

# Mechanising the worker/wrapper transformation

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## 1 Introduction

This mechanisation of the worker/wrapper theory of Gill and Hutton (2009) was carried out in Isabelle/HOLCF (Müller et al. 1999; Huffman 2009). It accompanies Gammie (2011). The reader should note that *oo* stands for function composition,  $\Lambda\_.$  for continuous function abstraction,  $\_ \cdot \_$  for continuous function application, **domain** for recursive-datatype definition. *(ML)*

## 2 Fixed-point theorems for program transformation

We begin by recounting some standard theorems from the early days of denotational semantics. The origins of these results are lost to history; the interested reader can find some of it in Bekić (1984); Manna (1974); Greibach (1975); Stoy (1977); de Bakker et al. (1980); Harel (1980); Plotkin (1983); Winskel (1993); Sangiorgi (2009).

### 2.1 The rolling rule

The *rolling rule* captures what intuitively happens when we re-order a recursive computation consisting of two parts. This theorem dates from the 1970s at the latest – see Stoy (1977, p210) and Plotkin (1983). The following proofs were provided by Gill and Hutton (2009).

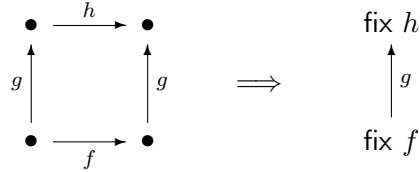
**lemma** *rolling-rule-ltr*:  $\text{fix} \cdot (g \text{ oo } f) \sqsubseteq g \cdot (\text{fix} \cdot (f \text{ oo } g))$   
*<proof>*

**lemma** *rolling-rule-rtl*:  $g \cdot (\text{fix} \cdot (f \text{ oo } g)) \sqsubseteq \text{fix} \cdot (g \text{ oo } f)$   
*<proof>*

**lemma** *rolling-rule*:  $\text{fix} \cdot (g \text{ oo } f) = g \cdot (\text{fix} \cdot (f \text{ oo } g))$   
*<proof>*

## 2.2 Least-fixed-point fusion

*Least-fixed-point fusion* provides a kind of induction that has proven to be very useful in calculational settings. Intuitively it lifts the step-by-step correspondence between  $f$  and  $h$  witnessed by the strict function  $g$  to the fixed points of  $f$  and  $g$ :



Fokkinga and Meijer (1991), and also their later Meijer, Fokkinga, and Paterson (1991), made extensive use of this rule, as did Tullsen (2002) in his program transformation tool PATH. This diagram is strongly reminiscent of the simulations used to establish refinement relations between imperative programs and their specifications (de Roever and Engelhardt 1998).

The following proof is close to the third variant of Stoy (1977, p215). We relate the two fixpoints using the rule `parallel_fix_ind`:

$$\frac{\text{adm } (\lambda x. ?P (fst x) (snd x)) \quad ?P \perp \perp \quad \bigwedge x y. \frac{?P x y}{?P (?F.x) (?G.y)}}{?P (\text{fix} \cdot ?F) (\text{fix} \cdot ?G)}$$

in a very straightforward way:

**lemma** *lfp-fusion*:

**assumes**  $g \cdot \perp = \perp$

**assumes**  $g \circ f = h \circ g$

**shows**  $g \cdot (\text{fix} \cdot f) = \text{fix} \cdot h$

*<proof>*

This lemma also goes by the name of *Plotkin's axiom* (Pitts 1996) or *uniformity* (Simpson and Plotkin 2000).

*<proof><proof><proof><proof><proof><proof><proof>*

## 3 The transformation according to Gill and Hutton

The worker/wrapper transformation and associated fusion rule as formalised by Gill and Hutton (2009) are reproduced in Figure 1, and the reader is referred to the original paper for further motivation and background.

Armed with the rolling rule we can show that Gill and Hutton's justification of the worker/wrapper transformation is sound. There is a battery of these transformations with varying strengths of hypothesis.

