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 of its concurrency functionality and safety properties, such as parallel compositions with orthogonal abortion, static memory management, and bounded reaction time and memory usage. We discuss three applications in the domains of incremental computation and control-oriented DSLs that contain reactive and recursive behavior at the same time.

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, Recursive Data Types, Structured Programming, Reactive Programming

1. INTRODUCTION

All examples have working implementations:
- TODO: compare the real code with the listing

- label "lst.list": rebls-15/list/list.ceu

- label "lst.list.sum": rebls-15/list/list.ceu

- label "lst.list.sum.react": rebls-15/list/list.ceu

- label "lst.bt1": rebls-15/bts-ceu/btree-1.ceu

- label "lst.bt1.interpreter": rebls-15/bts-ceu/btree-1.ceu

- label "lst.bt1.leaf": rebls-15/bts-ceu/domain-1.ceu

- label "lst.turtle.dsl": rebls-15/turtle/turtle-2.ceu

- label "lst.turtle.interpreter": rebls-15/turtle/turtle-2.ceu

- label "lst.turtle.queue": rebls-15/turtle/turtle-7.ceu

- label "lst.gray": rebls-15/loopless/gray/gray-vec.ceu

... CÉU [2, 3]

...

```
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 trails. 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 [2].

2.1 Recursive Data Types

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 recursive data type 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

```
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.CONS(10,
13             List.CONS(20,
14               List.CONS(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.CONS(10,
24             List.CONS(20,
25               List.CONS(30,
26                 List.NIL())));
27    lst2:CONS.tail =new List.CONS(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).

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.CONS 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 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.

In Céu, recursive data types have a number of restrictions.

```
1    pool List[3] l = new List.CONS(10,
2                        List.CONS(20,
3                          List.CONS(30,
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);
16        // prints 60
```

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

```
1    pool List[] l = <...>;   // 10, 20, 30
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            escape 0;
14         end
15      end;
16   _printf("sum = %d\n", sum);
```

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

Given that mutations deallocate whole subtrees, data types cannot represent general graphs: they must represent tree-like structures. 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.

We begin by showing the flavor of the construct through an example. The code 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`. When used without event control mechanisms, as in this simple example, a `traverse` block is equivalent to an anonymous closure called recursively.

The `traverse` construct does not simply amount to an anonymous recursive block, however. It is designed to take into account the event system and memory management discipline of the language. As such, it is an abstraction defined in terms of more fundamental CÉU features: *organisms*, which are objects with their own parallel trail of execution, akin to Simula objects; and orthogonal abortion, which handles cancellation of trails maintaining memory consistency [3].

Three aspects make `traverse` fundamentally different from an anonymous recursive function. First, each `traverse` call spawns a new anonymous organism, launching a new parallel trail of execution (as opposed to stacking a new frame in the current trail). Second, traversal is declared in terms of a specific memory pool. Therefore, for bounded pools (e.g., `List[3] l`), we can infer at compile time the maximum traversal depth. Third, the execution body of a `traverse` block is implicitly wrapped by a concurrency construct that watches for mutations of the current node. In practice, this means that it reacts consistently if another trail of execution modifies the data structure being traversed.

To illustrate these differences, Figure ?? extends the body of the previous example with reactive behavior. For each recursive iteration, `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 [3]. This ensures that if side effects occurring in parallel affect the pointed object, no code uses stale pointers 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.

The `traverse` construct allows us to enforce bounded execution time, by performing a limited number of steps, each of them a separate synchronous reaction. This can be asserted by verifying that the structure of the recursive steps converge to the base cases, or simply by using a bounded memory pools, which allows us to limit the maximum number of steps to the size of the pool. Enforcing execution limits is an important requirement for constrained and real-time embedded systems, which is the original application domain of CÉU [2].

3. APPLICATIONS

In this section, we present three applications that explore the reactive and incremental nature of the `traverse` construct. We start with standard *Behavior Trees* used in video games for AI modeling [?], and extend them with parallel compositions. Then, we show a *Logo Turtle* [?] that can execute commands in parallel (e.g., `move` and `rotate`) and also incorporates a dynamic queue of commands issued concurrently with the running program. Finally, we implement *Gray code* generation [?] to illustrate how `traverse` can also be used for more general recursive algorithms without an associated data type.

