The Design, Semantics, and Implementation of Céu: a Synchronous Reactive Language based on Esterel

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CÉU is a reactive language based on Esterel that targets constrained embedded platforms and ensures safe concurrency by handling threats at compile time, rather than at runtime. Based on the synchronous programming model, our design allows for a simple reasoning about concurrency that enables compile-time analysis and results in deterministic and memory-safe programs. In this work, we discuss the design of CÉU and propose a formal semantics focusing on its particular control mechanisms, such as parallel compositions, finalization, and stack-based internal events. We also present an implementation with two back ends: one aiming for resource efficiency and interoperability with *C*, and another based on a virtual machine that allows remote reprogramming.

Additional Key Words and Phrases: Concurrency, Determinism, Embedded Systems, Esterel, Synchronous, Reactivity

1. INTRODUCTION

An established alternative to *C* in the field of embedded systems is the family of reactive synchronous languages [Benveniste et al. 2003]. Two major styles of synchronous languages have evolved: in the *control–imperative* style, programs are structured with control flow primitives, such as parallelism, repetition, and preemption; in the *dataflow–declarative* style, programs can be seen as graphs of values, in which a change to a value is propagated through its dependencies without explicit programming. Considering the control-based languages, Esterel [Boussinot and de Simone 1991] was the first to appear and influenced a number of embedded languages, such as *Reactive-C* [Boussinot 1991], *OSM* [Kasten and Römer 2005], *Sync-C* [Von Hanxleden 2009], and *PRET-C* [Andalam et al. 2010].

CÉU is another Esterel-based language targeting embedded and (soft) real-time systems with novel functionalities:

— Stack-based execution for internal events, which provide a limited form of coroutines.
— A static temporal analysis and deterministic execution semantics that allows programs to safely share memory.
— A finalization mechanism for safe abortion of lines of execution holding external resources.
— First-class synchronized timers.

In this work, we discuss the design of CÉU and propose a formal semantics for a small synchronous kernel that represents a subset of the language covering these new functionalities. We also present an implementation of CÉU with two back ends: one aiming for resource efficiency and interoperability with *C*, and another based on a virtual machine that allows remote reprogramming. Our implementations target resource-constrained devices, such as *Arduino* and *MICAz* sensor nodes based on 8-bit microcontrollers.[1]

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[1] Arduino: https://www.arduino.cc/en/Main/arduinoBoardUno
MICAz: http://www.memsic.com/userfiles/files/Datasheets/WSN/micaz_datasheet-t.pdf
(Both use the *ATmega328* microcontroller with 32 Kbytes of FLASH and 2 Kbytes of SRAM.)

In previous work [Sant'Anna et al. 2013; Branco et al. 2015], we employed CÉU in the context of wireless sensor networks, developing a number of applications, protocols, and drivers. We evaluated the expressiveness of CÉU in comparison to event-driven code in *C* and attested a reduction in source code size (around 25%) with a small increase in memory usage (around 5–10% for *text* and *data*) [Sant'Anna et al. 2013]. For the *VM* back end, a simple application that blinks three LEDs periodically occupies less than 100 bytes and can be completely transmitted in 4 radio messages. In contrast, the full image of a *C*-compiled version occupies more than 2 Kbytes [Branco et al. 2015].[2]

The rest of the paper is organized as follows: Section 2 discusses the design of CÉU, focusing on the fundamental differences to Esterel. Section 3 presents a formal semantics for the control primitives of CÉU. Section 4 presents the *C* and *VM* implementation back ends. Section 5 discusses other synchronous languages targeting embedded systems. Section 6 concludes the paper.

2. THE DESIGN OF CÉU

CÉU is a synchronous reactive language based on Esterel with support for multiple concurrent lines of execution known as *trails*. By reactive, we mean that programs are stimulated by the environment through input events that are broadcast to all awaiting trails. By synchronous, we mean that all trails at any given moment are either reacting to the current event or are awaiting another event; in other words, trails are never reacting to different events.

In the sections that follow, we discuss the main differences between CÉU and Esterel: queue-based external events and stack-based internal events (Section 2.1), shared-memory concurrency and determinism (Section 2.2), safe abortion with finalization (Section 2.3), and first-class timers (Section 2.4).

Regarding the similarities, Figure 1 shows side-by-side the implementations in Esterel and CÉU for the following control specification [Berry 2000]: *"Emit an output O as soon as two inputs A and B have occurred. Reset this behavior each time the input R occurs"*. The first phrase of the specification, awaiting and emitting the events, is translated almost identically in the two languages (ln. 4–9, in both implementations), given that Esterel's '‖' and CÉU's par/and constructs are equivalent. For the second phrase, the reset behavior, the Esterel version uses a abort-when (ln. 3–10), which serves the same purpose of CÉU's par/or (ln. 3–12): the occurrence of event R aborts the awaiting statements in parallel and restarts the enclosing loop.

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[2]The *VM* is preloaded in the devices with some *I/O* functionality, whereas *C*-based binaries are full images.

```
1   // ESTEREL
2   loop
3     abort
4       [
5           await A
6       ‖
7           await B
8       ];
9       emit O
10    when R
11  end
```

```
1   // CEU
2   loop do
3     par/or do
4       par/and do
5           await A;
6       with
7           await B;
8       end
9       emit O;
10    with
11      await R;
12    end
13  end
```

Fig. 1. A control specification implemented in Esterel and CÉU: *"Emit O after A and B, resetting each R."*

CÉU has a strong imperative flavor, with explicit control flow through sequences, loops, parallels, and also assignments. Being designed for control-intensive applications, it provides support for concurrent lines of execution and broadcast communication through events. In addition, CÉU also employs the synchronous model, in which programs advance in a sequence of discrete reactions to external events. Internal computations within a reaction (e.g. expressions, assignments, and system calls) are considered to take no time in accordance with the synchronous hypothesis [Potop-Butucaru et al. 2005]. The `await` statements are the only ones that halt a running reaction and allow a program to advance in this notion of time. To ensure that reactions run in bounded time and programs always progress, loops are statically required to contain at least one `await` statement in all possible paths [Sant'Anna et al. 2013; Berry 2000]. CÉU shares the same limitations with Esterel and synchronous languages in general: computations that run in unbounded time (e.g., cryptography, image processing) do not fit the zero-delay hypothesis, and cannot be elegantly implemented.

2.1. Queue-Based External Events and Stack-Based Internal Events

Esterel makes no semantic distinctions between internal and external signals, both having only the notion of either presence or absence during an entire reaction [Berry 1993]. In CÉU, external input events are unique within reactions and programs cannot emit them, resulting in an intrinsic queue-based handling. In contrast, programs can emit internal events but these follow a stack-based execution policy, similar to subroutine calls in typical programming languages. Figure 2 illustrates the use of internal signals (events) in Esterel and CÉU. In the version in Esterel, when A occurs, B is emitted (ln. 5–6) and both events become active, resulting in the invocation of `f()` and `g()` in no particular order. In the version in CÉU, the occurrence of A makes the program behave as follows (with the stack contents in italics):

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

Internal events bring support for a limited form of subroutines, as depicted in Figure 3. The subroutine `inc` is defined as a loop (ln. 3–6) that continuously awaits its identifying event (ln. 4), incrementing the value passed as reference (ln. 5). A trail in parallel (ln. 8–11) invokes the subroutine in reaction to event A through an `emit` (ln. 10). Given the stacked execution for internal events, the calling trail pauses, the subroutine awakes (ln. 4), runs its body (yielding v=2), loops, and awaits the next "call" (ln.

```
1   // ESTEREL                      1   // CEU
2   input A;      // external       2   input void A;   // external (in uppercase)
3   signal B;     // internal       3   event void b;   // internal (in lowercase)
4   [[                              4   par/and do
5       await A;                    5       await A;
6       emit B;                     6       emit b;
7       call f();                   7       _f();
8   ||                              8   with
9       await B;                    9       await b;
10      call g();                   10      _g();
11  ]]                              11  end
```

Fig. 2. Internal signals (events) in Esterel and CÉU: similar syntax, but different semantics.