For a recursive definition  $comp = \text{fix } body$  for some  $body :: A \rightarrow A$  and a pair of functions  $wrap :: B \rightarrow A$  and  $unwrap :: A \rightarrow B$  where  $wrap \circ unwrap = id_A$ , we have:

$$\begin{aligned} comp &= wrap \ work \\ work &:: B && \text{(the worker/wrapper} \\ work &= \text{fix } (unwrap \circ body \circ wrap) \end{aligned}$$

transformation)

Also:

$$(unwrap \circ wrap) \ work = work \quad \text{(worker/wrapper fusion)}$$

Figure 1: The worker/wrapper transformation and fusion rule of Gill and Hutton (2009).

The first requires  $wrap \circ unwrap$  to be the identity for all values.

**lemma** *worker-wrapper-id:*

**fixes**  $wrap :: 'b::pcpo \rightarrow 'a::pcpo$

**fixes**  $unwrap :: 'a \rightarrow 'b$

**assumes**  $wrap\text{-}unwrap: wrap \circ unwrap = ID$

**assumes**  $comp\text{-}body: computation = \text{fix}\cdot body$

**shows**  $computation = wrap \cdot (\text{fix} \cdot (unwrap \circ body \circ wrap))$

*<proof>*

The second weakens this assumption by requiring that  $wrap \circ wrap$  only act as the identity on values in the image of  $body$ .

**lemma** *worker-wrapper-body:*

**fixes**  $wrap :: 'b::pcpo \rightarrow 'a::pcpo$

**fixes**  $unwrap :: 'a \rightarrow 'b$

**assumes**  $wrap\text{-}unwrap: wrap \circ unwrap \circ body = body$

**assumes**  $comp\text{-}body: computation = \text{fix}\cdot body$

**shows**  $computation = wrap \cdot (\text{fix} \cdot (unwrap \circ body \circ wrap))$

*<proof>*

This is particularly useful when the computation being transformed is strict in its argument.

Finally we can allow the identity to take the full recursive context into account. This rule was described by Gill and Hutton but not used.

**lemma** *worker-wrapper-fix:*

**fixes**  $wrap :: 'b::pcpo \rightarrow 'a::pcpo$

**fixes**  $unwrap :: 'a \rightarrow 'b$

**assumes**  $wrap\text{-}unwrap: \text{fix} \cdot (wrap \circ unwrap \circ body) = \text{fix} \cdot body$

**assumes**  $comp\text{-}body: computation = \text{fix}\cdot body$

**shows**  $computation = wrap \cdot (\text{fix} \cdot (unwrap \circ body \circ wrap))$

*<proof>*

Gill and Hutton’s *worker-wrapper-fusion* rule is intended to allow the transformation of  $(unwrap \circo wrap) \cdot R$  to  $R$  in recursive contexts, where  $R$  is meant to be a self-call. Note that it assumes that the first worker/wrapper hypothesis can be established.

**lemma** *worker-wrapper-fusion*:

**fixes**  $wrap :: 'b::pcpo \rightarrow 'a::pcpo$

**fixes**  $unwrap :: 'a \rightarrow 'b$

**assumes**  $wrap \circo unwrap = ID$

**assumes**  $work: work = fix \cdot (unwrap \circo body \circo wrap)$

**shows**  $(unwrap \circo wrap) \cdot work = work$

*<proof>*

The following sections show that this rule only preserves partial correctness. This is because Gill and Hutton apply it in the context of the fold/unfold program transformation framework of [Burstall and Darlington \(1977\)](#), which need not preserve termination. We show that the fusion rule does in fact require extra conditions to be totally correct and propose one such sufficient condition.

### 3.1 Worker/wrapper fusion is partially correct

We now examine how Gill and Hutton apply their worker/wrapper fusion rule in the context of the fold/unfold framework.

The key step of those left implicit in the original paper is the use of the fold rule to justify replacing the worker with the fused version. Schematically, the fold/unfold framework maintains a history of all definitions that have appeared during transformation, and the fold rule treats this as a set of rewrite rules oriented right-to-left. (The unfold rule treats the current working set of definitions as rewrite rules oriented left-to-right.) Hence as each definition  $f = body$  yields a rule of the form  $body \implies f$ , one can always derive  $f = f$ . Clearly this has dire implications for the preservation of termination behaviour.

