

Structured Reactive Programming with Céu

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ABSTRACT

We promote structured reactive programming, an extension to classical structured programming that supports continuous interaction with the environment. We revive the synchronous and imperative programming style of Esterel and aim to expand its limits from the strict embedded domain with the new abstraction mechanism of *organisms* for the language Céu.

Organisms extends objects with an execution body that compose multiple lines of execution and can react to the environment independently. Compositions bring structured reasoning to concurrency and can better describe state machines typical of reactive applications. Organisms are subject to lexical scope and automatic memory management similar to locals in a stack. We show that this model does not require garbage collection or a *free* primitive in the language, eliminating memory leaks by design.

Categories and Subject Descriptors

D.3.3 [Programming Languages]: Language Constructs and Features

General Terms

Design, Languages

Keywords

Concurrency, Determinism, Esterel, Imperative, Structured Programming, Synchronous, Reactivity

1. INTRODUCTION

Reactive applications interact continuously and in real time with external stimuli from the environment [17, 4]. They represent a wide range of software areas and platforms: from games in powerful desktops, “apps” in capable smart phones, to the emerging internet of things in constrained embedded systems.

Research on special-purpose reactive languages dates back

to the early 80’s with the co-development of two complementary styles [5, 23]: The imperative style of Esterel [8] organizes programs with structured control flow primitives, such as sequences, repetitions, and parallelism. The dataflow style of Lustre [16] represents programs as graphs of values, in which a change to a node updates its dependencies automatically.

In recent years, Functional Reactive Programming [27] modernized the dataflow style and became mainstream, deriving a number of languages and libraries, such as Flapjax [21], Rx (from Microsoft), React (from Facebook), and Elm [9]. In contrast, the imperative style of Esterel did not follow this trend and is now confined to the domain of real-time embedded control systems.

As a matter of fact, imperative reactivity is now often associated to the *observer pattern*, typical in object oriented systems, because it heavily relies on side effects [19, 24]. However, short-lived callbacks (i.e., the observers) eliminate any vestige of structured programming, such as support for long-lasting loops and automatic variables [3], which are elementary capabilities of imperative languages. In this sense, callbacks actually disrupt imperative reactivity, becoming “our generation’s *goto*” [12, 11, 14].

In this work, we revive the imperative style of Esterel, which we now refer as *Structured Reactive Programming (SRP)*. SRP extends the classical hierarchical control constructs of *Structured Programming (SP)* (i.e., concatenation, selection, and repetition [13]) to support continuous interaction with the environment. In practical terms, SRP provides two extensions to SP: an “*await* <event>” statement that suspends a line of execution until the referred event occurs, keeping all context alive; and parallel constructs that compose multiple lines of execution and make them concurrent. The *await* statement represents the imperative and reactive nature of SRP, recovering sequential execution lost with the observer pattern. Parallel compositions¹ allow for multiple *await* statements to coexist, which is necessary to handle concurrent events, common in reactive applications.

We advocate SRP through the Esterel-based language Céu [25], a contemporary outlook of imperative reactivity that aims to expand it from the rigid embedded domain.

¹We use the term *parallel composition* as a synonym for *side-by-side lexical composition*, which does not imply many-core parallel execution.

The rigorous semantics of Esterel, which focus on static safety guarantees, is not suitable for other reactive application domains, such as GUIs, games, and distributed systems. For instance, the lack of abstractions with dynamic lifetime makes difficult to deal with virtual resources such as graphical widgets, game units, and network sessions.

Our main contribution is a new abstraction mechanism for CÉU, the *organisms*, that encapsulate parallel compositions with an object-like interface. In brief, organisms are to SRP like procedures are to SP, i.e., one can abstract a portion of code with a name and manipulate (call) that name from multiple places. There are, however, additional challenges that apply to organisms:

- Organisms are themselves alive, acting as subprograms with continuous data and control state.
- Organisms are part of a concurrent program that can manipulate and affect their data and execution state.
- Organisms can be dynamically allocated, requiring a memory management model that must also apply to embedded systems.

