

Reactive Traversal of Recursive Data Types (?!)

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ABSTRACT

We propose a structured mechanism to traverse recursive data types incrementally, in successive reactions to input events. `traverse` is an iterator-like anonymous block that can be invoked recursively and suspended at any point, retaining the full state and stack frames alive. `traverse` is designed for the synchronous language CÉU, inheriting all existing concurrency functionality, such as parallel compositions with orthogonal abortion, static memory management, and bounded memory and reaction time. We present two application scenarios that take advantage of recursive and reactive behavior: *incremental computation* and *control-oriented domain specific languages*.

Categories and Subject Descriptors

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

General Terms

Design, Languages

Keywords

Behavior Trees, Domain Specific Languages, Incremental Computation, Logo, Structured Programming

1. INTRODUCTION

...

... CÉU [1, 2]

...

```
1 input void RESET; // declares an external event
2 var int v = 0; // variable shared by the trails
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 1: Introductory example in CÉU.

2. CÉU

CÉU is a concurrent and reactive language in which the lines of execution, known as *trails*, react all together continuously and in synchronous steps to external stimuli. The introductory example in Figure 1 defines an input event `RESET` (line 1), a shared variable `v` (line 2), and starts two trails with the `par` construct (lines 3-14): 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`. CÉU is tightly integrated with *C* and can access libraries of the underlying platform directly by prefixing symbols with an underscore (e.g., `_printf(<...>)`, in line 7).

In the synchronous model of CÉU, a program reacts to an occurring event completely 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 trails¹. If multiple trails react to the same event, the scheduler employs lexical order, i.e., the trail that appears first in the source code executes first. For this reason, programs are deterministic even in the presence of side effects in concurrent lines of execution. To avoid infinite execution for reactions, CÉU ensures that all loops contain `await` statements [1].

2.1 Recursive Data Types

¹The actual implementation enqueues incoming input events to process them in further reactions.

```

1 data List with
2   tag NIL;
3 or
4   tag CONS with
5     var int head;
6     var List* tail;
7   end
8 end
9
10 do
11   pool List[1] lst1;
12   lst1 =new List.CONNS(10,
13     List.CONNS(20,
14       List.CONNS(30,
15         List.NIL()));
16   _printf("%d, %d\n", lst1:CONS.head,
17     lst1:CONS.tail:NIL);
18   // prints 10, 1
19 end
20
21 do
22   pool List[] lst2;
23   lst2 =new List.CONNS(10,
24     List.CONNS(20,
25       List.CONNS(30,
26         List.NIL()));
27   lst2:CONS.tail =new List.CONNS(50, List.NIL());
28   _printf("%d\n", lst2:CONS.tail:CONS.head);
29   // prints 50 (20 and 30 have been freed)
30 end

```

Figure 2: A recursive List data type definition (lines 1–8) and uses (lines 10–18 and 20–28).

The `data` construct in CÉU provides a safer alternative to C’s `struct`, `union`, and `enum` definitions. A `data` entry declares either a non-recursive structure containing a set of mutable fields or a tagged union. A tagged union consists of a set of tag declarations, each of which may be a bare tag or contain mutable fields. If any of the tag declarations refers to the data type being declared, we have a recursive data type. In this case, the first tag of the tagged union must be a bare tag, and it will act as the union’s null type: in CÉU, every tagged union is an option type.

Figure 2 illustrates the recursive `List` data type, declared as a tagged union. The first tag, `NIL` (line 2), represents the empty list and is the union’s null type. The second tag, `CONS`, holds a value in its field `head` and a pointer to the rest of the list in the field `tail` (lines 4–7).

All memory allocated by CÉU constructs is managed by lexically-scoped memory pools. The `pool` keyword declares a memory pool of a given size and a reference to a root object. In line 11, we declare a pool of `List` objects of size 1, identified by root reference `lst1`, scoped by the `do` block in lines 10–19. The declaration also implicitly initializes the root to the null tag of the associated data type (i.e., `List.NIL`).

Then, in lines 12–15, we use the `=new` construct, which performs allocation and assignment: it attempts to dynamically allocate a list of three elements (using three `List.CONNS` constructors in the assignment *r-value*), inferring the destination memory pool based on the assignment’s *l-value* (i.e. `lst1`).

Since the pool has size 1, only the allocation of first element succeeds, with the failed allocations returning the null tag