[Tullsen \(2002\)](#) in his §3.1.2 observes that the semantic essence of the fold rule is Park induction:

$$\frac{f \cdot ?x = ?x}{fix \cdot f \sqsubseteq ?x} \text{fix\_least}$$

viz that  $f \cdot x = x$  implies only the partially correct  $fix \cdot f \sqsubseteq x$ , and not the totally correct  $fix \cdot f = x$ . We use this characterisation to show that if *unwrap* is non-strict (i.e.  $unwrap \perp \neq \perp$ ) then there are programs where worker/wrapper fusion as used by Gill and Hutton need only be partially correct.

Consider the scenario described in Figure 1. After applying the worker/wrapper transformation, we attempt to apply fusion by finding a residual expression  $body'$  such that the body of the worker, i.e. the expression  $unwrap \circ body \circ wrap$ , can be rewritten as  $body' \circ unwrap \circ wrap$ . Intuitively this is the semantic form of workers where all self-calls are fusible. Our goal is to justify redefining  $work$  to  $fix \cdot body'$ , i.e. to establish:

$$fix \cdot (unwrap \circ body \circ wrap) = fix \cdot body'$$

We show that worker/wrapper fusion as proposed by Gill and Hutton is partially correct using Park induction:

**lemma** *fusion-partially-correct*:

**assumes** *wrap-unwrap*:  $wrap \circ unwrap = ID$

**assumes** *work*:  $work = fix \cdot (unwrap \circ body \circ wrap)$

**assumes** *body'*:  $unwrap \circ body \circ wrap = body' \circ unwrap \circ wrap$

**shows**  $fix \cdot body' \sqsubseteq work$

*<proof>*

The next section shows the converse does not obtain.

### 3.2 A non-strict *unwrap* may go awry

If *unwrap* is non-strict, then it is possible that the fusion rule proposed by Gill and Hutton does not preserve termination. To show this we take a small artificial example. The type  $A$  is not important, but we need access to a non-bottom inhabitant. The target type  $B$  is the non-strict lift of  $A$ .

**domain**  $A = A$

**domain**  $B = B$  (**lazy**  $A$ )

The functions *wrap* and *unwrap* that map between these types are routine. Note that *wrap* is (necessarily) strict due to the property  $\forall x. ?f \cdot (?g \cdot x) = x \implies ?f \cdot \perp = \perp$ .

**fixrec** *wrap* ::  $B \rightarrow A$

**where**  $wrap \cdot (B \cdot a) = a$

*<proof>*

**fixrec** *unwrap* ::  $A \rightarrow B$

**where**  $unwrap = B$

Discharging the worker/wrapper hypothesis is similarly routine.

**lemma** *wrap-unwrap*:  $wrap \circ unwrap = ID$

*<proof>*

The candidate computation we transform can be any that uses the recursion parameter  $r$  non-strictly. The following is especially trivial.

**fixrec** *body* ::  $A \rightarrow A$

**where**  $body \cdot r = A$

The wrinkle is that the transformed worker can be strict in the recursion parameter  $r$ , as *unwrap* always lifts it.

**fixrec**  $body' :: B \rightarrow B$   
**where**  $body' \cdot (B \cdot a) = B \cdot A \langle proof \rangle$

As explained above, we set up the fusion opportunity:

**lemma**  $body\text{-}body'$ :  $unwrap \circ body \circ wrap = body' \circ unwrap \circ wrap$   
 $\langle proof \rangle$

This result depends crucially on *unwrap* being non-strict.

Our earlier result shows that the proposed transformation is partially correct:

**lemma**  $fix \cdot body' \sqsubseteq fix \cdot (unwrap \circ body \circ wrap)$   
 $\langle proof \rangle$

However it is easy to see that it is not totally correct:

**lemma**  $\neg fix \cdot (unwrap \circ body \circ wrap) \sqsubseteq fix \cdot body'$   
 $\langle proof \rangle$

This trick works whenever *unwrap* is not strict. In the following section we show that requiring *unwrap* to be strict leads to a straightforward proof of total correctness.

Note that if we have already established that  $wrap \circ unwrap = ID$ , then making *unwrap* strict preserves this equation:

**lemma**  
**assumes**  $wrap \circ unwrap = ID$   
**shows**  $wrap \circ strictify \cdot unwrap = ID$   
 $\langle proof \rangle$

From this we conclude that the worker/wrapper transformation itself cannot exploit any laziness in *unwrap* under the context-insensitive assumptions of *worker-wrapper-id*. This is not to say that other program transformations may not be able to.