How many applications will we present?
- behavior trees (DSL)
- logo turtle (DSL)

```
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.

- turtle stream (incremental)
- gray code gen (incremental)

I suggest gray code as the last one because it does not use a data type. We could show as an example of flexibility of traverse. BTs before turtle because they are simpler and because the stream example is the most complex and should follow the logo turtle.

3.1 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 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.

> 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"

```
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 ok1 = traverse t:SEQ.first;
8                if ok1 == 0 then
9                   escape ok1;
10               end
11               var int ok2 = traverse t:SEQ.second;
12               escape ok2;
13            else/if t:SEL then
14               var int ok1 = traverse t:SEL.first;
15               if ok1 != 0 then
16                  escape ok1;
17               end
18               var int ok2 = traverse t:SEL.second;
19               escape ok2;
20            else/if t:LEAF then
21               var int ret =
22                  do LeafHandler(t:LEAF.leaf);
23               escape ret;
24            end
25         end;
26      escape ret;
27   end
28
29   pool BTree[] btree =
30      new BTree.SELECTOR(
31         BTree.SEQ(
32            BTree.LEAF(Leaf.SENSEONTABLE(3)),
33            BTree.SEQ(
34               BTree.LEAF(Leaf.MOVEBLOCKTOBLOCK(2, 3, 1)),
35               BTree.LEAF(Leaf.MOVEFROMTABLE(3, 2))
36            )
37         ),
38         BTree.SEQ(
39            BTree.LEAF(Leaf.MOVETOTABLE(3, 2)),
40            BTree.SEQ(
41               BTree.LEAF(Leaf.MOVEFROMTABLE(2, 1)),
42               BTree.LEAF(Leaf.MOVEFROMTABLE(3, 2))
43            )
44         )
45      );
46
47   var int ret = do BTreeTraverse(btree);
48
49   _printf("ret = %d\n", ret);      // prints "3"
```

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

callback and can actually execute arbitrary code in CÉU.

3.2 Logo Turtle

Our second example is an interpreter for a simple variant of the classic Logo turtle-graphics interpreter [1], which extends the Logo paradigm with a CÉU-like parallel execution construct. In our variant, we can instruct the turtle to move and rotate in parallel, tracing curves. We declare a data type which defines our abstract syntax, with each tag representing one of the supported Logo commands. A tree of nodes represents a program, and the interpreter is implemented as a traversal of this tree. The aim of this example is to demonstrate parallel traversal.

Figure 8 presents the data type `Command`, which specifies the abstract syntax of our Logo variant. As in traditional Logo, commands can be listed in sequence to be executed one after the other (represented through a chain of `SEQ` nodes), and commands can be repeated a number of times (denoted through a `REPEAT` node). Our variant includes `MOVE` and `RO-TATE` nodes to move the turtle, but these are specified differently from traditional Logo: here, they take as arguments the speed at which they should affect the turtle. For example, a `Command.MOVE(50)` node directs the turtle to move at the speed of 50 pixels per second, indefinitely. The only way to make the turtle stop moving or rotating is through two CÉU-like extensions added to our Logo variant: `AWAIT` and `PAROR`. `AWAIT` simply awaits a given number of milliseconds. `PAROR`, modeled after the CÉU construct `par/or`, launches two commands in parallel, and aborts both of them as soon as one of them finishes. For example, the following construct would make the turtle move along a semicircle:

```
Command.PAROR(
    Command.AWAIT(1000),
    Command.PAROR(
        Command.MOVE(50),
        Command.ROTATE(180)))
```

Figure 9 depicts the interpreter. It is implemented as the `Interpreter` organism (declared with the `class` keyword). It holds as attributes a reference to the AST of commands (`cmds`, line 2) and a reference to a `Turtle` object which implements the UI. The execution body of the organism contains the `traverse` construct which runs the interpreter (lines 5–35).

We have then a test for each kind of tag in the data type. In lines 7–9, `SEQ` is handled by traversing each of its child commands, in sequence: the second invocation of `traverse` in that block (line 9) only runs after the first one (line 8) finishes. In lines 11–14, `REPEAT` is handled by traversing its command the specified number of times.

`MOVE` is handled in lines 16–18 by spawning a new organism called `TurtleMove`, which launches a separate trail of execution. The implementation of `TurtleMove` (not shown) updates the coordinates of the `turtle` instance it got as a parameter in its constructor. The implementation of `ROTATE` (lines 20–22) is similar.

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

In lines 24–25, `AWAIT` is implemented by simply causing the current trail of execution of the interpreter to await the given amount of time. Finally, `PAROR` (lines 27–32) uses the `par/or` construct to traverse both subcommands at the same time. As per the semantics of `par/or`, as soon as one of the subtrees terminate its execution, the other one will be aborted.

Note that the entire interpreter block is surrounded by a `watching` construct (line 6). The CÉU compiler enforces the presence of a guard, due to the use of the `cmd` pointer in code that spans multiple reactions. This ensures clean abortion in case the AST being interpreted is mutated by code running in another trail.

3.2.1 Enqueuing Commands

All examples so far create a fixed tree that does not vary during traversal. Figure 10 extends the Turtle application with a queue of pending commands to execute after the running commands terminate. We define a new `Queue` data type in (*CODE-1*): `ROOT` has a `runnning` subtree with the running commands, a `waiting` queue of pending commands to execute, and a `tmp` node that allows in-place manipulation of the tree. Given that all newly allocated nodes must reside in a pool, the `tmp` node represents a pointer TODO. `ITEM` represents a queue item and contains a `cmd` subtree with the command to execute, and a `prv` queue item pointing to an older item that should execute first (i.e., the queue is in reverse order). TODO...

3.3 Gray Code Generation
4. RELATED WORK

...

What to compare against???