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

Fig. 3.   Subroutine inc is defined in a loop (ln. 3–6), in parallel with the caller (ln. 8–11).

4, again). Only after this sequence the calling trail resumes and passes the assertion test (ln. 11).

On the one hand, this form of subroutines has a significant limitation that it cannot express recursive calls: an emit to itself is always ignored, given that a running body cannot be awaiting itself. On the other hand, this very same limitation brings some 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. Also, this form of subroutines can use the other primitives of CÉU, such as parallel compositions and the await statement. In particular, they await keeping context information such as locals and the program counter, similarly to coroutines [Moura and Ierusalimschy 2009].

Another distinction regarding event handling in comparison to CÉU is that Esterel supports same-cycle bi-directional communication [Edwards 1999], i.e., two threads can react to one another during the same cycle due to mutual signal dependency. CÉU imposes a restriction that an await is only valid for the next reaction, i.e., if an await and emit occur simultaneously in parallel trails, the await does not awake. These *delayed awaits* avoid corner cases of instantaneous termination and re-execution of statements in the same reaction (known as *schizophrenic statements* [Tardieu and De Simone 2003; Yun et al. 2013]). The example that follows relies on this restriction to avoid infinite execution:

```
1  event void e,f;
2  loop do
3      par/or do
4          await e;
5      with
6          emit e;       // w/o the restriction, the emit awakes 1st trail
7          await f;       // and restarts the loop instantaneously
8      end
9  end
```

Both sides of the par/or have an await statement to avoid instantaneous termination (ln. 4,7). However, if the emit (ln. 6) could awake the await (ln. 4) in the same reaction that reaches them, the par/or would terminate and restart the loop instantaneously, resulting in infinite execution.

In atypical scenarios requiring immediate awake, delayed awaits can be circumvented by manually copying or transforming the code to execute on awake. From our experience, in some cases we need to execute a block of code periodically from internal event requests, *including the current reaction*, as illustrated in the left of Figure 4. In this case, moving the await to the end of the loop (ln. 10) makes the periodic code to also execute immediately (ln. 9), and then in reactions to each emit request (ln. 5). If the periodic emit depends on a condition, as illustrated in the right of Figure 4, the code becomes more intricate because we need a state variable (ln. 2) and also to copy the

```
1   event void e;
2   par do
3       loop do
4           <...>       // code that awaits
5           emit e;    // periodic request
6       end
7   with
8       loop do
9           <...>       // code to execute
10          await e;   // await after
11      end
12  end
```

```
1   event void e;
2   var bool should_execute = false;
3   par do
4       loop do
5           <...>            // code that awaits
6           if <...> then // some conditon
7               should_execute = true;
8               emit e;
9           end
10      end
11  with
12      loop do
13          if should_execute then
14              <...>        // code to execute
15          end
16          await e;
17      end
18  end
```

Fig. 4. Examples that circumvent the *delayed await* restriction by post-fixing the await inside the loop (in the left), and by copying the condition test (in the right).

condition test to the periodic code (ln. 13). On the one hand, we transfer the burden of dealing with these corner cases to the programmer. On the other hand, we simplify the semantics of the language and eliminate the need for analysis to deal with schizophrenic statements.

2.2. Shared-Memory Concurrency and Determinism

Embedded applications make extensive use of global memory, such as for accessing resources through memory-mapped registers. Hence, an important goal of CÉU is to ensure a reliable behavior for programs with concurrent lines of execution sharing memory. Esterel is only deterministic with respect to reactive control: "the same sequence of inputs always produces the same sequence of outputs" [Berry 2000]. However, the execution order for operations with side-effects 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" [Berry 2000]. Therefore, Esterel forbids sharing memory between lines of execution: *"if a variable is written by some thread, then it can neither be read nor be written by concurrent threads"* [Berry 2000].

Concurrency in CÉU is characterized when two or more trail segments in parallel execute during the same reaction. A trail segment is a sequence of statements followed by an await (or termination). In the program in the left of Figure 5, the two assignments to x (ln. 5,8) can never run concurrently, because each trail segment reacts to a different input event (ln. 4,7) and, according to the semantics of CÉU, cannot occur simultaneously. However, the program in the right is non-deterministic, because the two assignments to y (ln. 5,8) occur in the same reaction to input A (ln. 4,7).

```
1   input void A, B;
2   var int x = 1;
3   par/and do
4       await A;
5       x = x + 1;
6   with
7       await B;
8       x = x * 2;
9   end
```

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

Fig. 5. Shared-memory concurrency in CÉU: the code in the left is safe because the trails access x atomically in different reactions; the code in the right is unsafe because both trails access y in the same reaction.

```
// ESTEREL                              // CEU
input A;                               input void A;
[                                      par/and do
    await A;                               await A;
    call f1();                             _f1();
||                                     with
    await A;                               await A;
    call f2();                             _f2();
];                                     end
```

Fig. 6. In Esterel, the execution order between `f1` and `f2` is unspecified, whereas in CÉU, `_f1` executes before `_f2` due to deterministic scheduling based on lexical order.

CÉU performs a temporal analysis at compile time and detects concurrent accesses to shared variables, as follows: *if a variable is written in a trail segment, then a concurrent trail segment cannot read or write to that variable, nor dereference a pointer of that variable type.* An analogous policy is applied for pointers *vs* variables and pointers *vs* pointers, as well as for system calls with side effects (e.g., `printf`).

Regardless of the temporal analysis of CÉU, when multiple trails are active during the same reaction, they are scheduled in the order they appear in the program source code. Therefore, even though the program in the right of Figure 5 is suspicious, the assignments to `y` are both atomic and deterministic, i.e., after the reaction to `A` terminates, the value of `y` is 4 (`(1+1)*2`). On the one hand, enforcing an execution order for concurrent operations may seen arbitrary and also precludes true parallelism. On the other hand, it provides a priority scheme for trails, and makes shared-memory concurrency more tractable. For constrained embedded development, we believe that deterministic shared-memory concurrency is beneficial, given the extensive use of memory mapped ports for I/O and the lack of hardware support for real parallelism. Other synchronous embedded languages, such as *SOL* [Karpinski and Cahill 2007] and *PRET-C* [Andalam et al. 2010], made a similar design choice.

Figure 6 compares the two syntactically equivalent code fragments in Esterel and CÉU to summarize the semantic difference regarding (non-)determinism. Even though the program in CÉU executes deterministically, the compiler still issues a warning, because an apparently innocuous reordering of trails modifies the semantics of the program. Note that in Esterel multiple external events can coexist in the same reaction, which disallows a similar temporal analysis.

2.3. Safe Abortion with Finalization

The introductory example of Figure 1 illustrates how synchronous languages can abort awaiting lines of execution without tweaking them with synchronization primitives. In contrast, traditional (asynchronous) multi-threaded languages cannot express thread termination safely [Berry 1993; ORACLE 2011]. Still, handling abortion when dealing with external resources is challenging because they are not subject to the same synchronous execution discipline.

To illustrate threats related to abortion, consider the unsafe example in the left of Figure 7, which does not compile in CÉU. It describes the state machine of a data collection protocol for sensor networks [Gnawali et al. 2009; Sant'Anna et al. 2013]. The input events STOP, RETRANSMIT, and SENDACK (ln. 1) represent the external interface of the protocol. The protocol has to transmit a packet every minute, unless it receives a RETRANSMIT request to immediately re-transmit it, or a STOP request to terminate. The protocol is composed of two main trails: one simply monitors the stopping event (ln. 3); the other periodically transmits the packet (ln. 5–18). The periodic transmission is a loop that starts two other trails (ln. 6–17): one handles the immediate retransmission request (ln. 7); the other transmits the packet and waits for a confirmation (ln. 9–16).

```
1   input void STOP, RETRANSMIT, SENDACK;        11  <...>
2   par/or do                                    12      var _pkt_t buffer;
3       await STOP;                              13      <fill—buffer—info>
4   with                                         14      finalize
5       loop do                                  15          _send_enqueue(&buffer);
6           par/or do                            16      with
7               await RETRANSMIT;                17          _send_cancel(&buffer);
8           with                                 18      end
9               par/and do                       19      await SENDACK;
10                  await 1min;                  20  <...>
11              with
12                  var _pkt_t buffer;
13                  <fill—buffer—info>
14                  _send_enqueue(&buffer);
15                  await SENDACK;
16              end
17          end
18      end
19  end
```

Fig. 7. The unsafe network protocol in the left, which does not compile, is extended with a finalization clause in the right to handle abortion properly.