The rest of the paper is organized as follows: Section 2 presents SRP through CÉU, with its underlying synchronous concurrency model and parallel compositions. Section 3 presents the organisms abstraction with static and dynamic instantiation, lexical scope, and automatic memory management. Section 4 discusses related work. Section 5 concludes the paper.

2. SRP WITH CÉU

CÉU is a concurrent language, in which its lines of execution, known as *trails*, react all together in synchronous steps and continuously to external stimuli. Figure 1 shows a compact reference of CÉU.

The introductory example of Figure 2 starts two trails with the `par` construct: the first (lines 4-8) increments variable `v` on every second and prints its value on screen; the second (lines 10-13) resets `v` on every external request to `RESET`. Programs in CÉU can access *C* libraries of the underlying platform by prefixing symbols with an underscore (e.g., `_printf(<...>)`, in line 7).

2.1 Synchronous concurrency

In the synchronous execution model of CÉU, a program must react completely to an occurring event before handling the next. A reaction represents a logical instant in which all trails awaiting the occurring event awake and execute, one after the other, until they await again or terminate. During a reaction, the environment is invariant and does not interrupt the running trails². If multiple trails react to the same event, the scheduler employs lexical order to preserve determinism, i.e., the trail that appears first in the source code executes first. To avoid infinite execution for reactions, CÉU ensures that all loops have `await` statements on their bodies [25].

As a result of synchronous execution, all operations to variable `v` in Figure 2 are atomic because reactions to `1s` and

²The actual implementation enqueues incoming input events to process them in further reactions.

```
// DECLARATIONS
input <type> <id>;           // external event
event <type> <id>;           // internal event
var <type> <id>;             // variable

// EVENT HANDLING
await <id>;                  // awaits event
emit <id> => <exp>;          // emits event

// COMPOUND STATEMENTS
<...> ; <...> ;              // sequence
if <...> then <...>          // conditional
    else <...> end
loop do <...> end            // repetition
    break                    // (escape repetition)

// PARALLEL COMPOSITIONS
par/and do <...>             // rejoins on both sides
    with <...> end
par/or do <...>              // rejoins on any side
    with <...> end
par do <...>                 // never rejoins
    with <...> end

// C INTEGRATION
_f();                        // C call (prefix '_'')
finalize <...>              // finalization
    with <...> end

// ORGANISMS
class <T> with               // class definition
    <interface>
do
    <body>
end
var <T> <id> with            // static instantiation
    <constructor>
end;
spawn <T> with              // dynamic instantiation
    <constructor>
end;
```

Figure 1: Syntax of Céu.

RESET can never interrupt each other. In contrast, in asynchronous models with nondeterministic scheduling, the occurrence of RESET could preempt the first trail during an increment to `v` (line 6) and reset it (line 12) before printing it (line 7), characterizing a race condition on the variable. The example illustrates the (arguably simpler) reasoning about concurrency aspects under the synchronous execution model.

The synchronous model also empowers SRP with an orthogonal abortion construct that simplifies the composition of activities³. Orthogonal abortion is the ability to abort an activity from outside it, without affecting the overall consistency of the program (e.g., properly releasing global resources). The example that follows shows the `par/or` construct of CÉU which composes trails and rejoin when either of them terminates, properly aborting the other:

```
par/or do
    <trail-1>
with
    <trail-2>
end
<subsequent-code>
```

The `par/or` is regarded as orthogonal because the composed trails do not know when and how they are aborted (i.e.,

³We use the term activity to generically refer to a language's unit of execution (e.g., *thread*, *actor*, *trail*, etc.).

```

1 input void RESET; // declares an external event
2 var int v = 0;
3 par do
4   loop do // 1st trail
5     await 1s;
6     v = v + 1;
7     _printf("v = %d\n", v);
8   end
9 with
10  loop do // 2nd trail
11    await RESET;
12    v = 0;
13  end
14 end

```

Figure 2: Introductory example in Céu.

abortion is external to them).