$\langle proof \rangle$

## 4 A totally-correct fusion rule

We now show that a termination-preserving worker/wrapper fusion rule can be obtained by requiring *unwrap* to be strict. (As we observed earlier, *wrap* must always be strict due to the assumption that  $wrap \circ unwrap = ID$ .)

Our first result shows that a combined worker/wrapper transformation and fusion rule is sound, using the assumptions of *worker-wrapper-id* and the ubiquitous *lfp-fusion* rule.

**lemma** *worker-wrapper-fusion-new*:

For a recursive definition  $comp = body$  of type  $A$  and a pair of functions  $wrap :: B \rightarrow A$  and  $unwrap :: A \rightarrow B$  where  $wrap \circ unwrap = id_A$  and  $unwrap \perp = \perp$ , define:

$$\begin{aligned} comp &= wrap \ work && \text{(the worker/wrapper} \\ work &= unwrap (body[wrap \ work/comp]) \end{aligned}$$

transformation)

In the scope of  $work$ , the following rewrite is admissible:

$$unwrap (wrap \ work) \Longrightarrow work \quad \text{(worker/wrapper fusion)}$$

Figure 2: The syntactic worker/wrapper transformation and fusion rule.

```

fixes wrap :: 'b::pcpo → 'a::pcpo
fixes unwrap :: 'a → 'b
fixes body' :: 'b → 'b
assumes wrap-unwrap: wrap oo unwrap = (ID :: 'a → 'a)
assumes unwrap-strict: unwrap.⊥ = ⊥
assumes body-body': unwrap oo body oo wrap = body' oo (unwrap oo wrap)
shows fix·body = wrap·(fix·body')
⟨proof⟩

```

We can also show a more general result which allows fusion to be optionally performed on a per-recursive-call basis using `parallel_fix_ind`:

```

lemma worker-wrapper-fusion-new-general:
fixes wrap :: 'b::pcpo → 'a::pcpo
fixes unwrap :: 'a → 'b
assumes wrap-unwrap: wrap oo unwrap = (ID :: 'a → 'a)
assumes unwrap-strict: unwrap.⊥ = ⊥
assumes body-body':  $\bigwedge r. (unwrap \ oo \ wrap) \cdot r = r$ 
shows  $\Longrightarrow (unwrap \ oo \ body \ oo \ wrap) \cdot r = body' \cdot r$ 
shows fix·body = wrap·(fix·body')
⟨proof⟩

```

This justifies the syntactically-oriented rules shown in Figure 2; note the scoping of the fusion rule.

Those familiar with the “bananas” work of Meijer, Fokkinga, and Paterson (1991) will not be surprised that adding a strictness assumption justifies an equational fusion rule.



## 5 Naive reverse becomes accumulator-reverse.

### 5.1 Hughes lists, naive reverse, worker-wrapper optimisation.

The “Hughes” list type.

**type-synonym**  $'a\ H = 'a\ \text{llist} \rightarrow 'a\ \text{llist}$

**definition**

$\text{list2H} :: 'a\ \text{llist} \rightarrow 'a\ H$  **where**  
 $\text{list2H} \equiv \text{lappend}$

**lemma** *acc-c2a-strict[simp]*:  $\text{list2H}.\perp = \perp$   
*<proof>*

**definition**

$H2\text{list} :: 'a\ H \rightarrow 'a\ \text{llist}$  **where**  
 $H2\text{list} \equiv \Lambda f . f.\text{lnil}$

The paper only claims the homomorphism holds for finite lists, but in fact it holds for all lazy lists in HOLCF. They are trying to dodge an explicit appeal to the equation  $\perp = (\Lambda x. \perp)$ , which does not hold in Haskell.

**lemma** *H-llist-hom-append*:  $\text{list2H}.(xs :++ ys) = \text{list2H}.xs\ \text{oo}\ \text{list2H}.ys$  (**is** *?lhs = ?rhs*)  
*<proof>*

**lemma** *H-llist-hom-id*:  $\text{list2H}.\text{lnil} = \text{ID}$  *<proof>*

**lemma** *H2list-list2H-inv*:  $H2\text{list}\ \text{oo}\ \text{list2H} = \text{ID}$   
*<proof>*

Gill and Hutton (2009, §4.2) define the naive reverse function as follows.

