p, n) &= true \\
isblocked(\texttt{@canrun}(m), n) &= (n > m) \\
isblocked(\texttt{fin}\ p, n) &= true \\
isblocked(p;\ q, n) &= isblocked(p, n) \\
isblocked(p\ \texttt{@loop}\ q, n) &= isblocked(p, n) \\
isblocked(p\ \texttt{@and}\ q, n) &= isblocked(p, n) \wedge isblocked(q, n) \\
isblocked(p\ \texttt{@or}\ q, n) &= isblocked(p, n) \wedge isblocked(q, n) \\
isblocked(\_, n) &= false\ (\texttt{mem}, \texttt{emit}_{int}, \texttt{break}, \\
&\qquad \texttt{if then else}, \texttt{loop}, \texttt{and}, \texttt{or}, \texttt{@nop})
\end{aligned}
$$

(iii) Function *clear*:

$$
\begin{aligned}
clear(\texttt{await}_{ext}(e)) &= \texttt{@nop} \\
clear(\texttt{await}_{int}(e)) &= \texttt{@nop} \\
clear(\texttt{every}\ e\ p) &= \texttt{@nop} \\
clear(\texttt{@canrun}(n)) &= \texttt{@nop} \\
clear(\texttt{fin}\ p) &= p \\
clear(p;\ q) &= clear(p) \\
clear(p\ \texttt{@loop}\ q) &= clear(p) \\
clear(p\ \texttt{@and}\ q) &= clear(p);\ clear(q) \\
clear(p\ \texttt{@or}\ q) &= clear(p);\ clear(q) \\
clear(\_) &= \bot\ (\texttt{mem}, \texttt{emit}_{int}, \texttt{break}, \\
&\qquad \texttt{if then else}, \texttt{loop}, \texttt{and}, \texttt{or}, \texttt{@nop})
\end{aligned}
$$

Figure 4. (i) Function *bcast* awakes awaiting trails matching the event by converting $\texttt{await}_{ext}$ and $\texttt{await}_{int}$ to `@nop` expressions, and by unwinding `every` expressions. (ii) Predicate *isblocked* is true only if all branches in parallel are blocked waiting for events, for finalization clauses, or for certain stack levels. (iii) Function *clear* extracts `fin` expressions in parallel and put their bodies in sequence.

(rule **or-nop1**). The only exceptions are rules **and-adv1** vs. **and-adv2**, and **or-adv1** vs. **or-adv2**. In both cases, we need to show that if the left branch can advance, then it cannot be blocked and vice-versa, i.e., that $\langle p, n, \epsilon \rangle \xrightarrow[nst]{} \langle p', n, e \rangle$ and $isblocked(n, p)$ are mutually exclusive, which is exactly the same reasoning for rule **pop** above.

Termination

- there is always a possible transition until n=0
  every cannot restart itself - break disallowed - emit ignored

Memory Bounds

- program is finite - lexical scope - no heap allocation - no code reentrancy - reexecution only due to loops - loop reuse nested vars -

4 Related Work

Céu was strongly influenced by Esterel but they differ in the most fundamental aspect of the notion of time [21]. Esterel defines time as a discrete sequence of logical unit instants or "ticks". At each tick, the program reacts to an arbitrary number of simultaneous input events from the environment. The presence of multiple inputs requires careful static analysis to detect and reject programs with *causality cycles* and *schizophrenia problems* [5, 8, 12, 23–26, 30]. In contrast, Céu defines time as a discrete sequence of reactions to unique input events. In the formal semantics, ...

Francisco: como isso aparece na semantica

... Céu also rejects some syntactically correct programs to avoid infinite execution, but with simple restrictions in the abstract syntax tree.

Another distinction is that, in Esterel, the behavior of internal and external events is equivalent, while in Céu internal events introduce stack-based micro reactions within external reactions, providing more fine-grained control for intra-reaction execution. In the formal semantics, ...

Francisco: como isso aparece na semantica

... Some variants of the Statecharts synchronous visual language also distinguish internal from external events [28]. In Statemate [14], *"reactions to external and internal events (...) can be sensed only after completion of the step"*, implying queue-based execution. In Stateflow [13], *"the receiving state (of the event) acts here as a function"*, which is similar to Céu's stack-based execution. We are not aware of formalizations for these ideas for a deeper comparison with Céu.

Like other synchronous languages (*Reactive C* [7], *Protothreads* [11], *SOL* [15], *SC* [29], and *PRET-C* [2]), Céu relies on deterministic scheduling to preserve intra-reaction determinism. In addition, it also performs concurrency checks to detect trails that, when reordered, change the observable behavior of the program, i.e., trails that actually rely on deterministic scheduling [21]. Esterel is only deterministic with respect to external behavior: *"the same sequence of inputs always produces the same sequence of outputs"* [6]. However, the execution order for operations within a reaction is non-deterministic: *"if there is no control dependency, as in* `(call f1() || call f2())`*, the order is unspecified and it would be an error to rely on it"* [6]. For this reason, Esterel, does not support shared-memory concurrency: *"if a variable*

is written by some thread, then it can neither be read nor be written by concurrent threads" [6].

Esterel describes a finalization mechanism in a standardization proposal [27] that is similar to Céu's. However, we are not aware of an open implementation or a formal semantics for a deeper comparison.

Francisco: outras linguagens sincronas

Francisco: outras linguagens deterministicas

Francisco: outras linguagens com terminacao

5 Conclusion

Francisco: TODO

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A Proofs