Abortion in asynchronous languages is challenging [6] because the activity to be aborted might be on a inconsistent state (e.g., holding pending messages or locks). This way, the language runtime needs to wait for the activity to be consistent before aborting it, resulting in two unsatisfactory semantics for a hypothetical **par/or**: either wait to rejoin, making the program unresponsive to incoming events for an arbitrary time; or rejoin immediately and let the activity complete termination in the background, which may cause race conditions with the subsequent code.

In fact, asynchronous languages do not provide effective abortion: *Java*’s `Thread.stop` primitive has been deprecated [22]; *pthread*’s `pthread_cancel` does not guarantee immediate cancellation [2]; *erlang*’s `exit` either enqueues a terminating message (which may take time), or unconditionally terminates the process (regardless of its state) [1]; and *CSP* only supports a composition operator that “*terminates when all of the combined processes terminate*” [18]. As an alternative, asynchronous activities typically agree a on common protocol to abort each other (e.g., through shared state variables or message passing), increasing coupling among them with implementation details that are not directly related to the problem specification.

Synchronous languages, however, provide accurate control over the life cycle of concurrent activities because in between every reaction, the whole system is idle and consistent [6]. In Section 2.2 we show how Céu deals with abortion of trails that use stateful resources from the environment, such as file and network handlers.

2.2 Parallel compositions

In terms of control structures, SRP basically extends SP with parallel compositions, allowing applications to handle multiple events concurrently. Céu provides three parallel constructs, which vary on how they rejoin: a **par/and** rejoins when all trails in parallel terminate; a **par/or** rejoins when any trail in parallel terminates; a **par** never rejoins (even if all trails in parallel terminate). The example that follows compares the **par/and** and **par/or** compositions side by side:

```

1 input void START, STOP, RETRANSMIT;
2 loop do
3   await START;
4   par/or do
5     await STOP;
6   with
7     loop do
8       par/or do
9         await RETRANSMIT;
10      with
11        await <rand> s;
12      par/and do
13        await 1min;
14      with
15        <send-beacon-packet>
16      end
17    end
18  end
19 with
20    <...> // the rest of the protocol
21  end
22 end

```

Figure 3: Parallel compositions can describe complex state machines.

<pre> loop do par/and do <...> with await 1s; end end </pre>	<pre> loop do par/or do <...> with await 1s; end end </pre>
--	---

The code `<...>` represents a complex behavior with any degree of nested compositions. In the **par/and** variation, the behavior repeats every second at minimum because both sides must terminate before re-executing the loop. In the **par/or** variation, if the behavior does not terminate within 1 second, it is restarted. These SRP archetypes represent, respectively, the *sampling* and *timeout* patterns, which are typical of reactive applications.

The code of Figure 3 relies on hierarchical **par/or** and **par/and** compositions to describe the state machine of a protocol for sensor networks [15, 25]. The input events `START`, `STOP`, and `RETRANSMIT` (line 1) represent the external interface of the protocol with a client application. The protocol enters the top-level loop and awaits the starting event (line 3). Once the client application makes a start request, the protocol starts three other trails: one to await the stopping event (line 5); one to periodically transmit a status packet (lines 7-18); and one with the remaining functionality of the protocol (collapsed in line 20). As compositions can be nested, the periodic transmission is another loop that starts two other trails (lines 8-17): one to handle an immediate retransmission request (line 9); and one to await a small random amount of time and transmit the status packet (lines 11-16). The transmission (collapsed in line 15) is enclosed with a **par/and** that takes at least one minute before looping, to avoid flooding the network. At any time, the client may request a retransmission (line 9), which terminates the **par/or** (line 8), aborts the ongoing transmission (line 15, if not idle), and restarts the loop (line 7). Also, the client may request to stop the whole protocol at any time (line 5), which terminates the outermost **par/or** and aborts the transmission and all composed trails. In this case, the top-

level loop restarts and waits for the next request to start the protocol (line 3), ignoring all other requests as specified.