**fixrec**  $\text{lrev} :: 'a\ \text{llist} \rightarrow 'a\ \text{llist}$

**where**

$\text{lrev}.\text{lnil} = \text{lnil}$   
 $|\ \text{lrev}(x :@ xs) = \text{lrev}.xs :++ (x :@ \text{lnil})$

Note “body” is the generator of *lrev-def*.

**lemma** *lrev-strict[simp]*:  $\text{lrev}.\perp = \perp$   
*<proof>*

**fixrec**  $\text{lrev-body} :: ('a\ \text{llist} \rightarrow 'a\ \text{llist}) \rightarrow 'a\ \text{llist} \rightarrow 'a\ \text{llist}$

**where**

$\text{lrev-body}.r.\text{lnil} = \text{lnil}$   
 $|\ \text{lrev-body}.r.(x :@ xs) = r.xs :++ (x :@ \text{lnil})$

**lemma** *lrev-body-strict[simp]*:  $\text{lrev-body}.r.\perp = \perp$

*<proof>*

This is trivial but syntactically a bit touchy. Would be nicer to define *lrev-body* as the generator of the fixpoint definition of *lrev* directly.

**lemma** *lrev-lrev-body-eq*:  $lrev = fix.lrev-body$   
*<proof>*

Wrap / unwrap functions.

**definition**  
 $unwrapH :: ('a\ llist \rightarrow 'a\ H) \rightarrow 'a\ llist \rightarrow 'a\ H$  **where**  
 $unwrapH \equiv \Lambda f\ xs . list2H.(f.xs)$

**lemma** *unwrapH-strict[simp]*:  $unwrapH.\perp = \perp$   
*<proof>*

**definition**  
 $wrapH :: ('a\ llist \rightarrow 'a\ H) \rightarrow 'a\ llist \rightarrow 'a\ llist$  **where**  
 $wrapH \equiv \Lambda f\ xs . H2list.(f.xs)$

**lemma** *wrapH-unwrapH-id*:  $wrapH\ oo\ unwrapH = ID$  (is ?lhs = ?rhs)  
*<proof>*

## 5.2 Gill/Hutton-style worker/wrapper.

**definition**  
 $lrev-work :: 'a\ llist \rightarrow 'a\ H$  **where**  
 $lrev-work \equiv fix.(unwrapH\ oo\ lrev-body\ oo\ wrapH)$

**definition**  
 $lrev-wrap :: 'a\ llist \rightarrow 'a\ llist$  **where**  
 $lrev-wrap \equiv wrapH.lrev-work$

**lemma** *lrev-lrev-wv-eq*:  $lrev = lrev-wrap$   
*<proof>*

## 5.3 Optimise worker/wrapper.

Intermediate worker.

**fixrec** *lrev-body1* ::  $('a\ llist \rightarrow 'a\ H) \rightarrow 'a\ llist \rightarrow 'a\ H$   
**where**  
 $lrev-body1.r.nil = list2H.nil$   
 $| lrev-body1.r.(x :@ xs) = list2H.(wrapH.r.xs :++ (x :@ nil))$

**definition**  
 $lrev-work1 :: 'a\ llist \rightarrow 'a\ H$  **where**  
 $lrev-work1 \equiv fix.lrev-body1$

**lemma** *lrev-body-lrev-body1-eq*:  $lrev-body1 = unwrapH\ oo\ lrev-body\ oo\ wrapH$

*<proof>*

**lemma** *lev-work1-lev-work-eq*:  $lev-work1 = lev-work$   
*<proof>*

Now use the homomorphism.

