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 internal determinism and time-bounded reactions to the environment. In this work, we present a small-step structural operational semantics for Céu and a proof that reactions are deterministic and always terminate: 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 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

ACM Reference Format:
Anonymous Author(s). 1997. A Deterministic and Terminating Semantics for the Synchronous Programming Language Céu. In *Proceedings of ACM Woodstock conference (WOODSTOCK'97).* ACM, New York, NY, USA, 10 pages. https://doi.org/10.475/123_4

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.

WOODSTOCK'97, July 1997, El Paso, Texas USA

ACM ISBN 123-4567-24-567/08/06…$15.00
https://doi.org/10.475/123_4

Structured reactive programming let developers write code in direct/sequential style, recovering from the inversion of control imposed by event-driven execution [1, 16, 18]. Synchronous languages offer a simple run-to-completion model of execution that enable 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], and as an alternative language in an undergraduate-level course on embedded systems for the past 6 years.

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:

- Stack-based execution for internal events, which provides a limited form of coroutines.
- Fine-grained, intra-reaction deterministic execution, which allows programs to safely share memory.
- Finalization mechanism for abortion of lines of execution, which safely release external resources.
- First-class synchronized timers.

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 in accordance to the

synchronous hypothesis [10]. Céu provides an **await** statement which is the only that actually "consumes" time. An **await** statement 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 [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 external input event
event ⟨type⟩ ⟨id⟩;          // declares internal event
var   ⟨type⟩ ⟨id⟩;          // declares variable

// Event handling
⟨id⟩ = await ⟨id⟩;          // awaits event and assigns received value
⟨id⟩ = await ⟨time⟩;        // awaits time and assigns delayed delta
emit ⟨id⟩(⟨exp⟩);           // emits event passing 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 value to variable
_⟨id⟩(⟨exps⟩)               // calls C function (id starts with '_')
```

Listing 1. The concrete syntax of Céu.

Listing 2 shows a complete example in Céu that blinks a LED with a frequency of 1 second, terminating with a button press always with the LED off. The implementation first declares the BUTTON as an input event (ln. 1). 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. 3), and an endless loop that blinks the LED on and off (ln. 8–13). The **finalize** clause (ln. 5–7) ensures that, no matter how its enclosing trail terminates, the LED will be unconditionally turned off (ln. 6).

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). This is possible to do safely in synchronous languages due to the accurate control of concurrent activities, i.e., in between every reaction, the whole system is idle and consistent [4]. 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 2.4.

Francisco: First-class timers.

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

Listing 2. A program in Céu that blinks a LED every second, 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 (i).

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. In the soft real-time systems targeted by Céu (e.g., sensor networks, multimedia systems, interactive games, etc.) such delay and postponed reactions might be tolerated by users 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.

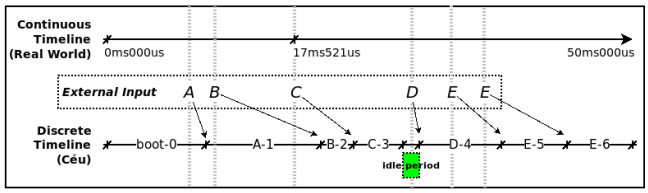

Figure 1. The discrete notion of time in Céu.

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:

```
1  event int* inc;          // declares subroutine "inc"
2  par/or do
3      var int* p;
4      every p in inc do    // implements subroutine with 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 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 for internal events. For instance, the body of the subroutine `inc` in Listing 3 could **`emit`** another internal event after awaking (ln. 4), 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 guaranteed to react in bounded time. Second, memory for locals is also bounded, not requiring data stacks.

At first sight, an event iterator for event `A` seems like a syntactic sugar for a **`loop`** followed by and **`await`** `A`. However, event iterators have an important restriction to enforce reaction termination, as we discuss in Section 3: they cannot contain **`break`** statements.