```

1 pool List[] l = new List.CONNS(1,
2   List.CONNS(2,
3     List.CONNS(3,
4       List.NIL())));
5
6 var int sum =
7   traverse e in l do
8     if e:NIL then
9       escape 0;
10    else
11      var int sum_tail = traverse e:CONS.tail;
12      escape sum_tail + e:CONS.head;
13    end
14  end;
15 _printf("sum = %d\n", sum);

```

Figure 3: Calculating the *sum* of a list.

for this type (i.e., `List.NIL`). The print command (line 16) outputs “10, 1”: the `head` of the first element (the operator ‘:’ is equivalent to C’s ‘->’) and a true value for the `NIL` check of the second element.

In the second block (lines 21–30), we declare the `lst2` pool with an unbounded memory limit (i.e., `List[]` in line 22). Now, the three-element allocation succeeds (lines 23–26). Then, we mutate the tail of the first element to point to a newly allocated element in the same pool, which also succeeds (line 27). The print command (line 28) outputs “50”, displaying the `head` of the new second element. In the moment of the mutation, the old subtree (containing values “20” and “30”) is completely removed from memory. Finally, the end of the block (line 30) deallocates the pool along with all of its elements.

Data types in CÉU have a number of restrictions. Given that mutations deallocate whole subtrees, data types cannot represent general graphs (in particular, they cannot contain cycles). Elements in different pools cannot be mixed; and pointers to subtrees (i.e., weak references) must be observed via the `watching` construct, as they can be invalidated at any time (to be discussed in Section 2.2).

2.2 Traversing Data Types

CÉU introduces a structured mechanism to traverse data types. The `traverse` construct integrates well with the synchronous execution model, supporting nested control compositions, such as `await` and all `par` variations. It also preserves explicit lexical scopes with static memory management.

The example in Figure 3 creates a list (lines 1–4) and traverses it to calculate the sum of elements (lines 6–15). The `traverse` block (line 7) starts with the element `e` pointing to the root of the list `l`. The `escape` statement (lines 9 and 12) returns a value to be assigned to the `sum` (line 6). A `NIL` list has `sum=0` (lines 8–9). A `CONS` list needs to calculate the `sum` of its tail recursively, invoking `traverse` again (line 11), which will create a nested instance of the enclosing `traverse` block (lines 7–14), now with `e` pointing to the `e:CONS.tail`. Without nested control mechanisms, `traverse` is just syntactic sugar for anonymous closures called recursively.

To distinguish `traverse` from standard recursive functions, Figure 4 extends the body of the previous example with re-

```

1 pool List[] l = <...>; // 1, 2, 3
2 var int sum =
3   traverse e in l do
4     if e:NIL then
5       escape 0;
6     else
7       watching e do
8         _printf("me = %d\n", e:CONS.head);
9         await 1s;
10        var int sum_tail = traverse e:CONS.tail;
11        escape sum_tail + e:CONS.head;
12      end
13    end
14  end;
15 end;
16 _printf("sum = %d\n", sum);

```

Figure 4: Calculating the *sum* of a list, one element each second.

active behavior. For each recursive iteration, the `traverse` prints the current `head` (line 8) and awaits 1 second before traversing the `tail` (lines 9–10). In CÉU, all accesses to pointers that cross `await` statements must be protected with `watching` blocks [2]. This ensures that if side effects occurring in parallel affect the pointed object, no harming code executes because the whole block is aborted. In the example (lines 7–12), if the list is mutated during that 1 second and the specific element is removed from memory, we simply ignore the whole subtree and return 0.

Note that for bounded pools (e.g., `List[3] l`), we can infer at compile time the maximum number of “stack frames” required for `traverse`. In addition, we can also enforce bounded execution time by asserting that the structure of the recursive steps converge to the base cases. This is an important requirement for constrained and real-time embedded systems, which is the original application domain of CÉU [1].

3. APPLICATIONS

incremental computation, behavior trees, control-dominated DSLs

...

3.1 Incremental Computation

...

- gray binary generation?

...

3.2 Domain Specific Languages

3.2.1 Behavior Trees

The term “Behavior Trees” denotes a family of DSLs used for Game AI. The term is loose, because different games use different languages, but generally it indicates an interpreted domain-specific language for creature behavior that includes at least sequence and selection combinators, and which are “ticked” periodically.

The semantics of the sequence combinator can be understood as short-circuit evaluation of a conjunction; the Seq

