

# 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

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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 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>(<exp>);                 // 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 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 blinks the LED on and off (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). 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 2.3.

---

```

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 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 C  U, 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 C  U. 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 C  U 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 C  U (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.

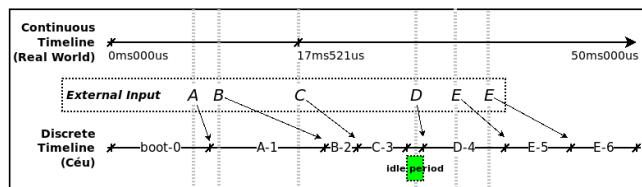


Figure 1. The discrete notion of time in C  U.

### Internal events as subroutines

In C  U, 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 C  U 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).

C  U 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 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.

<pre> 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 </pre>	<pre> 1 2 3 4 5 6 7 8 9 10 </pre>	<pre> input void A; // var int y = 1; par/and do   await A;   y = y + 1; with   await A;   y = y * 2; end </pre>
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[a] Accesses to x are never concurrent.      [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.

## 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

<pre> par/or do   var _msg_t msg;   &lt;...&gt; // prepare msg   finalize     _send(&amp;msg);   with     _cancel(&amp;msg);   end   await SEND_ACK; with   &lt;...&gt; end // </pre>	<pre> 1 2 3 4 5 6 7 8 9 10 11 12 13 </pre>	<pre> par/or do   var _FILE* f;   finalize     f = _fopen(...);   with     _fclose(f);   end   _fwrite(..., f);   await A;   _fwrite(..., f); with   &lt;...&gt; end </pre>	<pre> 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 </pre>
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[a] Local resource finalization      [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.

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.<sup>1</sup>

The finalization mechanism of C  U 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 of C  U and propose an operational semantics to formally describe the language. We describe a small synchronous kernel highlighting the peculiarities of C  U, 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

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

Listing 4. Reduced syntax of C  U.

Listing 4 shows the syntax for a subset of C  U 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 C  U, *mem* expressions are considered to be atomic and instantaneous. As the challenging parts of C  U 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*

<sup>1</sup> The compiler only forces the programmer to write the finalization clause, but cannot check if it actually handles the resource properly.

expressions do not share identifiers, i.e., an identifier is either a variable, an external event, or an internal event.

#### 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:

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

where

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

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 * *:

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

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:

$$\frac{e \neq \epsilon}{\langle p, n, e \rangle \xrightarrow{out} \langle bcast(p), n + 1, \epsilon \rangle} \quad (\text{push})$$

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

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 * *). 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:

$$\langle p, n, \epsilon \rangle \xrightarrow{nst} \langle p', n, \epsilon \rangle \quad (\text{rule-inner})$$

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:

$$\begin{aligned} a) & \quad \langle p, 0, ext \rangle \xrightarrow[out]{push} \langle q, 1, \epsilon \rangle \\ b) & \quad [ \xrightarrow[in]{*} \langle r, i, e \rangle \xrightarrow[out]{*} \langle s, j, \epsilon \rangle ]^* \\ c) & \quad \xrightarrow[in]{*} \langle t, k, \epsilon \rangle \xrightarrow[out]{pop} \langle u, 0, \epsilon \rangle \end{aligned}$$

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:

$$\langle mem(id), n, \epsilon \rangle \xrightarrow{nst} \langle @nop, n, \epsilon \rangle \quad (\text{mem})$$

$$\langle emit(id), n, \epsilon \rangle \xrightarrow{nst} \langle @canrun(n), n, id \rangle \quad (\text{emitInt})$$

$$\langle @canrun(n), n, \epsilon \rangle \xrightarrow{nst} \langle @nop, n, \epsilon \rangle \quad (\text{canrun})$$

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:

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

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

$$\frac{\langle p, n, \epsilon \rangle \xrightarrow{nst} \langle p', n, \epsilon \rangle}{\langle (p ; q), n, \epsilon \rangle \xrightarrow{nst} \langle (p' ; q), n, \epsilon \rangle} \quad (\text{seq-adv})$$

$$\langle (@nop ; q), n, \epsilon \rangle \xrightarrow{nst} \langle q, n, \epsilon \rangle \quad (\text{seq-nop})$$

$$\langle (break ; q), n, \epsilon \rangle \xrightarrow{nst} \langle break, n, \epsilon \rangle \quad (\text{seq-brk})$$

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  $\epsilon$  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:

$$\langle (loop \ p), n, \epsilon \rangle \xrightarrow{nst} \langle (p \ @loop \ p), n, \epsilon \rangle \quad (\text{loop-expd})$$

$$\frac{\langle p, n, \epsilon \rangle \xrightarrow{nst} \langle p', n, \epsilon \rangle}{\langle (p \ @loop \ q), n, \epsilon \rangle \xrightarrow{nst} \langle (p' \ @loop \ q), n, \epsilon \rangle} \quad (\text{loop-adv})$$

$$\langle (@nop \ @loop \ p), n, \epsilon \rangle \xrightarrow{nst} \langle (loop \ p), n, \epsilon \rangle \quad (\text{loop-nop})$$

$$\langle (break \ @loop \ p), n, \epsilon \rangle \xrightarrow{nst} \langle @nop, n, \epsilon \rangle \quad (\text{loop-brk})$$

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  $q$ :

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

$$\frac{\langle p, n, \epsilon \rangle \xrightarrow{nst} \langle p', n, \epsilon \rangle}{\langle (p \text{ @and } q), n, \epsilon \rangle \xrightarrow{nst} \langle (p' \text{ @and } q), n, \epsilon \rangle}$$

$$\frac{isblocked(n, p), \langle q, n, \epsilon \rangle \xrightarrow{nst} \langle q', n, \epsilon \rangle}{\langle (p \text{ @and } q), n, \epsilon \rangle \xrightarrow{nst} \langle (p \text{ @and } q'), n, \epsilon \rangle}$$

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

$$\frac{\langle p, n, \epsilon \rangle \xrightarrow{nst} \langle p', n, \epsilon \rangle}{\langle (p \text{ @or } q), n, \epsilon \rangle \xrightarrow{nst} \langle (p' \text{ @or } q), n, \epsilon \rangle}$$

$$\frac{isblocked(n, p), \langle q, n, \epsilon \rangle \xrightarrow{nst} \langle q', n, \epsilon \rangle}{\langle (p \text{ @or } q), n, \epsilon \rangle \xrightarrow{nst} \langle (p \text{ @or } q'), n, \epsilon \rangle}$$

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**):

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

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

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

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

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

$$bcast(e, awaitExt(e)) = @nop$$

$$bcast(e, awaitInt(e)) = @nop$$

$$bcast(e, @canrun(n)) = @canrun(n)$$

$$bcast(e, fin p) = fin p$$

$$(\text{and-adv1}) \quad bcast(e, p; q) = bcast(e, p); q$$

$$bcast(e, p \text{ @loop } q) = bcast(e, p) \text{ @loop } q$$

$$bcast(e, p \text{ @and } q) = bcast(e, p) \text{ @and } bcast(e, q)$$

$$bcast(e, p \text{ @or } q) = bcast(e, p) \text{ @or } bcast(e, q)$$

$$(\text{and-adv2}) \quad bcast(e, \_) = \perp \quad (mem, emitInt, break, if, loop, and, or, @nop)$$

**(or-expd)**

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

**(or-adv1)**

$fin$  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 **(or-adv2)** not contain awaiting expressions ( $awaitExt$ ,  $awaitInt$ , and  $fin$ ), i.e., they are 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:

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

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

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

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

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, there are some significant mismatches between the concrete and abstract CéU, and we (informally) present appropriate

