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### **This is the author's manuscript**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/1794961> since 2021-11-03T22:24:16Z

*Publisher:*

Springer International Publishing

*Published version:*

DOI:10.1007/978-3-030-79837-6\_12

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# Splitting recursion schemes into reversible and classical interacting threads

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**Abstract.** Given a simple recursive function, we show how to extract from it a reversible and an classical iterative part. Those parts can synchronously cooperate under a Producer/Consumer pattern in order to implement the original recursive function. The reversible producer is meant to run on reversible hardware. We also discuss how to extend the extraction to a more general compilation scheme.

## 1 Introduction

Our goal is to compile a class of recursive functions in a way that parts of the object code produced can leverage the promised green foot-print of truly reversible hardware. This work illustrates preliminary steps towards that goal. We focus on a basic class of recursive functions in order to demonstrate its feasibility.

*Contributions.* Let  $\text{recF}[p, b, h]$  be a recursive function defined in some programming formalism, where  $p$  is a *predecessor* function,  $h$  a *step* function, and  $b$  a *base* function. We show how to compile  $\text{recF}[p, b, h]$  into  $\text{itFClS}[b, h]$  and  $\text{itFRev}[p, p\text{Inv}]$  such that:

$$\text{recF}[p, b, h] \simeq \text{itFClS}[b, h] \parallel \text{itFRev}[p, p\text{Inv}] \quad , \quad (1)$$

where: (i) “ $\simeq$ ” stands for “*equivalent to*”; (ii)  $\text{itFClS}[b, h]$  is a classical **for**-loop that, starting from a value produced by  $b$ , iteratively applies  $h$ ; (iii)  $\text{itFRev}[p, p\text{Inv}]$  is a reversible code with two **for**-loops in it one iterating  $p$ , the other its inverse  $p\text{Inv}$ ; (iv) “ $\parallel$ ” is interpreted as an *interaction* between  $\text{itFClS}[b, h]$  and  $\text{itFRev}[p, p\text{Inv}]$ , according to a Producer/Consumer pattern, where  $\text{itFRev}[p, p\text{Inv}]$  produces the values that  $\text{itFClS}[b, h]$  consumes to implement the initially given recursion  $\text{recF}[p, b, h]$ . In principle,  $\text{itFRev}[p, p\text{Inv}]$  can drive a real reversible hardware to exploit its low energy consumption features.

In this work we limit the compilation scheme (1) to use: (i) a predecessor  $p$  such that the value  $p(x)-x$  is any *constant*  $\Delta_p$  equal to, or smaller than,  $-1$ ; (ii) recursion functions  $\text{recF}[p, b, h]$  whose *condition* identifying the base case

is  $x \leq 0$  instead than the more standard  $x == 0$ ; this means that more than one base *non positive* value for  $\text{recF}[p, b, h]$  exists in the interval  $[\Delta_p + 1, 0]$ . This slight generalization will require a careful management of the reversible behavior of  $\text{itFRev}[p, p\text{Inv}]$  and its interaction with  $\text{itFCls}[b, h]$  in order to reconstruct  $\text{recF}[p, b, h]$ .

*Contents.* Section 2 sets the stage to develop the main ideas about (1), restricting  $\text{recF}[p, b, h]$  to a recursive function that identifies its base case by means of the standard condition  $x == 0$ ; this ease the description of how  $\text{itFRev}[p, p\text{Inv}]$  and  $\text{itFCls}[b, h]$  interact. Section 3 extends (1) to deal with  $\text{recF}[p, b, h]$  having  $x \leq 0$ , and not  $x == 0$ , to identify its base case(s); this impacts on how  $\text{itFRev}[p, p\text{Inv}]$  must work. In both cases, the programming syntax we use can be interpreted into the reversible languages SRL [3,4] and RPP [5,6,4], up to minor syntactic details. Section 4 addresses future work.

```

1  Fix recF(x) {
2    if (c(x)) { b(x); }
3    else { h(x, recF(p(x))); } }