The actual transmission (ln. 12–15) is enclosed with a `par/and` that takes at least one minute before looping (ln. 10), in accordance with the specification. Note that the call to `_send_enqueue`[3] (ln. 14) is *asynchronous*, handing to the radio driver a pointer to the lexically-scoped packet (ln. 12). The driver makes the transmission in the background, holding the packet until it signals the application with the SENDACK to acknowledge completion (ln. 15). At any time, the client may request a retransmission (ln. 7), which terminates the `par/or` (ln. 6), aborts the ongoing transmission (ln. 14, if not idle), and restarts the loop (ln. 5). The client may also request to stop the whole protocol at any time (ln. 3). Therefore, if the sending trail is aborted by the STOP or RETRANSMIT requests, the packet buffer goes out of scope, leaving behind a *dangling pointer* in the radio driver, which will possibly transmit corrupted data.

The unsafe example in the left of Figure 7 does not compile because CÉU tracks the interaction of `par/or` compositions with local variables and stateful *C* functions (e.g., device drivers) in order to preserve safe abortion of trails. In fact, CÉU enforces the programmer to write a *finalization* clause to accompany the stateful *C* call. The code in the right of Figure 7 properly cancels the packet transmission when the block of `buffer` goes out of scope, i.e., the finalization clause (after the `with`) executes automatically on external abortion.[4]

2.4. First-Class Timers

Activities that involve reactions to *wall-clock time*[5] appear in typical patterns of embedded development, such as timeout watchdogs and sensor samplings. However, support for wall-clock time is somewhat low-level in existing languages, usually through timer callbacks or "sleep" blocking calls. Furthermore, in any concrete timer implementation, a requested timeout does not expire precisely without delays, a fact that is usually ignored in the development process. We define the difference between the requested timeout and the actual expiring time as the *residual delta time (delta)*. Without explicit manipulation, the recurrent use of timed activities in sequence (or

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[3]The underline prefix marks (e.g., `_send_enqueue`) make interactions with external *C* libraries explicit and are required in CÉU.

[4]Note that the compiler only enforces the programmer to write the finalization clause, but cannot check if it actually handles the resource properly.

[5]By wall-clock time we mean the passage of time from the real world, measured in hours, minutes, etc.

```
var int v;                          par/or do
await 10ms;                             await 10ms;
v = 1;                                  <...>           // any non—awaiting sequence
await 1ms;                              await  1ms;
v = 2;                                  v = 1;
                                    with
                                        await 12ms;
                                        v = 2;
                                    end
```

Fig. 8.   First-class timers in CÉU.

in a loop) may accumulate a considerable amount of deltas that can lead to incorrect behavior in programs.

The `await` statement of CÉU supports wall-clock time and handles deltas automatically, resulting in more robust applications. For the example in the left of Figure 8, suppose that after the first `await` request, the underlying system gets busy and takes 15ms to check for expiring awaits. The CÉU scheduler will notice that the `await 10ms` has not only already expired, but is delayed with `delta=5ms`. Then, the awaiting trail awakes, sets `v=1`, and invokes `await 1ms`. As the current delta is higher than the requested timeout (i.e. $5ms > 1ms$), the trail is rescheduled for execution, now with `delta=4ms`.

CÉU also takes into account the fact that time is a physical quantity that can be added and compared. For instance, for the program in the right of Figure 8, although the scheduler cannot guarantee that the first trail terminates exactly in 11ms, it can at least ensure that the program always terminates with `v=1`. Given that any non-awaiting sequence is considered to take no time in the synchronous model, the first trail is guaranteed to terminate before the second trail, because $10 + 1 < 12$. A similar program in a language without first-class support for timers would depend on the execution timings for the code marked as `<...>`, making the reasoning about the execution behavior more difficult.

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 with broadcast communication 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 *C* calls (which behave like in conventional imperative languages).

3.1. Abstract Syntax

Figure 9 shows the BNF-like syntax for a subset of CÉU that is sufficient to describe all semantic peculiarities of the language. Except for fin and all semantic-derived expressions (i.e., $awating$, $emitting$, and $p @ loop; p$), which are discussed further, all other expressions are equivalent to their counterparts in the concrete language.

The $mem(id)$ primitive represents all accesses, assignments, and *C* function calls that affect a memory location identified by id. As the challenging parts of CÉU reside on its control structures, we are not concerned here with a precise semantics for side effects, but only with their occurrences in programs. The special notation nop is used to represent an innocuous mem expression (it can be thought as a synonym for $mem(\epsilon)$, where ϵ is an unused identifier). Note that mem and $await/emit$ expressions do not share identifiers, i.e., an identifier is either a variable or an event.

```
                                    // primary expressions
p ::= mem(id)                       (any memory access to 'id')
    | await(id)                     (await event 'id')
    | emit(id)                      (emit event 'id')
    | break                         (loop escape)
                                    // compound expressions
    | 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
    | awaiting(id,n)                (awaiting 'id' since sequence number 'n')
    | emitting(n)                   (emitting on stack level 'n')
    | p @ loop p                    (unwinded loop)
```

Fig. 9.   Reduced syntax of CÉU.

3.2. Operational Semantics

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

$$\langle S, p \rangle \xrightarrow{n} \langle S', p' \rangle \qquad \textbf{(relation-inner)}$$

where

$$S, S' \in id^* \qquad (sequence\ of\ event\ identifiers : [id_{top}, ..., id_{bottom}])$$
$$p, p' \in P \qquad (program\ as\ described\ in\ Figure\ 9)$$
$$n \in \mathbb{N} \qquad (unique\ identifier\ for\ the\ reaction\ chain)$$

At the beginning of a reaction chain, the stack is initialized with the occurring external event ext ($S = [ext]$), but $emit$ expressions can push new events on top of it (we discuss how they are popped further). The ever-increasing sequence number n prevents that awaiting expressions awake in the same reaction they are reached (the *delayed awaits* as explained in Section 2.1).

We describe this relation with a set of small-step structural semantics rules, which are built in such a way that at most one transition is possible at any time, resulting in deterministic reaction chains. The transition rules for the primary expressions are as follows:

$$\langle S,\ await(id) \rangle \xrightarrow{n} \langle S,\ awaiting(id, n+1) \rangle \qquad \textbf{(await)}$$

$$\langle id : S,\ awaiting(id, m) \rangle \xrightarrow{n} \langle id : S,\ nop \rangle,\ \ m <= n \qquad \textbf{(awake)}$$

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

$$\langle S,\ emitting(|S|) \rangle \xrightarrow{n} \langle S,\ nop \rangle \qquad \textbf{(pop)}$$

An $await$ is simply transformed into an $awaiting$ (rule **await**) as an artifice to remember the external sequence number $n+1$ it can awake: an $awaiting$ can only transit to a nop (rule **awake**) if its referred event id matches the top of the stack and it was

reached in a previous reaction (i.e., sequence number $m <= n$). An *emit* transits to an *emitting* holding the current stack level ($|S|$ stands for the stack length), and pushing the referred event on the stack (rule **emit**). With the new stack level $|S| + 1$, the $emitting(|S|)$ itself cannot transit, as rule **pop** expects its parameter to match the current stack level. This trick provides the desired stack-based semantics for internal events.