2.2 First-Class Timers

2.3 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  //
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 do not affect the semantics of the language.

```
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.

2.4 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. 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 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.

2.5 Determinism, Termination, and Memory Bounds

3 Formal Semantics

In this section, we introduce a reduced syntax of 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

```
                                  // primary expressions
  p ::= mem(id)                   (any memory access to `id')
      | awaitExt(id)              (await external event `id')
      | awaitInt(id)              (await internal event `id')
      | emitInt(id)               (emit internal event `id')
      | break                     (loop escape)
                                  // compound expressions
      | if mem(id) then p else p  (conditional)
      | p ; p                     (sequence)
      | loop p                    (repetition)
      | p and p                   (par/and)
      | p or p                    (par/or)
      | fin p                     (finalization)
                                  // derived by semantic rules
      | p @loop p                 (unwinded loop)
      | p @and q                  (unwinded par/and)
      | p @or q                   (unwinded par/or)
      | @canrun(n)                (can run on stack level `n')
      | @nop                      (terminated expression)
```

Listing 4. Reduced syntax of Céu.

Listing 4 shows the syntax for a subset of Céu that is sufficient to describe all semantic peculiarities of the language. Except for fin and the expressions used internally by the semantics, which are prefixed with a character @, all other expressions are equivalent to their counterparts in the concrete language.

The *mem*(*id*) primitive represents all accesses, assignments, system calls, and output events 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. Note that *mem*, *awaitExt*, and *awaitInt* / *emitInt* expressions do not share identifiers, i.e., an identifier is either a variable, an external event, or an internal event.

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

3.2 Operational Semantics

The core of our semantics describes how a program reacts to a single external input event, i.e., starting from the input event, how the program behaves and becomes idle again to proceed to the 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:

$$\langle p, n, e\rangle \rightarrow \langle p', n', e'\rangle \qquad \textbf{(rule-general)}$$

where

$$\begin{aligned} &p, p' \in P && (\textit{program as described in Listing 4})\\ &n, n' \in \mathbb{N} && (\textit{current stack level})\\ &e, e' \in \mathbb{E} \cup \{\epsilon\} && (\textit{emitted event, possibly none}) \end{aligned}$$

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

$$\langle p, 0, ext\rangle \xrightarrow{*} \langle p', 0, \epsilon\rangle$$

We also define two transition rule subtypes $\xrightarrow[out]{}$ (for *outermost*) and $\xrightarrow[nst]{}$ (for *nested*).

The $\xrightarrow[out]{}$ rules **push** and **pop** are non-recursive definitions that manipulate the stack level as follows:

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

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

Rule **push** matches whenever there is an emitted event in the triple, and instantly broadcasts the event to the program, which means (a) awaking active **`await`** expressions altogether (see $bcast(p)$ in Figure 4), (b) creating a nested reaction by increasing the stack level, (c) and, at the same time, consuming the event (e becomes ϵ). Note that rule **push** is the only one in the semantics that matches an emitted event

and also immediately consumes it. The rule **pop** only decreases the stack level, not affecting the program, and does not apply if the program is not blocked (see $isblocked(n, p)$ in Figure 5). This condition ensures that an **`emit`** only resumes after its internal reaction completes, as discussed in Section 2.1.

Note that at the beginning of a reaction, an event ext is emitted, which will trigger rule **push**, which will immediately raise the stack level to 1. Since rule **pop** is the only to decrease the stack level and only applies to a blocked or terminated program, the semantics guarantees that a reaction only terminates with a blocked program at stack level 0.