```

Fig. 1. The recursive function  $\text{recF}$ .

```

1  /** Assumption: the initial value of x is 3 */
2  x = p(x) // ==2
3  x = p(x) // ==1
4  x = p(x) // ==0
5  y = b(x) // ==b(p(p(p(3))))
6  y = h(x,y) // ==h(p(p(p(3))), b(p(p(p(3))))
7  x = pInv(x) // ==pInv(p(p(p(3))))==p(3)
8  y = h(x,y) // ==h(p(p(3)), h(p(p(p(3))), b(p(p(p(3))))))
9  x = pInv(x) // ==pInv(p(p(3)))==p(3)
10 y = h(x,y) // ==h(p(3), h(p(p(3)))
11 // , h(p(p(p(3))), b(p(p(p(3))))))
12 x = pInv(x) // ==pInv(p(3))==3
13 y = h(x,y) // ==h(3, h(p(3), h(p(p(3)))
14 // , h(p(p(p(3))), b(p(p(p(3))))))

```

Fig. 2. Iterative unfolding  $\text{recF}(3)$ : the bottom-up part.

## 2 The driving idea

Let `recF[p,b,h]` in (1) have a structure as in **Fig. 1** where `b(x)` is the *base* function, `h(x,y)` the *step* function, `p(x)` the *predecessor* `x-1`, and `c(x)` the *condition* `x==0` to identify a unique base case.

**Fig. 2** details out `h(3,h(p(3),h(p(p(3))), h(p(p(p(3))),b(p(p(p(3))))))`, unfolding of `recF(3)`. Every comment asserts a property of the values that `x` or `y` stores. Lines 2–4 unfold an iteration that computes `p(p(p(3)))`, which eventually sets the value of `x` to 0. Line 5 starts the construction of the final value of `recF(3)` by applying the base case of `recF`, i.e. `b(x)`. By definition, let `pInv` denote the inverse of `p`, i.e. `pInv(p(z))==p(pInv(z))==z`, for any `z`. Clearly, in our running example, the function `pInv(x)` is `x+1`. Lines 6–13 alternate `h(x,y)`, whose result `y`, step by step, gets closer to the final value `recF(3)`, and `pInv(x)`, which produces a new value for `x`.

```

1  s = 0, e = 0, g = 0, w = 0
2  w = w + x;
3  for (i = 0; i<=w; i++)      {
4      if      (x> 0) { g++; }
5      else if (x==0) { e++; }
6      else          { s++; }
7      x = p(x);              }
8
9  for (i = 0; i<=w; i++)      {
10     x = pInv(x);
11     if      (x> 0) { g--; y = h(x,y); }
12     else if (x==0) { e--; y = b(x);   }
13     else          { s--;              } }
14  w = w - x;

```

**Fig. 3.** Iterative `itF` equivalent to `recF`.

Let us call `itF` the code in **Fig. 3**. It implements `recF` by means of finite iterations only. Continuing with our running example, if we run `itF` here above starting with `x==3`, then `x==0` holds at line 8, just after the first `for`-loop; after the second `for`-loop `y==recF(3)` holds at line 14.

The code of `itF` has two parts. Through lines 2–7 the variable `g` counts how many times `x` remains positive, the variable `e` how many it stays equal to 0, and the variable `s` how many it becomes negative. In this running example we notice that `x` never becomes negative, for the iteration at lines 3–7 is driven by the value of `x` which, initially, we can assume non negative, and which `p(x)` decreases of a single unity. We shall clarify the role of `s` later. Lines 9–13 undo what lines 2–7 do by executing `pInv(x)`, `g--`, `e--`, `s--`, i.e. the inverses, in reversed order, of `p(x)`, `g++`, `e++`, `s++`. So the correct values of `x` are available at lines 12, and

11, ready to be used as arguments of  $b(x)$  and  $h(x,y)$  to update  $y$  as in **Fig. 3**, according to the results we obtain by the recursive calls to `recF`.

```

1  s = 0, e = 0, g = 0, w = 0
2  w = w + x;
3  for (i=0; i<=w; i++)      {
4      if      (x> 0) { g++; } //number of times x is 'g'reater than 0
5      else if (x==0) { e++; } //number of times x is 'e'qual to 0
6      else      { s++; } //number of times x is 's'maller than 0
7      x = p(x);              }
8
9  for (i=0; i<=w; i++)      {
10     x = pInv(x);
11     if      (x> 0) { g--; /* Value of x for h availabe here */ }
12     else if (x==0) { e--; /* Value of x for b availabe here */ }
13     else      { s--; }
14     w = w - x;

```

**Fig. 4.** Reversible side of `itF`.

Now, let us focus on the main difference between **Fig. 4** and **Fig. 3**.