```

771 isblocked(n, awaitExt(id)) = true
772 isblocked(n, awaitInt(id)) = true
773 isblocked(n, @canrun(m)) = (n > m)
774 isblocked(n, fin p) = true
775 isblocked(n, fin p) = true
776 isblocked(n, p ; q) = isblocked(n, p)
777 isblocked(n, p @loop q) = isblocked(n, p)
778 isblocked(n, p @and q) = isblocked(n, p) ∧ isblocked(n, q)
779 isblocked(n, p @or q) = isblocked(n, p) ∧ isblocked(n, q)
780 isblocked(n, _) = false (mem, emitInt, break, if,
781 loop, and, or, @nop)
782
783
784

```

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

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.

```

809 clear(awaitExt(e)) = @nop
810 clear(awaitInt(e)) = @nop
811 clear(@canrun(n)) = @nop
812 clear(fin p) = p
813 clear(p ; q) = clear(p)
814 clear(p @loop q) = clear(p)
815 clear(p @and q) = clear(p) ; clear(q)
816 clear(p @or q) = clear(p) ; clear(q)
817 clear(_) = ⊥ (mem, emitInt, break, if,
818 loop, and, or, @nop)
819
820
821
822

```

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

<pre> par/or do   &lt;...&gt;   emit e =&gt; 1; with   v = await e;   _printf("%d\n", v); end </pre>	<pre> par/or do   &lt;...&gt;   e_ = 1;   emit e; with   v = e_;   _printf("%d\n", v); end </pre>	<pre> &lt;...&gt; ; mem ; emit(e) or await(e) ; mem ; mem </pre>	<pre> 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 </pre>
(a)	(b)	(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 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 8, 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 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



<pre> 881 do 882   var int* ptr 883   await A; 884   finalize 885     _hold(ptr); 886   with 887     _release(ptr) 888   end 889   await B; 890 end </pre>	<pre> 881 par/or do 882   var int* ptr 883   await A; 884   _hold(ptr); 885   with 886     _release(ptr) 887   end 888   { 889     fin 890   } 891 end </pre>	<pre> 881 f_ = 0; 882 mem; 883 var int* ptr = mem; 884 _hold(ptr); 885 mem; 886 f_ = 1; 887 mem; 888 await B; 889 { 890   fin 891 } 892 end </pre>	<pre> 881 mem; 882 _hold(ptr); 883 mem; 884 mem; 885 mem; 886 mem; 887 mem; 888 mem; 889 mem; 890 mem; 891 mem; 892 mem; 893 mem; 894 mem; 895 mem; 896 mem; 897 mem; 898 mem; 899 mem; 900 mem; 901 mem; 902 mem; 903 mem; 904 mem; 905 mem; 906 mem; 907 mem; 908 mem; 909 mem; 910 mem; 911 mem; 912 mem; 913 mem; 914 mem; 915 mem; 916 mem; 917 mem; 918 mem; 919 mem; 920 mem; 921 mem; 922 mem; 923 mem; 924 mem; 925 mem; 926 mem; 927 mem; 928 mem; 929 mem; 930 mem; 931 mem; 932 mem; 933 mem; 934 mem; 935 mem; </pre>
(a)	(b)	(c)	(d)

**Figure 8.** Three-step translation from concrete to abstract finalization.

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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