The $\xrightarrow[nst]{}$ rules are recursive definitions but do not affect the stack level and never have an emitted event as a precondition:

$$\langle p, n, \epsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle \qquad \textbf{(rule-inner)}$$

The distinction between $\xrightarrow[out]{}$ and $\xrightarrow[nst]{}$ prevents rules **push** and **pop** to match and inadvertently modify the current stack level before completing a nested reaction. A complete reaction behaves as follows:

$$a) \quad \langle p, 0, ext\rangle \xrightarrow[out]{push} \langle q, 1, \epsilon\rangle$$

$$b) \quad [\xrightarrow[in]{*} \langle r, i, e\rangle \xrightarrow[out]{} \langle s, j, \epsilon\rangle\ ]*$$

$$c) \quad \xrightarrow[in]{*} \langle t, k, \epsilon\rangle \xrightarrow[out]{pop} \langle u, 0, \epsilon\rangle$$

First, a $\xrightarrow[out]{push}$ starts a nested reaction at level 1 (case a). Then, a series of alternations between $\xrightarrow[nst]{}$ transitions followed by a single $\xrightarrow[out]{}$ transition represent nested reactions and stack operations (case b). Finally, at some point, a $\xrightarrow[out]{pop}$ lowers the stack level to 0 and terminates the reaction.

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

$$\langle mem(id), n, \epsilon\rangle \xrightarrow[nst]{} \langle @nop, n, \epsilon\rangle \qquad \textbf{(mem)}$$

$$\langle emit(id), n, \epsilon\rangle \xrightarrow[nst]{} \langle @canrun(n), n, id\rangle \qquad \textbf{(emitInt)}$$

$$\langle @canrun(n), n, \epsilon\rangle \xrightarrow[nst]{} \langle @nop, n, \epsilon\rangle \qquad \textbf{(canrun)}$$

A mem operation becomes a nop which indicates termination (rule **mem**). An $emitInt(id)$ generates an event id and transits to a $@canrun(n)$ which can only resume at level n (rule **emitInt**). Since nested rules cannot transit with $e \neq \epsilon$, this rule will cause 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 $@canrun(n)$ itself cannot transit, providing the desired stack-based semantics for internal events.

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

$$\frac{val(id) \neq 0}{\langle (if\ mem(id)\ then\ p\ else\ q), n, \epsilon\rangle \xrightarrow[nst]{} \langle p, n, \epsilon\rangle} \qquad \textbf{(if-true)}$$

$$\frac{val(id, n) = 0}{\langle (if\ mem(id)\ then\ p\ else\ q), n, \epsilon\rangle \xrightarrow[nst]{} \langle q, n, \epsilon\rangle} \qquad \textbf{(if-false)}$$

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

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

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

Given that our semantics focuses on control, rules **if-true** and **if-false** are the only to query mem expressions. Function val receives a memory identifier and returns the current memory value.

As determined for nested rules, compound expressions also can only have ϵ as a precondition and they never modify n. However, they can still emit an event to nest another reaction. For instance, in rule **seq-adv**, if the sub-expression p emits event e, the whole composition also emits e.

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

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

$$\frac{\langle p, n, \epsilon\rangle \xrightarrow[nst]{} \langle p', n, e\rangle}{\langle (p\ @loop\ q), n, \epsilon\rangle \xrightarrow[nst]{} \langle (p'\ @loop\ q), n, e\rangle} \qquad \textbf{(loop-adv)}$$

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

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

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 they reach 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 $@nop$.

Proceeding to parallel compositions, the semantic rules for *and* and *or* always force transitions on their left branches p to occur before their right branches q:

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

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

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

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

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

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

Rules **and-expd** and **or-expd** insert a $@canrun(n)$ at the beginning of the right branch. This ensures that an *emitInt* on the left branch, which would transit to a $@canrun(n)$, still resumes before the right branch starts. The deterministic behavior of the semantics relies on the *isblocked* predicate (Figure 5) which appears in rules **and-adv2** and **or-adv2**. These rules require the left branch p to be blocked in order to allow the right branch transition from q to q'.