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

$$\frac{val(id, n) \neq 0}{\langle S, (if\ mem(id)\ then\ p\ else\ q)\rangle \underset{n}{\longrightarrow} \langle S, p\rangle} \textbf{ (if-true)}$$

$$\frac{val(id, n) = 0}{\langle S, (if\ mem(id)\ then\ p\ else\ q)\rangle \underset{n}{\longrightarrow} \langle S, q\rangle} \textbf{ (if-false)}$$

$$\frac{\langle S, p\rangle \underset{n}{\longrightarrow} \langle S', p'\rangle}{\langle S, (p\ ;\ q)\rangle \underset{n}{\longrightarrow} \langle S', (p'\ ;\ q)\rangle} \qquad \textbf{(seq-adv)}$$

$$\langle S, (mem(id)\ ;\ q)\rangle \underset{n}{\longrightarrow} \langle S, q\rangle \qquad \textbf{(seq-nop)}$$

$$\langle S, (break\ ;\ q)\rangle \underset{n}{\longrightarrow} \langle S, break\rangle \qquad \textbf{(seq-brk)}$$

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

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

$$\langle S, (loop\ p)\rangle \underset{n}{\longrightarrow} \langle S, (p\ @\ loop\ p)\rangle \qquad \textbf{(loop-expd)}$$

$$\frac{\langle S, p\rangle \underset{n}{\longrightarrow} \langle S', p'\rangle}{\langle S, (p\ @\ loop\ q)\rangle \underset{n}{\longrightarrow} \langle S', (p'\ @\ loop\ q)\rangle} \textbf{ (loop-adv)}$$

$$\langle S, (mem(id)\ @\ loop\ p)\rangle \underset{n}{\longrightarrow} \langle S, loop\ p\rangle \textbf{ (loop-nop)}$$

$$\langle S, (break\ @\ loop\ p)\rangle \underset{n}{\longrightarrow} \langle S, nop\rangle \qquad \textbf{(loop-brk)}$$

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 $mem(id)$. However, what follows the

$$isBlocked(n, a : S, awaiting(b, m)) = (a \neq b \ \lor \ m > n)$$
$$isBlocked(n, S, emitting(s)) = (|S| \neq s)$$
$$isBlocked(n, S, (p \ ; \ q)) = isBlocked(n, S, p)$$
$$isBlocked(n, S, (p \ @ \ loop \ q)) = isBlocked(n, S, p)$$
$$isBlocked(n, S, (p \ and \ q)) = isBlocked(n, S, p) \land isBlocked(n, S, q)$$
$$isBlocked(n, S, (p \ or \ q)) = isBlocked(n, S, p) \land isBlocked(n, S, q)$$
$$isBlocked(n, S, \_) = false \ \ (mem, await,$$
$$emit, break, if, loop)$$

Fig. 10.   The recursive predicate $isBlocked$ is true only if all branches in parallel are hanged in $awaiting$ or $emitting$ expressions that cannot transit.

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:

$$\frac{\langle S, p \rangle \ \underset{n}{\longrightarrow} \ \langle S', p' \rangle}{\langle S, (p \ and \ q) \rangle \ \underset{n}{\longrightarrow} \ \langle S', (p' \ and \ q) \rangle} \quad \textbf{(and-adv1)}$$

$$\frac{isBlocked(n, S, p) \ , \ \langle S, q \rangle \ \underset{n}{\longrightarrow} \ \langle S', q' \rangle}{\langle S, (p \ and \ q) \rangle \ \underset{n}{\longrightarrow} \ \langle S', (p \ and \ q') \rangle} \quad \textbf{(and-adv2)}$$

$$\frac{\langle S, p \rangle \ \underset{n}{\longrightarrow} \ \langle S', p' \rangle}{\langle S, (p \ or \ q) \rangle \ \underset{n}{\longrightarrow} \ \langle S', (p' \ or \ q) \rangle} \quad \textbf{(or-adv1)}$$

$$\frac{isBlocked(n, S, p) \ , \ \langle S, q \rangle \ \underset{n}{\longrightarrow} \ \langle S', q' \rangle}{\langle S(p \ or \ q) \rangle \ \underset{n}{\longrightarrow} \ \langle S', (p \ or \ q') \rangle} \quad \textbf{(or-adv2)}$$

   The deterministic behavior of the semantics relies on the *isBlocked* predicate, which is defined in Figure 10 and used in rules **and-adv2** and **or-adv2**. These rules require the left branch p to be blocked in order to allow the right transition from q to q'. Basically, the *isBlocked* predicate determines that an expression becomes blocked when all of its trails in parallel hang in $awaiting$ and $emitting$ expressions that cannot advance.

   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**, as follows). 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**):

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

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

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

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

The $clear$ function, defined in Figure 11, 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. In Section 3.3.3, we show how to map a finalization block in the concrete language to a fin in the formal semantics. Note that there is a syntactic restriction that a fin body can only contain mem expressions, i.e., they are guaranteed to execute entirely within a reaction chain.

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:

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

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

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

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

A reaction chain eventually blocks in $awaiting$ and $emitting$ expressions in parallel trails. If all trails hangs only in $awaiting$ expressions, it means that the program

$$clear(fin\ p) = p$$
$$clear(p\ ;\ q) = clear(p)$$
$$clear(p\ @\ loop\ q)) = clear(p)$$
$$clear(p\ and\ q) = clear(p)\ ;\ clear(q)$$
$$clear(p\ or\ q) = clear(p)\ ;\ clear(q)$$
$$clear(\_) = nop$$

Fig. 11. The function $clear$ extracts fin expressions in parallel and put their bodies in sequence.

cannot advance in the current reaction chain. However, $emitting$ expressions are pending in lower stack indexes and should eventualy resume in the ongoing reaction (see rule **pop**). Therefore, we define another relation that behaves as **relation-inner** (presented above) if the program can advance, and, otherwise, pops the stack:

$$\frac{\langle S,p\rangle \xrightarrow{\ }_n \langle S',p'\rangle}{\langle S,p\rangle \Longrightarrow_n \langle S',p'\rangle} \qquad \frac{isBlocked(n,\ s:S,\ p)}{\langle s:S,p\rangle \Longrightarrow_n \langle S,p\rangle} \qquad \textbf{(relation-outer)}$$

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

$$\langle S,p\rangle \overset{*}{\Longrightarrow_n} \langle S',p'\rangle$$

Finally, to describe the complete execution of a program, we trigger multiple "invocations" of reaction chains in sequence:

$$\langle [e1],p\rangle \overset{*}{\Longrightarrow_1} \langle [],p'\rangle$$
$$\langle [e2],p'\rangle \overset{*}{\Longrightarrow_2} \langle [],p''\rangle$$
$$\langle [e3],p''\rangle \overset{*}{\Longrightarrow_3} \langle [],p'''\rangle$$
$$...$$

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

3.3. Concrete Language Mapping

Most statements from CÉU ("concrete CÉU") map directly to those presented in the reduced syntax of Figure 9 ("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) propose 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 of Figure 12, we start with the concrete program in CÉU, which communicates the value 1 between the `emit` and `await` in parallel (left-most code). In the intermediate translation, 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, translating side-effect statements into mem expressions. External events require a similar translation, i.e., each external event has a corresponding variable that is explicitly set by the environment before each reaction chain.

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

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

Fig. 12. Two-step translation from concrete to abstract `emit` and `await` expressions. The concrete code in the left communicates the value 1 from the `emit` to the `await`. The abstract code uses a shared variable to hold the value.

$$\langle [DT], p \rangle \xRightarrow[1]{*} \langle [], p' \rangle$$

$$\langle [e1], p' \rangle \xRightarrow[2]{*} \langle [], p'' \rangle$$

$$\langle [DT], p'' \rangle \xRightarrow[3]{*} \langle [], p''' \rangle$$

$$\langle [e2], p''' \rangle \xRightarrow[4]{*} \langle [], p'''' \rangle$$

...

The `DT` event has an associated variable `DT_` carrying the wall-clock time elapsed between the two occurrences, as depicted by the two-step translation of Figure 13. In the concrete program in the left, the variable `dt` will hold the residual delta time (as described in Section 2.4) after awaking from the timer. In the first step of the translation, 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, we convert the program to the abstract syntax.