The example shows how parallel compositions can describe complex state machines in a structured way, eliminating the use of global state variables for this purpose [25].

2.2.1 Finalization

The C  U compiler tracks the interaction of `par/or` compositions with local variables and stateful native *C* functions (e.g., device drivers) to guarantee that trail abortion is always safe.

Consider the code that follows on the left side, which expands the sending trail of Figure 3 (line 15):

<pre>var _packet_t buffer; <fill-buffer-info> _send_enqueue(&buffer); await SEND_ACK;</pre>	<pre>var _packet_t buffer; <fill-buffer-info> finalize _send_enqueue(&buffer) with _send_dequeue(&buffer); end await SEND_ACK;</pre>
---	--

The `buffer` packet is a local variable whose address is passed to native function `_send_enqueue`. The call enqueues the pointer in the radio driver, which holds it up to the occurrence of `SEND_ACK` acknowledging the packet transmission. In the meantime, the sending trail might be aborted from `STOP` or `RETRANSMIT` requests (Figure 3, lines 5 and 9), making the packet buffer to go out of scope, and leading to a *dangling pointer* in the radio driver. C  U refuses to compile programs like this and requires *finalization* clauses to accompany stateful native calls [25]. The code on the right above properly dequeues the packet if the block of `buffer` goes out of scope, i.e., the finalization clause (after the `with`) executes automatically on abortion.

Finalization clauses are fundamental to preserve the orthogonality of `par/or` compositions in SRP.

3. ORGANISMS: SRP ABSTRACTIONS

Applications often need to replicate a behavior and rely on abstractions that the language provides. In SP, the typical abstraction mechanism are procedures, which abstract recurrent routines with meaningful names that can be invoked multiple times with different parameters. However, procedures have a single entry point, and were not devised for continuous and concurrent input. For instance, procedures cannot express parallel compositions as described in Section 2.2. The prevailing imperative abstraction mechanism for reactive applications are objects used in conjunction with the observer pattern. Even though objects abstract data with proper encapsulation, they cannot encapsulate control flow because methods have to return as quickly as possible to keep the application responsive [?].

C  U abstracts data and control state into the single concept of organisms. A class of organisms describes an interface and a single execution body. The interface exposes public variables, methods, and also internal events (exemplified further). The body can contain any valid code in

C  U, including parallel compositions. When an organism is instantiated, its body starts to execute in parallel with the program. Organism instantiation can be either static or dynamic.

The example of Figure 4 introduces static organisms with three code chunks:

- The leftmost code (*CODE-1*) blinks two LEDs with different frequencies in parallel and terminates after 1 minute.
- The code in the middle (*CODE-2*) abstracts the blinking LEDs in an organism class and uses two instances to reproduce the same behavior of *CODE-1*.
- The rightmost code (*CODE-3*) is the equivalent expansion of the organisms bodies, which should resemble the original *CODE-1*.

In *CODE-2*, the `Blink` class (lines 1-9) exposes the `pin` and `dt` properties, corresponding to the LED I/O pin and the blinking period, respectively. The application then creates two instances, specifying those properties in the constructors (lines 12-15 and 17-20). Inside constructors, the identifier `this` refers to the organism under instantiation. The constructors automatically start the organisms bodies (lines 5-8) to run in parallel in the background, i.e., both instances are already running before the `await 1min` (line 22).

CODE-3 is semantically equivalent to *CODE-2*, but with the organisms constructors and bodies expanded (lines 10-17 and 19-26). The generated `par/or` makes the instances concurrent with the rest of the application (i.e., `await 1min`, in line 28). Note the `await FOREVER` statements (lines 17 and 26) to avoid the organisms bodies to terminate the `par/or`. The `_Blink` type (lines 1-4) corresponds to a simple datatype without an execution body. The actual implementation of C  U does not expand the organisms bodies like in *CODE-3*, instead, a class generates a single code for its body, which is shared by all instances (in the same way as objects share class methods).