**fixrec** *lev-body2* :: ( $'a\ list \rightarrow 'a\ H$ )  $\rightarrow 'a\ list \rightarrow 'a\ H$   
**where**  
   $lev-body2 \cdot r \cdot nil = ID$   
   $| lev-body2 \cdot r \cdot (x :@ xs) = list2H \cdot (wrapH \cdot r \cdot xs) \ o\ list2H \cdot (x :@ nil)$

**lemma** *lev-body2-strict[simp]*:  $lev-body2 \cdot r \cdot \perp = \perp$   
*<proof>*

**definition**

*lev-work2* ::  $'a\ list \rightarrow 'a\ H$  **where**  
 $lev-work2 \equiv fix \cdot lev-body2$

**lemma** *lev-work2-strict[simp]*:  $lev-work2 \cdot \perp = \perp$   
*<proof>*

**lemma** *lev-body2-lev-body1-eq*:  $lev-body2 = lev-body1$   
*<proof>*

**lemma** *lev-work2-lev-work1-eq*:  $lev-work2 = lev-work1$   
*<proof>*

Simplify.

**fixrec** *lev-body3* :: ( $'a\ list \rightarrow 'a\ H$ )  $\rightarrow 'a\ list \rightarrow 'a\ H$   
**where**  
   $lev-body3 \cdot r \cdot nil = ID$   
   $| lev-body3 \cdot r \cdot (x :@ xs) = r \cdot xs \ o\ list2H \cdot (x :@ nil)$

**lemma** *lev-body3-strict[simp]*:  $lev-body3 \cdot r \cdot \perp = \perp$   
*<proof>*

**definition**

*lev-work3* ::  $'a\ list \rightarrow 'a\ H$  **where**  
 $lev-work3 \equiv fix \cdot lev-body3$

**lemma** *lev-wwfusion*:  $list2H \cdot ((wrapH \cdot lev-work2) \cdot xs) = lev-work2 \cdot xs$   
*<proof>*

If we use this result directly, we only get a partially-correct program transformation, see [Tullsen \(2002\)](#) for details.

**lemma** *lev-work3*  $\sqsubseteq$  *lev-work2*  
*<proof>*

We can't show the reverse inclusion in the same way as the fusion law doesn't

hold for the optimised definition. (Intuitively we haven't established that it is equal to the original *lev* definition.) We could show termination of the optimised definition though, as it operates on finite lists. Alternatively we can use induction (over the list argument) to show total equivalence.

The following lemma shows that the fusion Gill/Hutton want to do is completely sound in this context, by appealing to the lazy list induction principle.

**lemma** *lev-work3-lev-work2-eq*:  $lev\text{-}work3 = lev\text{-}work2$  (**is** ?lhs = ?rhs)  
 ⟨proof⟩

Use the combined worker/wrapper-fusion rule. Note we get a weaker lemma.

**lemma** *lev3-2-syntactic*:  $lev\text{-}body3 \circ (unwrapH \circ wrapH) = lev\text{-}body2$   
 ⟨proof⟩

**lemma** *lev-work3-lev-work2-eq'*:  $lev = wrapH \cdot lev\text{-}work3$   
 ⟨proof⟩

Final syntactic tidy-up.

**fixrec** *lev-body-final* :: ('a llist → 'a H) → 'a llist → 'a H

**where**

$lev\text{-}body\text{-}final \cdot r \cdot lnil \cdot ys = ys$   
 $| lev\text{-}body\text{-}final \cdot r \cdot (x :@ xs) \cdot ys = r \cdot xs \cdot (x :@ ys)$

**definition**

*lev-work-final* :: 'a llist → 'a H **where**  
 $lev\text{-}work\text{-}final \equiv fix \cdot lev\text{-}body\text{-}final$

**definition**

*lev-final* :: 'a llist → 'a llist **where**  
 $lev\text{-}final \equiv \Lambda xs. lev\text{-}work\text{-}final \cdot xs \cdot lnil$

**lemma** *lev-body-final-lev-body3-eq'*:  $lev\text{-}body\text{-}final \cdot r \cdot xs = lev\text{-}body3 \cdot r \cdot xs$   
 ⟨proof⟩

**lemma** *lev-body-final-lev-body3-eq*:  $lev\text{-}body\text{-}final = lev\text{-}body3$   
 ⟨proof⟩

**lemma** *lev-final-lev-eq*:  $lev = lev\text{-}final$  (**is** ?lhs = ?rhs)  
 ⟨proof⟩

## 6 Unboxing types.

The original application of the worker/wrapper transformation was the unboxing of flat types by Peyton Jones and Launchbury (1991). We can model the boxed and unboxed types as (respectively) pointed and unpointed domains in HOLCF. Concretely *UNat* denotes the discrete domain of naturals,

$UNat_{\perp}$  the lifted (flat and pointed) variant, and  $Nat$  the standard boxed domain, isomorphic to  $UNat_{\perp}$ . This latter distinction helps us keep the boxed naturals and lifted function codomains separated; applications of *unbox* should be thought of in the same way as Haskell’s *newtype* constructors, i.e. operationally equivalent to *ID*.