3.3.3. Finalization Blocks. The biggest mismatch between concrete and abstract CÉU is regarding finalization blocks, which require more complex modifications in the program for a proper mapping using the fin expressions. In the three-step translation of Figure 14, we start with a concrete program (`CODE-1`) 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 `do-end` termination to run the finalization code. For this, we translate the block into a `par/or` (`CODE-2`) with the original body in parallel with a fin to run the finalization code. This way, the fin body executes whenever 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

```
dt = await 10ms;            var int tot = 10000; // 10ms      mem;
                            loop do                           loop(
                                await DT;                         await(DT);
                                tot = tot − DT_;                  mem;
                                if tot <= 0 then                  if mem then
                                    dt = tot;                         mem;
                                    break;                            break
                                end                               else
                            end                                       nop
                                                              )
```

Fig. 13. Two-step translation from concrete to abstract timer.

```
do                          par/or do                   f_ = 0;                     mem;
  var int* ptr = <...>;       var int* ptr = <...>;     par/or do                   (
  await A;                     await A;                    var int* ptr = <...>;       mem;
  finalize                    _hold(ptr);                 await A;                    await(A);
    _hold(ptr);               await B;                    _hold(ptr);                 mem;
  with                      with                          f_ = 1;                     mem;
    _release(ptr);            { fin                       await B;                    await(B);
  end                             _release(ptr); }      with                       or
  await B;                   end                           { fin                       fin
end                                                           if f_ then                if mem then
                                                                _release(ptr);            mem
                                                             end }                      else
                                                          end                             nop
                                                                                      )
// CODE—1                    // CODE—2                    // CODE—3                    // CODE—4
```

Fig. 14. Three-step translation from concrete to abstract finalization.

need a corresponding flag to keep track of code that needs to be finalized (`CODE-3`). 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 (`CODE-4`).

4. IMPLEMENTATION

The compilation process of a program in CÉU is composed of three main phases, as illustrated in Figure 15:

> *Parsing.* The parser of CÉU is written in *LPeg* [Ierusalimschy 2009], a pattern matching library that also recognize grammars, making it possible to write the tokenizer and grammar with the same tool. The source code is then converted to an *abstract syntax tree (AST)* to be used in further phases. This phase may be aborted due to syntax errors in the CÉU source file.
> *Temporal Analysis.* This phase detects inconsistencies in CÉU programs, such as unbounded loops, suspicious accesses to shared memory, and also "classical" semantic analysis, such as building a symbol table for checking variable declarations. This phase outputs code in *C*, given the way CÉU is tied to *C* by design. Some type checking is delayed to the last phase to take advantage of `gcc`'s error handling. Therefore, we annotate the *C* output file with `#line` pragmas matching the original file in CÉU.
> *Code Generation.* The final phase packs the generated *C* file with the CÉU runtime and platform-dependent functionality, compiling them with *gcc* and generating the final binary. The CÉU runtime comprehends the scheduler, timer management, and the external *C* API. The platform files include libraries for I/O and bindings to invoke the CÉU scheduler on external events.
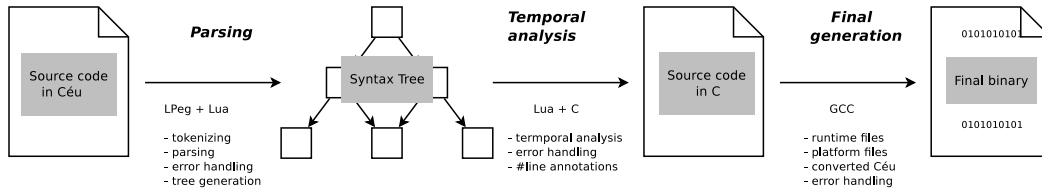
Fig. 15. Compilation process: from the source code in CÉU to the final binary.

```
1   input void A, B;                1   Stmts I={.} O={A}
2   var int y;                      2      Dcl_y I={.} O={.}
3   par/or do                       3      ParOr I={.} O={A,B}
4      await A;                      4         Stmts I={.} O={A}
5      y = 1;                        5            Await_A I={.} O={A}
6   with                            6            Set_y I={A} O={A}
7      await B;                      7         Stmts I={.} O={B}
8      y = 2;                        8            Await_B I={.} O={B}
9   end                             9            Set_y I={B} O={B}
10  await A;                        10     Await_A I={A,B} O={A}
11  y = 3;                          11     Set_y I={A} O={A}
```

Fig. 16. A program with a corresponding AST describing the sets I and O. The program is safe because accesses to y in parallel have no intersections for I.

4.1. Temporal Analysis for Shared-Memory Concurrency

The compile-time *temporal analysis* phase detects inconsistencies in CÉU programs. Here, we focus on the algorithm that detects suspicious access to shared variables, as discussed in Section 2.2.

For each node representing a statement in the program AST, we keep the set of events I (for *incoming*) that can lead to the execution of the node, and also the set of events O (for *outgoing*) that can terminate the node.

A node inherits the set I from its direct parent and calculates O according to its type:

— Nodes that represent expressions, assignments, C calls, and declarations simply reproduce $O = I$, as they do not await;
— An await e statement has $O = \{e\}$.
— A break statement has $O = \{\}$ as it escapes the innermost loop and never terminates, i.e., never proceeds to the statement immediately following it (see also loop below);
— A *sequence node (;)* modifies each of its children to have $I_n = O_{n-1}$. The first child inherits I from its parent node, and the set O for the sequence node is copied from its last child, i.e., $O = O_n$.
— A loop node includes its body's O on its own I ($I = I \cup O_{body}$), as the loop is also reached from its own body. The union of all break statements' O forms the set O for a loop.
— An if node has $O = O_{true} \cup O_{false}$.
— A parallel composition may terminate from any of its branches, hence $O = O_1 \cup ... \cup O_n$.

With all sets calculated, we take all pairs of nodes that perform side effects and are in parallel branches, comparing their sets I for intersections. For each pair, if the intersection is not the empty set, we mark both nodes as suspicious.

The example in the left of Figure 16 has a corresponding AST, in the right of the figure, with the sets I and O for each node. The event . (dot) represents the "boot" reaction. The assignments to y in parallel (ln. 5,8 in the code) have an empty intersection of I (ln. 6,9 in the AST), hence, they do not conflict. Note that although the accesses in ln. 5,11 in the code (ln. 6,11 in the AST) do have an intersection, they are not in parallel and are also safe.

4.2. Memory Layout

CÉU favors a fine-grained use of trails, being common the use of trails that await a single event. For this reason, CÉU does not allocate per-trail stacks; instead, all data resides in fixed memory slots—this is true for the program variables as well as for temporary values and runtime flags. Memory for trails in parallel must coexist, while statements in sequence can reuse it. Translating this idea to C is straightforward [Kas-

```
input int A, B, C;              union {              // sequence
do                                  int a_1;         //   do_1
    var int a = await A;            int b_2;         //   do_2
end                                 struct {         //   par/and
do                                      int _and_3: 1;
    var int b = await B;                int _and_4: 1;
end                                 };
par/and do                      } MEM ;
    await B;
with
    await C;
end
```

Fig. 17. A program with blocks in sequence and in parallel, with corresponding memory layout that the compiler generates.

ten and Römer 2005; Bernauer and Römer 2013]: memory for blocks in sequence are packed in a struct, while blocks in parallel, in a union. CÉU reserves a single static block of memory to hold all memory slots, whose size is the maximum the program uses at a given time. A given position in the memory may hold different data (with variable sizes) during runtime. As an example, Figure 17 shows a program with corresponding memory layout. Each variable is assigned a unique id (e.g. a_1) so that variables with the same name can be distinguished. The do-end blocks in sequence are packed in a union, given that their variables cannot be in scope at the same time, e.g., MEM.a_1 and MEM.b_2 can safely share the same memory slot. The example also illustrates the presence of runtime flags related to the parallel composition, which also reside in reusable slots in the static memory.

4.3. Trail Allocation

Each line of execution in CÉU needs to carry associated data, such as which event it is awaiting and which code to execute when it awakes. The compiler statically infers the maximum number of trails a program can have at the same time and creates a static vector to hold the runtime information about them. Like normal variables, trails that cannot be active at the same time can share slots in the static memory vector.