Both  $x=b(x)$  and  $y=h(x,y)$  at lines 12, and 11 of **Fig. 3** are missing from lines 12, and 11 of **Fig. 4**. Dropping them let **Fig. 4** be the *reversible side* of `itF`; calling  $b(x)$  and  $h(x,y)$  in it generates  $y$ , which is the result we need, so preventing the possibility to reset the value of every variable dealt with in **Fig. 4** to their initial value. This is why we also need a *classical side* of `itF` that generates  $y$  in collaboration with the *reversible side* in order to implement the initial `recF` correctly.

```

1  /** Assumption. The value of the input x is available here */
2  /* Inject the current x at line 2 of itFRev to let it start */
3  iterations = /* Probe line 9 of itFRev to get the
4                number of iterations to execute */
5  y = b(/* Probe line 14 of itFRev to get the argument */);
6  for (i = 0; i<iterations; i++)      {
7      y = h(/* Probe line 12 itFRev to get
8            the first argument of h    */ , y); }

```

**Fig. 5.** Classical side of `itF`: the consumer `itFCls`.

The previous observations lead to **Fig. 5** which defines the *classical side* `itFCls` of `recF`, and to **Fig. 6** which defines the *reversible side* `itFRev` of `recF`.

```

1  s = 0, e = 0, g = 0, w = 0;
2  x = /* Inject here the value of x at line 2 of itFClS */
3  w = w + x;
4  for (i = 0; i<=w; i++)      {
5      if      (x> 0) { g++; }
6      else if (x==0) { e++; }
7      else           { s++; }
8      x = p(x);           }
9  /* itFClS probes here g which has the number of iterations */
10 for (i = 0; i<=w; i++)      {
11     x = pInv(x);
12     if      (x> 0) { g--; /* itFClS probes here the
13                          first argument value of h */ }
14     else if (x==0) { e--; /* itFClS probes here the
15                          argument value of b          */ }
16     else           { s--;           } }
17     w = w - x;

```

**Fig. 6.** Reversible side of `itF` updated to be the producer `itFRev` of the values that the consumer `itFClS` needs.

So, here below we can illustrate how `itFClS` and `itFRev` synchronously interact, `itFRev` producing values, `itFClS` consuming them as arguments of `b(x)` and `h(x,y)`.

Line 2 of `itFClS` is the starting point of the synchronous interaction between `itFClS` and `itFRev`; its comment:

```
/* Inject the current x at line 2 of itFRev to let it start */
```

describes what, in a fully implemented version of `itFClS`, we expect in that line of code. The comment says that `itFClS` injects (sends, puts) its input value `x` to line 2 of the *reversible side* `itFRev` (cf. **Fig. 6**). Once `itFRev` obtains that value at line 2, as outlined by:

```
/* Inject here the value of x from line 2 of itFClS */
```

its `for`-loop at lines 4–8 executes.

After line 2, `itFClS` stops at line 3. It waits for `itFRev` to produce the number of times that `itFClS` has to iterate line 7. Accordingly to:

```
/* Probe line 9 of itFRev to get the number of iterations to execute */
```

`itFRev` makes that value available in its variable `g` at line 9:

```
/* itFClS probes here g which has the number of iterations */ .
```

Once gotten the value in `iterations`, `itFClS` proceeds to line 5 and stops, waiting for `itFRev` to produce the argument of `b` which is eventually available for probing at line 14 of `itFRev`.

Once the argument becomes available `b` is applied, and `itFClS` enters its `for`-loop, stopping at line 7 at every iteration. The reason is that `itFClS` waits for line 12 in `itFRev` to produce the value of the first argument of `h(x,y)`. This interleaved dialog between line 7 of `itFClS` and line 12 of `itFRev` lasts `iterations` times.

```

1  Fix recG(x)                                {
2    if (x<=0) { b(x);                        }
3    else     { h(x,recG(p(x))); } }

```

Fig. 7. The generic structure of `recG`.