The main distinction from organisms to standard objects is how they can react independently and directly to the environment, i.e., once instantiated they become alive and reactive (hence the name *organisms*). For instance, organisms need not be included in observer lists for events, or rely on the main program to feed their methods with input from the environment. Even though the organisms run independently from the main program, they are still subject to the disciplined synchronous model, which keeps the whole system deterministic, as the static expansion of *CODE-3* suggests (and based on the scheduler description of Section 2.1).

The memory model for organisms eliminates memory leaks, dangling pointers, and the need for garbage collection. The model is similar to stack-living local variables of procedures, providing lexical scope and automatic bookkeeping of organisms. We also restrict explicit manipulation of references to organisms to avoid unsafe access after they go out of scope, as we discuss in Section 3.2.

Regarding lexical scope and automatic memory management, note that *CODE-2* uses a `do-end` block (lines 11-23)

<pre> par/or do loop do await 600ms; _toggle(11); end with loop do await 1s; _toggle(12); end with await 1min; end </pre> <p>/* CODE-1: original blinking */</p>	<pre> 1 class Blink with 2 var int pin; 3 var int dt; 4 do 5 loop do 6 await (this.dt)ms; 7 _toggle(this.pin); 8 end 9 end 10 11 do 12 var Blink b1 with 13 this.pin = 11; 14 this.dt = 600; 15 end; 16 17 var Blink b2 with 18 this.pin = 12; 19 this.dt = 1000; 20 end; 21 22 await 1min; 23 end 24 25 26 27 28 29 30 31 32 </pre> <p>/* CODE-2: blinking organisms */</p>	<pre> 1 struct _Blink with 2 var int pin; 3 var int dt; 4 end; 5 6 do 7 var _Blink b1, b2; 8 9 par/or do 10 // body of b1 11 b1.pin = 11; 12 b1.dt = 600; 13 loop do 14 await (b1.dt)ms; 15 _toggle(b1.pin); 16 end 17 await FOREVER; 18 with 19 // body of b2 20 b2.pin = 12; 21 b2.dt = 1000; 22 loop do 23 await (b2.dt)ms; 24 _toggle(b2.pin); 25 end 26 await FOREVER; 27 with 28 await 1min; 29 end 30 end 31 32 </pre> <p>/* CODE-3: organisms expansion */</p>
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Figure 4: Two blinking LEDs using organisms.

that limits the scope of the organisms for 1 minute (line 22). During that period, the organisms are accessible (through `b1` and `b2`) and reactive to the environment (i.e., blinking continuously). After that period, the organisms go out of scope and not only they become inaccessible but their bodies are automatically aborted, as the expansion of *CODE-3* makes clear: The `par/or` (lines 9-29) aborts the organisms bodies after 1 minute (line 28), just before they go out of scope (line 30). The `par/or` termination also properly triggers all active finalization clauses inside the organisms (if any). Lexical scope extends the idea of orthogonal abortion to organisms, as they are automatically aborted when going out of scope.

In addition to properties and methods, organisms also expose internal events which support `await` and `emit` operations. In the example of Figure 5, the class `Unit` (lines 1-16) defines the position property `pos` with default value 0 (line 2), and the event `move` for requests to move the unit position (line 3). The main program (lines 18-28) creates two units and requests them to move to position 500 with a interval of 1 second. The body of the class initializes the current unit's destination position `dst` to the current position (line 5). Then, the body enters a continuous loop (lines 6-15) to handle `move` requests (line 8) while performing the actual moving operation (lines 10-13) in parallel. The `par/or` restarts the loop on every `move` request, which updates the `dst` position. The moving operation can be as complex as needed, for example, using another loop to apply physics over time. The `await FOREVER` (line 13) halts the trail after the move completes. An advantage of event handling over method calls is that they can be composed in the organism body to affect other ongoing operations. In the example, the `await move` (line 8) aborts and restarts the moving operation,

just like the timeout pattern of Section 2.2.