```

1 data BTree with
2   tag NIL;
3 or
4   tag SEQ with
5     var BTree* first;
6     var BTree* second;
7   end
8 or
9   tag SEL with
10    var BTree* first;
11    var BTree* second;
12  end
13 or
14   tag LEAF with
15     var Leaf leaf;
16   end
17 end

```

Figure 5: A standard behavior tree with *sequence* and *selector* composite nodes.

node ticks its left subtree until it finishes, and if it finishes successfully, ticks its right subtree until it finishes. The semantics of the selection combinator can be understood as short-circuit evaluation of an alternation; the Sel node ticks its left subtree until it finishes, and if it did not finish successfully, ticks its right subtree until it finishes.

This skeleton, augmented with leaves that test properties, set properties, perform animations and sounds, and other custom combinators, can be preferable to finite state machines (hierarchical, augmented, or otherwise) for authoring Game AI.

Ceu’s parallel features make implementing a parallel combinator for behavior trees much easier.

...

3.3 TODO: Standard Behavior Tree

COMMENTS:

Most “standard” BTs I found have these “sequence” and “selector” composite nodes. I thought about starting with this one and maybe expanding it with a “parallel/or” further.

Two things to discuss: (1) how the implementation of the interpreter is straightforward; (2) that leaf nodes are not restricted to a “tick” callback and can actually execute arbitrary code in CÉU.

3.3.1 Logo Turtle

...

4. RELATED WORK

...

5. CONCLUSION

...

6. REFERENCES

- [1] F. Sant’Anna et al. Safe System-level Concurrency on Resource-Constrained Nodes. In *Proceedings of SenSys’13*. ACM, 2013.

```

1 class BTreeInterpreter with
2   pool BTree[] & btree;
3 do
4   var int ret =
5     traverse t in btree do
6       if t:SEQ then
7         var int ret1 = traverse t:SEQ.first;
8         if ret1 > 0 then
9           var int ret2 = traverse t:SEQ.second;
10          if ret2 > 0 then
11            escape ret1+ret2;
12          end
13        end
14        escape 0;
15      else/if t:SEL then
16        var int ret = traverse t:SEQ.first;
17        if ret == 0 then
18          ret = traverse t:SEL.second;
19        end
20        escape ret;
21      else/if t:LEAF then
22        var int ret =
23          do LeafHandler with
24            this.leaf = t:LEAF.leaf;
25          end;
26        escape ret;
27      end
28    end;
29  escape ret;
30 end
31
32 pool BTree[] btree = new
33   BTree.SEQ(
34     BTree.SEL(
35       BTree.LEAF(Leaf(0)),
36       BTree.LEAF(Leaf(1)),
37       BTree.LEAF(Leaf(2)));
38
39 var int ret =
40   do BTreeTraverse with
41     this.btree = btree;
42   end;
43
44 _printf("ret = %d\n", ret); // prints "3"

```

Figure 6: A straightforward interpreter for the standard behavior tree of Figure 5 and a sample tree to execute.

```

1 class LeafHandler with
2   var Leaf& leaf;
3 do
4   // TODO: what to show here?
5   escape leaf.v;
6 end

```

Figure 7: A leaf node with complex behavior.

```

1 data Command with
2   tag NOTHING;
3 or
4   tag ROTATE with
5     var int angle;
6   end
7 or
8   tag MOVE with
9     var int pixels;
10  end
11 or
12   tag AWAIT with
13     var int ms;
14   end
15 or
16   tag SEQ with
17     var Command* one;
18     var Command* two;
19   end
20 or
21   tag REPEAT with
22     var int times;
23     var Command* command;
24   end
25 or
26   tag PAROR with
27     var Command* one;
28     var Command* two;
29   end
30 end

```

Figure 8: DSL for a LOGO turtle.

```

1 class Interpreter with
2   pool Command[] & cmds;
3   var Turtle& turtle;
4 do
5   traverse cmd in cmds do
6     watching cmd do
7       if cmd:AWAIT then
8         await (cmd:AWAIT.ms) ms;
9       end
10      else/if cmd:ROTATE then
11        do TurtleRotate with
12          this.turtle = turtle;
13          this.angle = cmd:ROTATE.angle;
14        end;
15      end
16      else/if cmd:MOVE then
17        do TurtleMove with
18          this.turtle = turtle;
19          this.pixels = cmd:MOVE.pixels;
20        end;
21      end
22      else/if cmd:PAROR then
23        par/or do
24          traverse cmd:PAROR.one;
25          with
26            traverse cmd:PAROR.two;
27          end
28        end
29      end
30      else/if cmd:SEQ then
31        traverse cmd:SEQ.one;
32        traverse cmd:SEQ.two;
33      end
34      else/if cmd:REPEAT then
35        loop i in cmd:REPEAT.times do
36          traverse cmd:REPEAT.command;
37        end
38      end
39    end
40  end
end

```

Figure 9: The turtle interpreter.

- [2] F. Sant'Anna et al. Structured Synchronous Reactive Programming with Céu. In *Proceedings of Modularity'15*, 2015. to appear.