### 3 From recursion to iteration

We now generalize what we have seen in Section 2. Inside (1) we use `recG` of Fig. 7 instead than `recF` of Fig. 1. This requires to generalize Fig. 6.

From the introduction we recall that, given a *predecessor* `p(x)`, we define  $\Delta_p = p(x) - x$ , which is a negative value. In this section  $\Delta_p$  can be any *constant*  $k < -1$ , not only  $k == -1$ ; this requires to consider the slightly more general *condition* `x <= 0` in `recG`. For example, let `p(x)` be `x-2`. The computation of `recG(3)` is `h(3,h(p(3),h(p(p(3)),b(p(p(3))))))` which looks for the least  $n$  of iterated applications of `p(x)` such that `p(...p(3)...) <= 0`; in our case we have  $2 == n < 3$ .

Fig. 8 introduces `itG` which generalizes `itF` in Fig. 3.

The scheme `itG` iteratively implements any recursive function whose structure can be brought back to the one of `recG`. We remark that line 1 in Fig. 8 initializes ancillae `s`, `e`, `g`, and `w`, like Fig. 3 initializes the namesake variables of `itF`, but line 2 of `itG` has new ancillae `z`, `predDivX`, and `predNotDivX`.

We also assume an initial *non negative* value for `x`. The reason is twofold. Firstly, it keeps our discussion as simple as possible, with no need to use the absolute value of `x` to set the upper limit of every index `i` in the `for`-loops that occur in the code. Second, negative values of `x` would widen our discussion about what a classical recursive function on negative values is and about what its reversible equivalent iteration has to be; we see this as a very interesting subject connected to [1], which is much more oriented than us to optimization issues of recursively defined functions.

We start observing that line 3 of `itG` sets `w` to the initial value of `x`; the reason is that every `for`-loop, but the one at lines 10–12, has to last `x+1` iterations, and `x` changes in the course of the computation; so, `w` stores the initial value of `x` and stays constant from line 4 through line 21. In fact it can change at lines 22–33. We will see why, but `w` is eventually reset to its initial value `0` at line 36.

```

1  s = 0, e = 0, g = 0, w = 0;
2  z = 0, predDivX = 0, predNotDivX = 1;
3  w = w + x; /* x is assumed to be the input */
4  for (i = 0; i <= w; i++) {
5      if (x > 0) { g++; }
6      else if (x == 0) { e++; }
7      else { s++; }
8      x = p(x);
9
10 for (i = 0; i < e; i++) {
11     predDivX = predDivX + predNotDivX;
12     predNotDivX = predDivX - predNotDivX; }
13
14 for (j = 0; j < predDivX; j++) {
15     for (i = 0; i <= w; i++) {
16         x = pInv(x);
17         if (x > 0) { g--; y = h(x,y); }
18         else if (x == 0) { e--; y = b(x); }
19         else { s--; }}}
20
21 for (j = 0; j < predNotDivX; j++) {
22     w++;
23     for (i = 0; i <= w; i++) {
24         x = pInv(x);
25         if (x > 0) { g--;
26                     x = p(x);
27                     if (z < 0) { }
28                     else if (z == 0) { y = b(x); z++; }
29                     else { y = h(x,y); }
30                     x = pInv(x); }
31         else if (x == 0) { e--; }
32         else { s--; }}}
33     w--;
34 for (i = 0; i < predNotDivX; i++) {
35     z--;
36 w = w - x;
37 /* y carries the output */

```

Fig. 8. The iterative function `itG`.



With the here above assumptions, given a non negative  $x$ , and in analogy to `itF`, the `for`-loop at lines 4–8 of `itG` iterates the application of  $p(x)$  as many times as  $w+1$ , i.e. the initial value of  $x$  plus 1. So, the value of  $x$  at line 9 is equal to  $w+(w+1)*\Delta_p$  which cannot be positive. In particular, all the values that  $x$  assumes in the `for`-loop at lines 4–8 belong to the following interval:

$$I(w) \triangleq [w+(w+1)*\Delta_p, w+w*\Delta_p, \dots, w+\Delta_p, w] \quad (2)$$

from the least to the greatest; the counters  $g$ ,  $e$ ,  $s$  say how many elements of  $I(x)$  are greater, equal or smaller than 0, respectively. Depending on 0 to belong to  $I(x)$  determines the behavior of the reminder part of `itG`, i.e. lines 10–36.