3.1 Dynamic organisms

Static embedded systems typically manipulate real sensors and actuators hardware with a one-to-one correspondence in software, i.e., a static piece of software deals with a corresponding piece of hardware. In contrast, more general reactive systems have to deal with resource virtualization that require dynamic allocation, such as multiplexing protocols in a network, or simulating entire civilizations in a game. Dynamic allocation for organisms extends the power of SRP to handle virtual resources in reactive applications.

C  U supports dynamic instantiation of organisms through the `spawn` primitive. The example that follows spawns a new instance of `Unit` on every second and moves it to a random position:

```

loop do
  await 1s;
  var Unit* u = spawn Unit with
    this.pos = _rand() % 500;
  end;
  emit u:move => _rand() % 500;
end

```

The `spawn` allocates the new organism and returns a pointer to it, which can be later dereferenced with the operator `:'` (analogous to `'->'` of *C/C++*).

Dynamic instances also execute in parallel with the rest of the application, but have different lifetime and scoping rules than static ones: A static instance has an identifier and a well-defined scope that holds its memory resources; A dynamic instance is anonymous (i.e., `spawn` returns a pointer to it) and outlives the scope that spawns it.

```

1 class Unit with
2   var int pos = 0;
3   event int move;
4 do
5   var int dst = this.pos;
6   loop do
7     par/or do
8       dst = await this.move;
9     with
10      if dst != pos then
11        <code-to-move-pos-to-dst>
12      end
13      await FOREVER;
14    end
15  end
16 end
17
18 var Unit u1 with
19   this.pos = 100;
20 end;
21
22 var Unit u2 with
23   this.pos = 200;
24 end;
25
26 emit u1.move => 500;
27 await 1s;
28 emit u2.move => 500;

```

Figure 5: Organism manipulation through interface events.

In accordance with the reactive and independent nature of organisms, CÉU supports that a dynamic instance control its own lifetime: once its body terminates, a dynamic organism is automatically freed from memory. The example that follows redefines the body of the `Unit` class of Figure 5 to terminate after 1 hour, imposing a maximum life span in which a unit can react to move requests. After that, the body terminates and the organism is automatically freed:

```

class Unit with
  <...>           // interface
do
  par/or do
    <...>         // moving trail
  with
    await 1h;
  end
end
end

```

The lack of scopes for dynamic organisms prevents orthogonal abortion, given that there is no way to externally abort the execution of dynamic instances. To overcome this limitation, CÉU provides lexically scoped *pools* as containers that hold dynamic organisms instances. The example that follows declares the `units` pool to hold a maximum of 10 instances (line 3):

```

1 input void CLICK;
2 do
3   pool Unit[10] units;
4   par/or do
5     loop do
6       await 1s;
7       spawn Unit in units with
8         <...> // constructor
9       end;
10    end
11  with
12    await CLICK;
13  end
14 end

```

A new unit is spawned in this pool on every second (note the

in `units`, in line 7). Once the application receives a `CLICK` (line 12), the `par/or` terminates, making the `units` pool to go out of scope and abort/free all units alive.

Pools with bounded dimension (e.g., `pool Unit[10] units`), have static pre-allocation, resulting in efficient and deterministic organism instantiation. This opens the possibility for dynamic behavior also in constrained embedded systems. If a pool does not specify a dimension (e.g., `pool Unit[] units`), the instances go to the heap but are still subject to the pool scope. If a `spawn` does not specify a pool, as in “`spawn Unit;`”, the instances go to a predefined dimension-less pool in the top of the current class (and are still subject to that pool scope).

Note that lexical scope support for both static and dynamic organisms eliminate garbage collection, `free` primitives, and memory leaks altogether.