At any given moment, a trail can be awaiting in one of the following states: INACTIVE, STACKED, FIN, or in any of the events defined in the program:

```
enum {
    INACTIVE = 0,
    STACKED,
    FIN,
    EVT_A,        // input void A;
    EVT_e,        // event int e;
    <...>         // other events
}
```

All terminated or not-yet-started trails stay in the INACTIVE state and are ignored by the scheduler. A STACKED trail holds an associated stack level and is delayed until the scheduler runtime reaches that level again. A FIN trail represents a hanged finalization block which is only scheduled when its corresponding block goes out of scope. A trail waiting for an event stays in the state of the corresponding event, also holding the minimum sequence number (*seqno*) in which it can awake. In concrete terms, a trail is represented by the following struct:

```
struct trail_t {
    state_t evt;
    label_t lbl;
    union {
        unsigned char seqno;
        stack_t       stk;
```

```
    };
};
```

The field `evt` holds the state of the trail (or the event it is awaiting); the field `lbl` holds the entry point in the code to execute when the trail is scheduled; the third field depends on the `evt` field and may hold the `seqno` for an event, or the stack level `stk` for a `STACKED` state.

The size of `state_t` depends on the number of events in the application; for an application with less than 253 events (plus the 3 states), one byte is enough. The size of `label_t` depends primarily on the number of `await` statements in the application—each `await` splits the code in two segments and requires a unique entry point in the code for its continuation. Additionally, split & join points for parallel compositions, `emit` continuations, and finalization blocks also require labels. The `seqno` could eventually overflow during execution (i.e., every 256 reactions). However, given that the scheduler traverses all trails on every reaction, it can adjust them to properly handle overflows (actually, 2 bits to hold the `seqno` is already enough). The size of `stack_t` depends on the maximum depth of nested emissions and is bounded to the maximum number of trails. In the worst case, a trail emits an event that awakes another trail, which emits an event that awakes another trail, and so on. The last trail cannot awake any trail, because they are all hanged in the `STACKED` state.

In the context of embedded systems, the size of `trail_t` is typically only 3 bytes (1 byte for each field), imposing a negligible memory overhead even for trails that only await a single event and terminate. For instance, the *CTP* collection protocol ported to CÉU reaches eight simultaneous lines of execution with an overhead of 2% in comparison to the original version in *nesC* [Gay et al. 2003] (a dialect of *C* for event-driven programming) [Sant'Anna et al. 2013].

4.4. Code Generation and Scheduling

In the final generated code in *C*, each trail label representing an entry point becomes a *switch case* with the associated code to execute. Figure 18 illustrates the generation process. For the program in the left of the figure, the compiler extracts the entry points and associated trails, e.g., the label `Awake_e` will execute on `TRAIL-0` (ln. 7). For each statement that pauses (`emit` and `await`), resumes (`par/and`, `par/or`, and `finalize`), or aborts (`par/or` and `break`), the compiler splits the trail into segments with associated entry points. The entry points translate to an `enum` in the generated code (ln. 1–10, in the middle of the figure). The state of trails translate to a vector of type `trail_t` with the maximum number of simultaneous trails (ln. 12–15). On initialization, `TRAIL-0` is set to execute the `Main` entry point (ln. 13), while all others are set to `INACTIVE` (in the example, only one, in ln. 14).

The scheduler executes in two passes: In the *broadcast* pass, the scheduler sets all trails that are waiting for the current event to `STACKED` in the current stack level. In the *dispatch* pass, the scheduler executes each trail that is `STACKED` to run in the current level, setting it immediately to `INACTIVE`.

During the dispatch pass, if a trail executes and emits an internal event, the scheduler increments the stack level and re-executes the two passes. After all trails are properly dispatched, the scheduler decrements the stack level and resumes the previous execution. For the first reaction chain, the scheduler starts from the *dispatch* pass, given that the `Main` label is the only one that can be active at the stack level 0 (ln. 13, in the middle of Figure 18).

The code the right of the Figure 18 dispatches a trail according to the current label to execute. For the first reaction, it executes the `Main` label in `TRAIL-0`. When the `Main` label reaches the `par/and`, it stacks `TRAIL-1` (ln. 4–7) and proceeds to the code in `TRAIL-0` (ln. 9–14), respecting the deterministic execution order. The code sets the running `TRAIL-0` to

```
input void A;                    1    enum {                         1    void dispatch (trail_t* t) {
event void e;                    2      Main = 1,   // ln 3           2      switch (t−>lbl) {
// TRAIL 0 — lbl Main           3      Awake_e,    // ln 7           3        case Main:
par/and do                       4      And_chk,    // ln 8,15        4          // activate TRAIL 1
  // TRAIL 0 — lbl Main          5      And_sub_2,  // ln 10          5          TRLS[1].evt = STACKED;
  await e;                       6      Awake_A_1,  // ln 12          6          TRLS[1].lbl = And_sub_2;
  // TRAIL 0 — lbl Awake_e       7      Emit_cont,  // ln 14          7          TRLS[1].stk = cur_stack;
  // TRAIL 0 — lbl And_chk       8      And_out,    // ln 17          8
with                             9      Awake_A_2   // ln 19          9          // code in the 1st trail
  // TRAIL 1 — lbl And_sub_2    10    };                             10          // await e;
  await A;                      11                                   11          TRLS[0].evt = EVT_e;
  // TRAIL 1 — lbl Awake_A_1    12    trail_t TRLS[2] = {            12          TRLS[0].lbl = Awake_e;
  emit e;                       13      { STACKED,  Main, 0 };        13          TRLS[0].seq = cur_seqno;
  // TRAIL 1 — lbl Emit_cont    14      { INACTIVE, 0,    0 };        14          break;
  // TRAIL 1 — lbl And_chk      15    };                             15
end                             16                                   16        case And_sub_2:
// TRAIL 0 — lbl And_out        17                                   17          // await A;
await A;                        18                                   18          TRLS[1].evt = EVT_A;
// TRAIL 0 — lbl Awake_A_2      19                                   19          TRLS[1].lbl = Awake_A_1;
                                20                                   20          TRLS[1].seq = cur_seqno;
                                21                                   21          break;
                                22                                   22
                                23                                   23        <...>  // other labels
                                24                                   24      }
.                               25    .                              25    }
```

Fig. 18. From left to right: static allocation of trails, entry-point labels, and dispatch function. In the left, the comments identify the trail indexes inferred by the compiler. In the middle, each trail segment has an associated numeric identifier generated by the compiler. In the right, the dispatcher uses a `switch` to associate each segment identifier with the corresponding code to execute.

await EVT_e on label Awake_e, and then halts with a break. The next iteration of dispatch takes TRAIL-1 and executes its registered label And_sub_2 (ln. 16–21), which sets TRAIL-1 to await EVT_A and also halts.

Regarding abortion and finalization, when a par/or terminates, the scheduler makes a *broadcast* pass for the FIN event, but limited to the range of trails covered by the terminating par/or. Trails that do not match the FIN are set to INACTIVE, as they have to be aborted. Given that trails in parallel are allocated in subsequent slots in the static vector TRLS, this pass only aborts the desirable trails. The subsequent *dispatch* pass executes the finalization code. Escaping a loop that contains parallel compositions also triggers the same abortion process.

4.5. The External *C* API

As a reactive language, the execution of a program in CÉU is guided entirely by the occurrence of external events. From the implementation perspective, there are three external sources of input into programs, which are all exposed as functions in a *C* API:

ceu_go_init():. initializes the program (e.g. trails) and executes the "boot" reaction (i.e., the Main label).

ceu_go_event(id,param):. executes the reaction for the received event id and associated parameter.

ceu_go_wclock(us):. increments the current time in microseconds and runs a reaction if any timer expires.

Given the semantics of CÉU, the functions are guaranteed to take a bounded time to execute. They also return a status code that says if the CÉU program has terminated after the reactions. Further calls to the API have no effect on terminated programs.