For a parallel *@and*, if one of the sides terminates, the composition is simply substituted by the other side (rules **and-nop1** and **and-nop2**. For a parallel *or*, if one of the sides terminates, the whole composition terminates, also applying the *clear* function to properly finalize the aborted side (rules **or-nop1** and **or-nop2**):

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

$$\langle (p \ @and \ @nop), n, \epsilon \rangle \xrightarrow[nst]{} \langle p, n, \epsilon \rangle \quad \textbf{(and-nop2)}$$

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

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

The *clear* function (Figure 6) 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 trail in parallel and is expanded by the *clear* function. Note also that there is a syntactic restriction that fin bodies cannot contain awaiting expressions (*awaitExt*, *awaitInt*, and fin), i.e., they are guaranteed to execute entirely within a reaction.

$$\begin{aligned}
bcast(e, awaitExt(e)) &= @nop \\
bcast(e, awaitInt(e)) &= @nop \\
bcast(e, @canrun(n)) &= @canrun(n) \\
bcast(e, fin \ p) &= fin \ p \\
bcast(e, p \ ; \ q) &= bcast(e, p) \ ; \ q \\
bcast(e, p \ @loop \ q) &= bcast(e, p) \ @loop \ q \\
bcast(e, p \ @and \ q) &= bcast(e, p) \ @and \ bcast(e, q) \\
bcast(e, p \ @or \ q) &= bcast(e, p) \ @or \ bcast(e, q) \\
bcast(e, _) &= \bot \quad (mem, emitInt, break, if, \\
&\qquad loop, and, or, @nop)
\end{aligned}$$

Figure 4. The function *bcast* awakes awaiting trails matching the event by converting `awaitExt` and `awaitInt` to `@nop` expressions.

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:

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

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

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

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

A reaction eventually blocks in *awaitExt*, *awaitInt*, 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 Concrete Language Mapping

Most statements from Céu ("concrete Céu") map directly to those presented in the reduced syntax in Figure 4 ("abstract Céu"). For instance, the **`if`** in the concrete language behaves exactly like the if in the formal semantics. However,

$$
\begin{aligned}
isblocked(n,\ awaitExt(id)) &= true \\
isblocked(n,\ awaitInt(id)) &= true \\
isblocked(n,\ @canrun(m)) &= (n > m) \\
isblocked(n,\ fin\ p) &= true \\
isblocked(n,\ p\ ;\ q) &= isblocked(n,p) \\
isblocked(n,\ p\ @loop\ q) &= isblocked(n,p) \\
isblocked(n,\ p\ @and\ q) &= isblocked(n,p) \wedge isblocked(n,q) \\
isblocked(n,\ p\ @or\ q) &= isblocked(n,p) \wedge isblocked(n,q) \\
isblocked(n,\ \_) &= false \quad (mem, emitInt, break, if, \\
&\qquad loop, and, or, @nop)
\end{aligned}
$$

Figure 5. The predicate *isblocked* is true only if all branches in parallel are blocked waiting for events, finalization clauses, or certain stack levels.

there are some significant mismatches between the concrete and abstract Céu, and we (informally) present appropriate mappings in this section. Again, we are not considering side-effects, which are all mapped to the *mem* semantic construct.

3.3.1 await and emit

The concrete **await** and **emit** primitives support communication of values between them. In the two-step translation in Figure 7, we start with the concrete program in Céu (a), which communicates the value 1 between the **emit** and **await** in parallel. In the intermediate translation (b), we include the shared variable `e\_` to hold the value being communicated between the two trails in order to simplify the **emit**. Finally, we convert the program into the equivalent in the abstract syntax (c), translating side-effect statements into *mem* expressions. External events have a similar translation, i.e., each external event requires a corresponding variable that is explicitly set by the environment before each reaction.

$$
\begin{aligned}
clear(awaitExt(e)) &= @nop \\
clear(awaitInt(e)) &= @nop \\
clear(@canrun(n)) &= @nop \\
clear(fin\ p) &= p \\
clear(p\ ;\ q) &= clear(p) \\
clear(p\ @loop\ q) &= clear(p) \\
clear(p\ @and\ q) &= clear(p)\ ;\ clear(q) \\
clear(p\ @or\ q) &= clear(p)\ ;\ clear(q) \\
clear(\_) &= \bot \quad (mem, emitInt, break, if, \\
&\qquad loop, and, or, @nop)
\end{aligned}
$$

Figure 6. The function *clear* extracts *fin* expressions in parallel and put their bodies in sequence.