The divergence monad is used to handle the unboxing, see below.

## 6.1 Factorial example.

Standard definition of factorial.

**fixrec**  $fac :: Nat \rightarrow Nat$

**where**

$fac.n = \text{If } n =_B 0 \text{ then } 1 \text{ else } n * fac.(n - 1)$

**declare**  $fac.simps[simp\ del]$

**lemma**  $fac\text{-strict}[simp]: fac.\perp = \perp$

$\langle proof \rangle$

**definition**

$fac\text{-body} :: (Nat \rightarrow Nat) \rightarrow Nat \rightarrow Nat$  **where**

$fac\text{-body} \equiv \Lambda r\ n. \text{If } n =_B 0 \text{ then } 1 \text{ else } n * r.(n - 1)$

**lemma**  $fac\text{-body-strict}[simp]: fac\text{-body}.r.\perp = \perp$

$\langle proof \rangle$

**lemma**  $fac\text{-fac-body-eq}: fac = fix.fac\text{-body}$

$\langle proof \rangle$

Wrap / unwrap functions. Note the explicit lifting of the co-domain. For some reason the published version of [Gill and Hutton \(2009\)](#) does not discuss this point: if we’re going to handle recursive functions, we need a bottom.

*unbox* simply removes the tag, yielding a possibly-divergent unboxed value, the result of the function.

**definition**

$unwrapB :: (Nat \rightarrow Nat) \rightarrow UNat \rightarrow UNat_{\perp}$  **where**

$unwrapB \equiv \Lambda f. unbox\ oo\ f\ oo\ box$

Note that the monadic bind operator ( $>>=$ ) here stands in for the case construct in the paper.

**definition**

$wrapB :: (UNat \rightarrow UNat_{\perp}) \rightarrow Nat \rightarrow Nat$  **where**

$wrapB \equiv \Lambda f\ x. unbox.x >>= f >>= box$

**lemma**  $wrapB\text{-unwrapB-body}:$

**assumes**  $strictF: f.\perp = \perp$

**shows**  $(wrapB \text{ oo } unwrapB) \cdot f = f$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

Apply worker/wrapper.

**definition**

$fac\text{-}work :: UNat \rightarrow UNat_{\perp}$  **where**  
 $fac\text{-}work \equiv fix \cdot (unwrapB \text{ oo } fac\text{-}body \text{ oo } wrapB)$

**definition**

$fac\text{-}wrap :: Nat \rightarrow Nat$  **where**  
 $fac\text{-}wrap \equiv wrapB \cdot fac\text{-}work$

**lemma**  $fac\text{-}fac\text{-}ww\text{-}eq$ :  $fac = fac\text{-}wrap$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

This is not entirely faithful to the paper, as they don't explicitly handle the lifting of the codomain.

**definition**

$fac\text{-}body' :: (UNat \rightarrow UNat_{\perp}) \rightarrow UNat \rightarrow UNat_{\perp}$  **where**  
 $fac\text{-}body' \equiv \Lambda r \ n.$   
 $unbox \cdot (If \ box \cdot n =_B \ 0$   
 $\quad \text{then } 1$   
 $\quad \text{else } unbox \cdot (box \cdot n - 1) \gg = r \gg = (\Lambda b. \ box \cdot n * box \cdot b))$

**lemma**  $fac\text{-}body'\text{-}fac\text{-}body$ :  $fac\text{-}body' = unwrapB \text{ oo } fac\text{-}body \text{ oo } wrapB$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

The *up* constructors here again mediate the isomorphism, operationally doing nothing. Note the switch to the machine-oriented *if* construct: the test  $n = (0 :: 'a)$  cannot diverge.