```
data Queue with
  tag NIL;
or
  tag ROOT with
    var Queue running;
    var Queue waiting;
    var Queue tmp;
  end
or
  tag ITEM with
    var Command cmd;
    var Queue   prv;
  end
end
.
```

CODE-1: The `Queue` data type

```
1   traverse qu in queue do
2     watching qu do
3       if qu:ROOT then
4         loop do
5           par/and do
6             traverse qu:ROOT.running;
7           with
8             await qu:ROOT.waiting;
9           end
10          qu:ROOT.running =
11            qu:ROOT.waiting;
12          qu:ROOT.waiting =
13            new Queue.ITEM(
14                  Command.NOTHING(),
15                  Queue.NIL());
16        end
17      else/if qu:ITEM then
18        traverse qu:ITEM.prv;
19        do Interpreter with
20          this.turtle = turtle;
21          this.cmds   = qu:ITEM.cmd;
22        end;
23      end
24    end
25  end
```

CODE-2: Queue traversal

```
1   every (cmd,vel,time) in ENQUEUE do
2     if _strcmp(cmd,"move") == 0 then
3       move_or_rotate = true;
4       queue:ROOT.tmp =
5         new Queue.ITEM(
6             Command.NOTHING(),
7             Queue.ITEM(
8               Command.PAROR(
9                 Command.MOVE(vel),
10                Command.AWAIT(time)),
11              Queue.NIL()));
12      queue:ROOT.tmp:ITEM.prv:ITEM.prv =
13        queue:ROOT.waiting:ITEM.prv;
14      queue:ROOT.waiting =
15        queue:ROOT.tmp;
16    else
17      <...>
18    end
19  end
.
```

CODE-3: Command enqueuing

Figure 10: Queue extension for the Turtle DSL of Figures 8 and 9.

```
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:SEQ then
8           traverse cmd:SEQ.one;
9           traverse cmd:SEQ.two;
10
11        else/if cmd:REPEAT then
12          loop i in cmd:REPEAT.times do
13            traverse cmd:REPEAT.command;
14          end
15
16        else/if cmd:MOVE then
17          do TurtleMove(turtle,
18                cmd:MOVE.pixels);
19
20        else/if cmd:ROTATE then
21          do TurtleRotate(turtle,
22                  cmd:ROTATE.angle);
23
24        else/if cmd:AWAIT then
25          await (cmd:AWAIT.ms) ms;
26
27        else/if cmd:PAROR then
28          par/or do
29            traverse cmd:PAROR.one;
30          with
31            traverse cmd:PAROR.two;
32          end
33        end
34      end
35    end
36  end
```

Figure 9: The turtle interpreter.

```
1   var int[4] bits = [0, 0, 0, 0];
2
3   par/or do
4     every VISIT do
5       _printf("( ");
6       loop i in $$bits do // $$ is the array size
7         _printf("%d ", bits[i]);
8       end
9       _printf(")\n");
10    end
11  with
12    traverse idx in [$$bits] do
13      if idx == $$bits then
14        await NEXT;
15      else
16        traverse idx + 1;
17        bits[idx] = 1 — bits[idx];
18        traverse idx + 1;
19      end
20    end
21  end
```

Figure 11: Generator for 4-bit Gray code.

Found this: http://arxiv.org/pdf/1104.2293.pdf
Follow the references.

5. CONCLUSION

...

Limitations:

- high-order programming

- planar-only recursive data types

6. REFERENCES

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