```
par/or do
  <...>
  emit e => 1;
with
  v = await e;
  _printf("%d\n",v);
end
.
```
(a)

```
par/or do
  <...>
  e_ = 1;
  emit e;
with
  await e;
  v = e_;
  _printf("%d\n",v);
end
.
```
(b)

```
<...> ; mem ; emit(e)
        or
await(e) ; mem ; mem;
.
```
(c)

Figure 7. Two-step translation from concrete to abstract **emit** and **await** expressions. The concrete code in (a) communicates the value 1 from the **emit** to the **await**. The abstract code in (c) uses a shared variable to hold the value.

3.3.2 First-class Timers

To encompass first-class timers, we introduce a special external event `DT` that is intercalated with each other event occurrence in an application (e.g. *e1, e2*):

$$
\begin{aligned}
\langle [DT], p \rangle &\overset{*}{\underset{1}{\Longrightarrow}} \langle [], p' \rangle \\
\langle [e1], p' \rangle &\overset{*}{\underset{2}{\Longrightarrow}} \langle [], p'' \rangle \\
\langle [DT], p'' \rangle &\overset{*}{\underset{3}{\Longrightarrow}} \langle [], p''' \rangle \\
\langle [e2], p''' \rangle &\overset{*}{\underset{4}{\Longrightarrow}} \langle [], p'''' \rangle \\
&\ldots
\end{aligned}
$$

The event `DT` has an associated variable `DT\_` carrying the wall-clock time elapsed between two occurrences in sequence, as depicted by the two-step translation in Figure 8. In the concrete program (a), the variable `dt` holds the residual delta time (as described in Section 2.2) after awaking from the timer. In the first step of the translation (b), we expand the **await** `10ms` to a **loop** that decrements the elapsed number of microseconds for each occurrence of `DT`. When the variable `tot` reaches zero, we escape the **loop** setting the variable `dt` to contain the appropriate delta. In the last step (c), we convert the program to the abstract syntax.

3.3.3 Finalization Blocks

The biggest mismatch between concrete and abstract Céu is regarding the **finalize** blocks, which require more complex modifications in the program for a proper mapping using *fin* expressions. In the three-step translation in Figure 9, we start with a concrete program (a) that uses a **finalize** to safely `\_release` the reference to `ptr` kept after the call to `\_hold`. In the translation, we first need to catch the outermost **do-end** termination to run the finalization code. For this, we translate the block into a **par/or** (b) with the original

```
dt = await 10ms;
```
(a)

```
var int tot = 10000;
loop do
    await DT;
    tot = tot - DT_;
    if tot <= 0 then
        dt = -tot;
        break;
    end
end
.
```
(b)

```
loop(
    await(DT);
    mem;
    if mem then
        mem;
        break
    else
        nop
)
```
(c)

Figure 8. Two-step translation from concrete to abstract timer.

```
do
  var int* ptr =
  await A;
  finalize
    _hold(ptr);
  with
    _release(ptr);
  end
  await B;
end
```
(a)

```
par/or do
  var int* ptr =
  await A;
  _hold(ptr);
  await B;
with
  _release(ptr);
end
```
(b)

```
f_ = 0;
par/or do
  var int* ptr =
  await A;
  _hold(ptr);
  f_ = 1;
  await B;
  _release(ptr);
{ fin
    if f_ then
      _release(ptr);
    end }
end
.
```
(c)

```
mem;
(
  <mem;.>;
  await(A);
  mem;
  mem;
  await(B);
or
  fin
    if mem then
      mem;
    else
      nop
)
```
(d)

Figure 9. Three-step translation from concrete to abstract finalization.

body in parallel with a fin expression to run the finalization code. Note that the fin has no transition rules in the semantics, keeping the **par/or** alive. This way, the fin body only executes when the **par/or** terminates either normally (after the **await** B), or aborted from an outer composition. However, the fin still (incorrectly) executes even if the call to _hold is not reached in the body due to an abort before awaking from the **await** A. To deal with this issue, for each fin we need a corresponding flag to keep track of code that needs to be finalized (c). The flag is initially set to false, avoiding the finalization code to execute. Only after the call to _hold that we set the flag to true and enable the fin body to execute. The complete translation substitutes the side-effect operations with *mem* expressions (d).

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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