We distinguish two cases in order to illustrate them.

*First case.* Let  $w\% \Delta_p == 0$ , i.e. the integer value  $\Delta_p$  divides with no remainder the initial value of  $x$  that we find in  $w$ . So,  $0 \in I(x)$ , which implies the following relations hold at line 9:

$$e == 1 \quad g == -\frac{w}{\Delta_p} \quad s == (w+1)-g-e . \quad (3)$$

```

1  if      (e < 0) {
2  else if (e == 0) { predDivX = predDivX+predNotDivX;
3                    predNotDivX = predDivX - predNotDivX; }
4  else      {

```

**Fig. 9.** A possible replacement of lines 10–12 in **Fig. 8**.

Lines 10–12 execute exactly once, swapping `predDivX` and `predNotDivX`. As a remark, we could have well used the `if`-selection in **Fig. 9** (a construct of RPP) in place of the `for`-loop at lines 10–12, but we opt for a more compact code.

Swapping `predDivX` and `predNotDivX` sets `predDivX==1` and `predNotDivX==0`, computationally exploiting that  $\Delta_p$  divides  $w$  with no remainder: the `for`-loop body at lines 15–19 becomes accessible, while lines 22–33, with `for`-loops among them, do not. Lines 15–19 are identical to lines 10–16 of `itF` in **Fig. 4** which we already know to correctly apply  $b(x)$  and  $h(x,y)$  in order to simulate the recursive function we start from.

*As a second case.* Let  $w\% \Delta_p != 0$ , i.e. the integer value  $\Delta_p$  divides the initial value of  $x$  that  $w$  stores, *but with some remainder*. So,  $0 \notin I(x)$ , which imply:

$$e == 0 \quad g == -\left\lfloor \frac{w}{\Delta_p} \right\rfloor \quad s == (w+1)-g-e \quad (4)$$

hold at line 9. Lines 11–12 cannot execute, leaving `predDivX` and `predNotDivX` as they are: lines 22–33 become accessible and the `for`-loop at lines 15–19 does not. Line 22 increments `w` to balance the information loss that the rounding of `g` in (4) introduces; line 33 recovers the value of `w` when the outer `for`-loop starts. The `if`-selection at lines 25–32 identifies when to apply `b(x)`, which must be followed by the required applications of `h(x,y)`. We know that  $0 \notin I(x)$ , so `x==0` can never hold. Clearly, `s--` is executed until `x>0`. But the *first* time `x>0` holds true we must compute `b(p(x))`, because the *base* function `b(x)` *must be used the last time* `x` assumes a negative value, *not the first time* it gets positive; lines 26–30 implement our needs. Whenever `x>0` is true, the value of `x` is one step ahead the required one: we get one step back with line 26 and, if it is the first time we step back, i.e. `z==0` holds, then we must execute line 28. If not, i.e. `z!=0`, we must apply the *step* function at line 29. Line 30, restores the right value of `x`. Finally, the `for`-loop at line 34 sets `z` to its initial value.

At this point, in order to obtain the fully reversible version of **Fig. 8** we must think of replacing the calls to `h(x,y)` and `b(x)` at lines in 28, and 29 by means of actions that probe the value of `x`, in analogy to **Fig. 6**, lines 12 and 14. The full details are in [7] which we look as a playground with Java classes that implement **Fig. 8** and **Fig. 5** as synchronous and parallel threads, acting as a producer and a consumer.

## 4 Future work

We have shown that we can decompose every classical recursive function, based on a *predecessor* that decreases every of its input by a constant value, into reversible and classical components that cooperate to implement the original recursive functions under a Producer/Consumer pattern (see (1)).

Firstly, we plan to extend (1) to recursive functions `recF` based on predecessors `p` not limited to a constant  $\Delta_p$  not greater than `-1`. A predecessor `p` should be at least such that:

1.  $\Delta_p$  is not necessarily a constant. For example,  $\Delta_p == -3$  on even arguments, and `-2` on odd ones can be useful;
2. the predecessor can be an integer division `x/k`, for some given `k>0`, like in a dichotomic search, which has `k==2`.