The bindings for the specific platforms are responsible for calling the functions in the API in the order that better suit their requirements. As an example, it is possible

```
1   implementation
2   {
3       #include "ceu.h"
4       #include "ceu.c"
5
6       event void Boot.booted () {
7           ceu_sys_init();
8   #ifdef CEU_WCLOCKS
9           call Timer.startPeriodic(10);
10  #endif
11      }
12
13  #ifdef CEU_WCLOCKS
14      event void Timer.fired () {
15          ceu_sys_wclock(10000);
16      }
17  #endif
18
19  #ifdef EVT_PHOTO_READDONE
20      event void Photo.readDone (uint16_t val) {
21          ceu_sys_go(EVT_PHOTO_READDONE, &val);
22      }
23  #endif
24
25  #ifdef EVT_RADIO_SENDDONE
26      event void RadioSend.sendDone (message_t* msg) {
27          ceu_sys_go(EVT_RADIO_SENDDONE, &msg);
28      }
29  #endif
30
31  #ifdef EVT_RADIO_RECEIVE
32      event message_t* RadioReceive.receive (message_t* msg) {
33          ceu_sys_go(EVT_RADIO_RECEIVE, &msg);
34          return msg;
35      }
36  #endif
37
38      <...>   // other events
39  }
```

Fig. 19. The *TinyOS* binding for CÉU.

to set different priorities for events that occur concurrently (i.e. while a reaction chain is running). However, a binding must never interleave or run multiple functions in parallel. This would break the CÉU sequential/discrete semantics of time.

As an example, Figure 19 shows our binding for *TinyOS* [Hill et al. 2000], which maps callbacks to input events in CÉU. The file ceu.h (ln. 3) contains all definitions for the compiled CÉU program, which are further queried through #ifdef's. The file ceu.c (ln. 4) contains the main loop of CÉU pointing to the labels defined in the program. The callback Boot.booted (ln. 6–11) is called by TinyOS on startup, so we initialize CÉU inside it (ln. 7). If the CÉU program uses timers, we also start a periodic timer (ln. 8–10) that triggers callback Timer.fired (ln. 13–17) every 10 milliseconds and advances the wall-clock time of CÉU (ln. 15)[6]. The remaining lines map pre-defined TinyOS events that can be used in CÉU programs, such as the light sensor (ln. 19–23) and the radio transceiver (ln. 25–36).

4.6. The Terra Virtual Machine

Terra is a system for programming wireless sensor network applications that uses CÉU as its scripting language [Branco et al. 2015]. Figure 20 shows the three basic elements

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[6]We also offer a mechanism to start the underlying timer on demand to avoid the "battery unfriendly" 10ms polling.

of Terra: CÉU as the scripting language, a set of customized pre-built components, and the embedded virtual-machine engine which can disseminate and install bytecode images dynamically. This approach aims to combine the flexibility of remotely uploading code with the expressiveness and safety guarantees of CÉU.
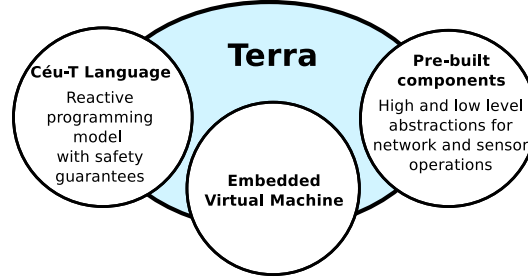

Fig. 20. Terra programming system basic elements.

In Terra, CÉU scripts cannot execute arbitrary *C* code, instead, they rely on pre-built components that can be customized for different application domains. Considering the domain of sensor networks, Terra already provides components organized in four areas: radio communication, group management, data aggregation, and local operations (e.g., access to sensors and actuators). When creating an instance of the *VM*, the programmer can choose whether or not to include each component, setting different abstraction boundaries for scripts. The generated *VM* has to be preloaded into the embedded devices before they are physically distributed.

The communication between scripts in CÉU and the components in the *VM* is mostly through events: scripts `emit` requests through `output` events and `await` answers through `input` events. Terra also provides system calls for initialization and configuration of components. TODO: explicar Figura 21.

TODO: dizer o que eh manual/automatico nos lsts de ceu

TODO-VM: exemplo de implementacao/uso de um componente - Terra: binding em nesC - Ceu: header de configuracao - (analogo a Figura 19)

Considering the compilation process illustrated in Figure 15 for the *C* back end, the main difference resides in the *Code Generation* phase, which here outputs assembly instructions for the Terra *VM*, instead of *C*.

```
// Message definition                        1
regtype sensorMsg with                       2   typedef nx_struct sensorMsg{
    var ubyte  id;                           3     nx_uint8_t   id;
    var ushort value;                        4     nx_uint16_t value;
end                                          5   } sensorMsg_t;
                                             6
// Output events definition                  7   enum {
output void REQ_TEMP void        1;          8     O_REQ_TEMP    = 1;
output void SEND_SENSOR sensorMsg 2;         9     O_SEND_SENSOR = 2;
                                            10
// Input events definition                  11
input void TEMP void             1;         12     I_TEMP        = 1;
                                            13
// functions definitions                    14
function ubyte getNodeId()       1;         15     F_GETNODEID   = 1;
function ubyte queuePut(sensorMsg) 2;       16     F_QUEUEPUT    = 2;
.                                           17   };
```

Fig. 21. Terra control block sample and the equivalent definition for VM implementation.

```
1   // Output event dispatcher
2   command void VM.procOutEvt(uint8_t id, uint32_t value){
3     switch (id){
4       case O_REQ_TEMP    : proc_req_temp(id,value);     break;
5       case O_SEND_SENSOR : proc_send_sensor(id,value); break;
6     }
7   }
8
9   // Function dispatcher
10  command void VM.callFunction(uint8_t id){
11    switch (id){
12      case F_GETNODEID : func_getNodeId(id); break;
13      case F_QUEUEPUT  : func_queuePut(id);  break;
14    }
15  }
16
17  // Pushing a value to the stack
18  void  func_getNodeId(uint16_t id){
19    uint16_t stat;
20    stat = TOS_NODE_ID;
21    signal VM.push(stat);
22  }
23
24  // Calling a output event
25  void  proc_req_temp(uint16_t id, uint32_t value){
26    call S_TEMP.read();
27  }
28
29  // Queueing an input event + value
30  uint16_t lastTemp;
31  event void S_TEMP.readDone(error_t result, uint16_t val)
32    lastTemp = val;
33    signal VM.queueEvt(I_TEMP, 0, &lastTemp);
34  }
```

Fig. 22.   VM Customization – input/output events and functions.

TODO-VM: falar um pouco do assembly/bytecode, quais as decisoes envolvidas - (analogo a Figura 18)

5. RELATED WORK

(As subsecoes serao retiradas do texto ao final...)

5.1. Semantics

CÉU has a strong influence from Esterel and embraces the disciplined synchronous-reactive model and support for lexical composition of lines of execution. However, there are fundamental semantic differences that prevents the design of CÉU as pure extensions to Esterel (i.e., on top of its formal semantics). In particular, Esterel has a notion of time similar to that of digital circuits in which multiple signals can be active at a clock tick. In fact, Esterel is also used in hardware design. In CÉU, instead of clock ticks, the occurrence of a single external event that defines a time unit. CÉU also distinguishes external events from stack-based internal events, which provide a limited form of coroutines supporting reactive statements (e.g., await and par/or).

The event-driven approach of CÉU is well known [Ousterhout 1996] and popular in many software communities, such as client and server-side web frameworks (e.g., *jQuery* [Chaffer 2009] and *Node.js* [Tilkov and Vinoski 2010]), GUI toolkits (e.g., *Tcl/Tk* [Ousterhout 1991] and *Java Swing* [Eckstein et al. 1998]), and Games [Nystrom 2014]. Like CÉU, event-driven programming is essentially synchronous, i.e., events go through a queue and are dispatched sequentially and atomically to prevent race conditions. We believe that for software design, this approach is more famil-

iar to programmers and simplifies the reasoning about concurrency. For instance, the uniqueness of external events in CÉU is a prerequisite for the temporal analysis that enables safe shared-memory concurrency.

A number of synchronous languages have been designed to interoperate with C, such as *Reactive C* [Boussinot 1991], Protothreads [Dunkels et al. 2006], *PRET-C* [Andalam et al. 2010] and *SC* [Von Hanxleden 2009]. They offer Esterel-like parallel compositions with communication via shared variables, relying on deterministic scheduling to preserve determinism. However, it is the responsibility of the programmer to specify the execution order for threads, based on either explicit priorities, or source code lexical order (like CÉU). These languages have a tick-based notion of time similar to Esterel, which prevents the event-based temporal analysis of CÉU.