3.2 Pointers and References

As organisms react independently to the environment, it is often not necessary to hold pointers to organisms. In fact, pointers can be dangerous because they may last longer than the organisms they refer:

```

var Unit* u = spawn Unit;
u:pos = 0;           // this access is safe
await 2h;
emit u:move => 100;   // this access is unsafe

```

The example first acquires a pointer `u` to `Unit`. Then, it dereferences the pointer in two occasions: in the same reaction, just after acquiring the reference; and in another reaction, after `2h`, when the pointed organism may have already terminated and being freed.

CÉU enforces all pointer accesses across reactions to use the `watching` construct which supervises organism termination:

<pre> var Unit* u = spawn Unit; u:pos = 0; watching u do await 2h; emit u:move => 100; end </pre>	<pre> var Unit* u = spawn Unit; u:pos = 0; par/or do await u:__killed; with await 2h emit u:move => 100; end </pre>
--	--

The whole `watching` construct aborts whenever the referred organism terminates, eliminating possible dangling pointers in the program. The code in the right shows the equivalent expansion of the `watching` construct to a `par/or` that awaits the special event `__killed` (which all classes have internally).

4. RELATED WORK

Esterel provides module abstractions through the `run` command, which syntactically replaces the command by the referred module body [7]. Similarly, ESPranto [26] extends Esterel with a macro-based abstraction mechanism that enables the creation of domain specific languages. However, macros expand at compile-time, being impossible to describe dynamic instantiation. Furthermore, each use of a macro results in code replication, having a negative impact on code size.

Simula is a simulation language that introduced the concepts of objects and coroutines [10]. The syntactic structure of classes in Simula is very similar to C  U, exposing an interface that encapsulates an execution body. However, the underlying execution models are fundamentally distinct: C  U employs a reactive scheduler to resume trails based on external stimuli, while Simula relies on cooperation between processes (i.e., `detach` and `resume` calls, at the lowest level). Simula has no notion of compositions and each process has a single line of execution. In particular, the lack of a `par/or` precludes orthogonal abortion and many derived C  U features, such as lexically scoped organisms, finalization, and reference watching. Without scopes, Simula objects and processes have to live on the heap and rely on garbage collection. As far as we know, Simula processes cannot be terminated explicitly from other processes.

ReactiveML [20] is a functional variant of Esterel that introduces dynamic synchronous abstractions through *processes*. Processes are functions that support hierarchical reactive constructs, such as parallel compositions and an `await` primitive, similarly to organism bodies in C  U. A process can create dynamic abstractions by executing an arbitrary expression in parallel with a recursive invocation of the process. Being a functional language, ReactiveML heavily relies on heap allocation and garbage collection and may not be suitable for constrained embedded systems. ReactiveML lacks a finalization mechanism that may hinder proper orthogonal abortion because a process that uses stateful resources cannot be safely aborted. For instance, C  U relies on finalization for handling stateful resources as well as for watching references.

5. CONCLUSION

C  U provides comprehensive support for structured reactive programming, extending classical structure programming with continuous interaction with external stimuli.

C  U introduces organisms which reconcile data and control state in a single abstraction. In contrast with objects, organisms have an execution body that can react independently to stimuli from the environment. Both static and dynamic instances of organisms are subject to lexical scope with automatic memory management, which eliminates memory leaks and the need for a garbage collector.

C  U is suitable for wide range of reactive applications and platforms. We have been using it in constrained platforms for sensor networks (e.g., 16MHz CPU with 4Kb of RAM) as well as in full-fledged tablets for games and graphical applications.