Secondly, we aim at generalizing (1) to a compiler  $\llbracket \cdot \rrbracket$ :

$$\begin{aligned}
 \llbracket p \rrbracket &= \text{some implementation code} \\
 \llbracket p\text{Inv} \rrbracket &= !\llbracket p \rrbracket, \text{ i.e. implementation that inverts } \llbracket p \rrbracket \\
 \llbracket \text{recF}[p,b,h] \rrbracket &= \text{itFCls}[\llbracket b \rrbracket, \llbracket h \rrbracket] \parallel \text{itFRev}[\llbracket p \rrbracket, \llbracket p\text{Inv} \rrbracket] .
 \end{aligned} \tag{5}$$

The domain of  $\llbracket \cdot \rrbracket$  should be a class `R` of recursive functions built by means of standard composition schemes, starting from a class of predecessors `p1`, `p2`, ... each of which must have the corresponding inverse function `p1Inv`, `p2Inv`, ...

In these lines we want to explore interpretations of  $\parallel$  more liberal than the essentially obvious synchronous Producer/Consumer that we implement in [7]. We shall very likely take advantage of parallel discrete events simulators as described in [8,9] in order to get rid of any explicit synchronization between the pairs of reversible-producer/classical-consumer that (5) would recursively generate when applied to an element in  $R$ .

We also plan to follow a more abstract line of research. The compilation scheme (5) recalls Girard’s decomposition  $A \rightarrow B \simeq !A \multimap B$  of a classical computation into a linear one that can erase/duplicate computational resources. Decomposing  $\text{recF}[p, b, h]$  in terms of  $\text{itFClS}[b, h]$  and  $\text{itFRev}[p, p\text{Inv}]$  suggests that the relation between reversible and classical computations can be formalized by a linear isomorphism  $A^n \multimap B^n$  between tensor products  $A^n$ , and  $B^n$  of  $A$ , and  $B$ , in analogy to [2]. Then we can think of recovering classical computations by some functor, say  $\gamma$ , whose purpose is, at least, to forget, or to inject replicas, of parts of  $A^n$ , and  $B^n$  in a way that  $(\gamma A^n \rightarrow \gamma A^n) \uplus (\gamma A^n \leftarrow \gamma A^n)$  can be their type. The type says that we move from a reversible computation to a classical one by choosing which is input and which is output, so recovering the freedom to manage computational resources as we are used to when writing classical programs.

## References

1. E. A. Boiten. Improving recursive functions by inverting the order of evaluation. *Science of Computer Programming*, 18(2):139 – 179, 1992.
2. R. P. James and A. Sabry. Information effects. In J. Field and M. Hicks, editors, *Proceedings of the 39th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2012, Philadelphia, Pennsylvania, USA, January 22-28, 2012*, pages 73–84. ACM, 2012.
3. A. B. Matos. Linear programs in a simple reversible language. *Theor. Comput. Sci.*, 290(3):2063–2074, 2003.
4. A. B. Matos, L. Paolini, and L. Roversi. On the expressivity of total reversible programming languages. In I. Lanese and M. Rawski, editors, *Reversible Computation*, pages 128–143, Cham, 2020. Springer International Publishing.
5. L. Paolini, M. Piccolo, and L. Roversi. On a class of reversible primitive recursive functions and its turing-complete extensions. *New Generation Computing*, 36(3):233–256, Jul 2018.
6. L. Paolini, M. Piccolo, and L. Roversi. A class of recursive permutations which is primitive recursive complete. *Theor. Comput. Sci.*, 813:218–233, 2020.
7. L. Roversi, A. Matos, and L. Paolini. Eclipse java project rev2iterrev. <https://github.com/LucaRoversi/Rec2IterRev>.
8. M. Schordan, T. Opielstrup, D. R. Jefferson, and P. D. B. Jr. Generation of reversible C++ code for optimistic parallel discrete event simulation. *New Gener. Comput.*, 36(3):257–280, 2018.
9. M. Schordan, T. Opielstrup, M. K. Thomsen, and R. Glück. *Reversible Languages and Incremental State Saving in Optimistic Parallel Discrete Event Simulation*, pages 187–207. Springer International Publishing, Cham, 2020.