URBI [Baillie 2005] is a reactive scripting language with a rich set of control constructs for time management, event-driven communication, and concurrency. Concurrency is based on stackful coroutines, diverging from our goals regarding resource efficiency and static bounds for memory and execution time.

TODO-VM

5.2. Implementation

Esterel has different compilation back ends that synthesizes to software and also to hardware circuits [Dayaratne et al. 2005; Edwards 2003]. Among the software-based approaches, *SAXO–RT* [Closse et al. 2002] is the closest to our implementation with respect to trail allocation and scheduling: the compiler slices programs into "control points" (analogous to our "entry points") and rearranges them into a directed acyclic graph respecting the constructive semantics of Esterel. Then, it flattens the graph into sequential code in *C* suitable for static scheduling.

TODO-VM

6. CONCLUSION

We presented the design, semantics, and implementation of CÉU, a synchronous reactive language based on Esterel targeting constrained embedded systems.

CÉU is a concurrency-safe language, employing a static analysis that encompass all control constructs and ensures that the high degree of concurrency in embedded systems does not pose safety threats to applications. As a summary, the following safety properties hold for all programs that successfully compile in CÉU: time and memory-bounded reactions to the environment (except for external system calls), no race conditions in shared memory, reliable abortion for activities handling resources, and automatic synchronization for timers. These properties are usually desirable in applications and are guaranteed as preconditions in CÉU by design.

CÉU is a resource-efficient language suitable for constrained embedded systems. The reference implementation compiles to portable event-driven code in *C*, with no special requirements for OS threads or per-trail data stacks. The *VM* implementation uses the same front end and imposes no extra restrictions, being equally suitable for constrained systems.

CÉU is a practical language with expressive control constructs, such as lexically scoped parallel compositions, convenient first-class timers, and a unique stack-based signaling mechanism. Programs interoperate seamlessly with *C*, and can take advantage of existing libraries, lowering the entry barrier for adoption. CÉU has an open source implementation and bindings for *TinyOS*, *Arduino*, and the *SDL* graphical library.[7]

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[7]Website of CÉU: http://www.ceu-lang.org/

For the past three years, we have been teaching CÉU for undergraduate and graduate students in research projects and two hands-on courses on *distributed systems* and *reactive programming*. Our experience shows that students take advantage of the sequential-imperative style of CÉU and can implement non-trivial concurrent applications in a few of weeks.

REFERENCES

Sidharta Andalam and others. 2010. Predictable multithreading of embedded applications using PRET-C. In *Proceeding of MEMOCODE'10*. IEEE, 159–168.

Jean-Christophe Baillie. 2005. Urbi: Towards a universal robotic low-level programming language. In *International Conference on Intelligent Robots and Systems*. IEEE, 820–825.

Albert Benveniste and others. 2003. The synchronous languages twelve years later. In *Proceedings of the IEEE*, Vol. 91. 64–83.

Alexander Bernauer and Kay Römer. 2013. A Comprehensive Compiler-Assisted Thread Abstraction for Resource-Constrained Systems. In *Proceedings of IPSN'13*. Philadelphia, USA.

Gérard Berry. 1993. Preemption in Concurrent Systems.. In *FSTTCS (LNCS)*, Vol. 761. Springer, 72–93.

G. Berry. 2000. *The Esterel-V5 Language Primer*. CMA and Inria, Sophia-Antipolis, France. Version 5.10, Release 2.0.

Frédéric Boussinot. 1991. Reactive C: An extension of C to program reactive systems. *Software: Practice and Experience* 21, 4 (1991), 401–428.

F. Boussinot and R. de Simone. 1991. The Esterel language. *Proc. IEEE* 79, 9 (Sep 1991), 1293–1304.

Adriano Branco, Francisco Sant'anna, Roberto Ierusalimschy, Noemi Rodriguez, and Silvana Rossetto. 2015. Terra: Flexibility and Safety in Wireless Sensor Networks. *ACM Trans. Sen. Netw.* 11, 4, Article 59 (Sept. 2015), 27 pages. DOI:http://dx.doi.org/10.1145/2811267

Jonathan Chaffer. 2009. *Learning JQuery 1.3: Better Interaction and Web Development with Simple JavaScript Techniques*. Packt Publishing Ltd.

Etienne Closse and others. 2002. Saxo–RT: Interpreting esterel semantic on a sequential execution structure. *Electronic Notes in Theoretical Computer Science* 65, 5 (2002), 80–94.

Sajeewa Dayaratne and others. 2005. Direct Execution of Esterel Using Reactive Microprocessors. In *Proceedings of SLAP'05*.

Dunkels and others. 2006. Protothreads: simplifying event-driven programming of memory-constrained embedded systems. In *Proceedings of SenSys'06*. ACM, 29–42.

Robert Eckstein, Marc Loy, and Dave Wood. 1998. *Java swing*. O'Reilly & Associates, Inc.

Stephen A Edwards. 1999. Compiling Esterel into sequential code. In *7th International Workshop on Hardware/Software Codesign*. ACM, 147–151.

Stephen A Edwards. 2003. Tutorial: Compiling concurrent languages for sequential processors. *ACM Transactions on Design Automation of Electronic Systems* 8, 2 (2003), 141–187.

David Gay and others. 2003. The nesC Language: A Holistic Approach to Networked Embedded Systems. In *PLDI'03*. 1–11.

Omprakash Gnawali and others. 2009. Collection tree protocol. In *Proceedings of SenSys'09*. ACM, 1–14.

Hill and others. 2000. System architecture directions for networked sensors. *SIGPLAN Notices* 35 (November 2000), 93–104. Issue 11.

Roberto Ierusalimschy. 2009. A text pattern-matching tool based on Parsing Expression Grammars. *Softw. Pract. Exper.* 39 (March 2009), 221–258. Issue 3.

Marcin Karpinski and Vinny Cahill. 2007. High-Level Application Development is Realistic for Wireless Sensor Networks. In *Proceedings of SECON'07*. 610–619.

Oliver Kasten and Kay Römer. 2005. Beyond Event Handlers: Programming Wireless Sensors with Attributed State Machines. In *Proceedings of IPSN '05*. 45–52.

Ana Lúcia De Moura and Roberto Ierusalimschy. 2009. Revisiting coroutines. *ACM TOPLAS* 31, 2 (Feb. 2009), 6:1–6:31.

Robert Nystrom. 2014. *Game Programming Patterns*. Genever Benning.

ORACLE. 2011. Java Thread Primitive Deprecation. http://docs.oracle.com/javase/6/docs/technotes/guides/concurrency/threadPrimitiveDeprecation.html (accessed in Aug-2014). (2011).

John Ousterhout. 1996. Why Threads Are A Bad Idea (for most purposes). (January 1996).

John K Ousterhout. 1991. An X11 Toolkit Based on the Tcl Language.. In *USENIX Winter*. 105–116.

Dumitru Potop-Butucaru and others. 2005. The Synchronous Hypothesis and Synchronous Languages. In *Embedded Systems Handbook*, R. Zurawski (Ed.).

Francisco Sant'Anna and others. 2013. Safe System-level Concurrency on Resource-Constrained Nodes. In *Proceedings of SenSys'13*. ACM.

Olivier Tardieu and Robert De Simone. 2003. Instantaneous termination in pure Esterel. In *Static Analysis*. Springer, 91–108.

Stefan Tilkov and Steve Vinoski. 2010. Node.js: Using JavaScript to build high-performance network programs. *IEEE Internet Computing* 6 (2010), 80–83.

Reinhard Von Hanxleden. 2009. SyncCharts in C: a proposal for light-weight, deterministic concurrency. In *Proceedings of the seventh ACM international conference on Embedded software*. ACM, 225–234.

Jeong-Han Yun, Chul-Joo Kim, Seonggun Kim, Kwang-Moo Choe, and Taisook Han. 2013. Detection of harmful schizophrenic statements in esterel. *ACM Transactions on Embedded Computing Systems (TECS)* 12, 3 (2013), 80.