6. REFERENCES

- [1] erlang manual. http://www.erlang.org/doc/reference_manual/processes.html (accessed in Aug-2014).
- [2] UNIX man page for `pthread_cancel`. man `pthread_cancel`.
- [3] A. Adya et al. Cooperative task management without manual stack management. In *ATEC'02*, pages 289–302. USENIX Association, 2002.
- [4] A. Benveniste and G. Berry. The synchronous approach to reactive and real-time systems. *Proceedings of the IEEE*, 79(9):1270–1282, 1991.
- [5] A. Benveniste et al. The synchronous languages twelve years later. In *Proceedings of the IEEE*, volume 91, pages 64–83, Jan 2003.
- [6] G. Berry. Preemption in concurrent systems. In *FSTTCS*, volume 761 of *Lecture Notes in Computer Science*, pages 72–93. Springer, 1993.
- [7] G. Berry. *The Esterel-V5 Language Primer*. CMA and Inria, Sophia-Antipolis, France, June 2000. Version 5.10, Release 2.0.
- [8] F. Boussinot and R. de Simone. The Esterel language. *Proceedings of the IEEE*, 79(9):1293–1304, Sep 1991.
- [9] E. Czaplicki and S. Chong. Asynchronous functional reactive programming for guis. In *PLDI'13*, pages 411–422, 2013.
- [10] O.-J. Dahl and K. Nygaard. Simula: an algol-based simulation language. *Communications of the ACM*, 9(9):671–678, 1966.
- [11] M. de Icaza. Callbacks as our generations' go to statement. <http://tirania.org/blog/archive/2013/Aug-15.html> (accessed in Aug-2014), 2013.
- [12] E. W. Dijkstra. Letters to the editor: go to statement considered harmful. *Communications of the ACM*, 11(3):147–148, 1968.
- [13] E. W. Dijkstra, E. W. Dijkstra, and E. W. Dijkstra. *Notes on structured programming*. Technological University Eindhoven Netherlands, 1970.
- [14] Elm Language Web Site. Escape from callback hell. <http://elm-lang.org/learn/Escape-from-Callback-Hell.elm> (accessed in Aug-2014).
- [15] O. Gnawali et al. Collection tree protocol. In *Proceedings of SenSys'09*, pages 1–14. ACM, 2009.
- [16] N. Halbwachs et al. The synchronous data-flow programming language LUSTRE. *Proceedings of the IEEE*, 79:1305–1320, September 1991.
- [17] D. Harel and A. Pnueli. *On the development of reactive systems*. Springer, 1985.
- [18] C. A. R. Hoare. Communicating sequential processes. *Communications of the ACM*, 21(8):666–677, 1978.
- [19] I. Maier, T. Rompf, and M. Odersky. Deprecating the observer pattern. Technical report, 2010.
- [20] L. Mandel and M. Pouzet. Reactiveml: a reactive extension to ml. In *Proceedings of the 7th ACM SIGPLAN international conference on Principles and practice of declarative programming*, pages 82–93. ACM, 2005.
- [21] L. A. Meyerovich, A. Guha, J. Baskin, G. H. Cooper, M. Greenberg, A. Bromfield, and S. Krishnamurthi. Flapjax: a programming language for ajax applications. In *ACM SIGPLAN Notices*, volume 44, pages 1–20. ACM, 2009.
- [22] ORACLE. Java thread primitive deprecation. <http://docs.oracle.com/javase/6/docs/technotes/guides/concurrency/threadPrimitiveDeprecation.html> (accessed in Aug-2014), 2011.
- [23] D. Potop-Butucaru et al. The synchronous hypothesis and synchronous languages. In R. Zurawski, editor,

Embedded Systems Handbook. 2005.

- [24] G. Salvaneschi, G. Hintz, and M. Mezini. Rescala: Bridging between object-oriented and functional style in reactive applications. In *Proceedings of the of the 13th international conference on Modularity*, pages 25–36. ACM, 2014.
- [25] F. Sant’Anna et al. Safe system-level concurrency on resource-constrained nodes. In *Proceedings of SenSys’13*. ACM, 2013.
- [26] R. van Herk and L. Holenderski. Espranto: a framework for developing applications for adaptive hardware. In *Proceedings of ADAPTATIVE’2010*, pages 184–193, Lisbon, Portugal, 2010.
- [27] Z. Wan and P. Hudak. Functional reactive programming from first principles. *SIGPLAN Notices*, 35(5):242–252, 2000.