**definition**

$fac\text{-}body\text{-}final :: (UNat \rightarrow UNat_{\perp}) \rightarrow UNat \rightarrow UNat_{\perp}$  **where**  
 $fac\text{-}body\text{-}final \equiv \Lambda r \ n.$   
 $if \ n = 0 \ \text{then } up \cdot 1 \ \text{else } r \cdot (n - \# \ 1) \gg = (\Lambda b. \ up \cdot (n * \# \ b))$

**lemma**  $fac\text{-}body\text{-}final\text{-}fac\text{-}body'$ :  $fac\text{-}body\text{-}final = fac\text{-}body'$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

**definition**

$fac\text{-}work\text{-}final :: UNat \rightarrow UNat_{\perp}$  **where**  
 $fac\text{-}work\text{-}final \equiv fix \cdot fac\text{-}body\text{-}final$

**definition**

$fac\text{-}final :: Nat \rightarrow Nat$  **where**  
 $fac\text{-}final \equiv \Lambda n. \ unbox \cdot n \gg = fac\text{-}work\text{-}final \gg = box$

**lemma**  $fac\text{-}fac\text{-}final$ :  $fac = fac\text{-}final$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

## 6.2 Introducing an accumulator.

The final version of factorial uses unboxed naturals but is not tail-recursive. We can apply worker/wrapper once more to introduce an accumulator, similar to §5.

The monadic machinery complicates things slightly here. We use *Kleisli composition*, denoted ( $\>=>$ ), in the homomorphism.

Firstly we introduce an “accumulator” monoid and show the homomorphism.

**type-synonym**  $UNatAcc = UNat \rightarrow UNat_{\perp}$

**definition**

$n2a :: UNat \rightarrow UNatAcc$  **where**  
 $n2a \equiv \Lambda m n. up.(m *_{\#} n)$

**definition**

$a2n :: UNatAcc \rightarrow UNat_{\perp}$  **where**  
 $a2n \equiv \Lambda a. a \cdot 1$

**lemma**  $a2n\text{-strict}[simp]$ :  $a2n.\perp = \perp$   
 $\langle proof \rangle$

**lemma**  $a2n\text{-}n2a$ :  $a2n.(n2a \cdot u) = up \cdot u$   
 $\langle proof \rangle$

**lemma**  $A\text{-hom-mult}$ :  $n2a.(x *_{\#} y) = (n2a \cdot x \>=> n2a \cdot y)$   
 $\langle proof \rangle$

**definition**

$unwrapA :: (UNat \rightarrow UNat_{\perp}) \rightarrow UNat \rightarrow UNatAcc$  **where**  
 $unwrapA \equiv \Lambda f n. f \cdot n \>>= n2a$

**lemma**  $unwrapA\text{-strict}[simp]$ :  $unwrapA.\perp = \perp$   
 $\langle proof \rangle$

**definition**

$wrapA :: (UNat \rightarrow UNatAcc) \rightarrow UNat \rightarrow UNat_{\perp}$  **where**  
 $wrapA \equiv \Lambda f. a2n \text{ oo } f$

**lemma**  $wrapA\text{-}unwrapA\text{-id}$ :  $wrapA \text{ oo } unwrapA = ID$   
 $\langle proof \rangle$

Some steps along the way.

**definition**

$fac\text{-acc-body1} :: (UNat \rightarrow UNatAcc) \rightarrow UNat \rightarrow UNatAcc$  **where**  
 $fac\text{-acc-body1} \equiv \Lambda r n.$   
 $\text{if } n = 0 \text{ then } n2a \cdot 1 \text{ else } wrapA \cdot r \cdot (n -_{\#} 1) \>>= (\Lambda res. n2a \cdot (n *_{\#} res))$

**lemma** *fac-acc-body1-fac-body-final-eq*:  $fac-acc-body1 = unwrapA \circo fac-body-final \circo wrapA$   
 ⟨proof⟩

Use the homomorphism.

**definition**

$fac-acc-body2 :: (UNat \rightarrow UNatAcc) \rightarrow UNat \rightarrow UNatAcc$  **where**  
 $fac-acc-body2 \equiv \Lambda r n.$   
*if*  $n = 0$  *then*  $n2a \cdot 1$  *else*  $wrapA \cdot r \cdot (n -\# 1) >>= (\Lambda res. n2a \cdot n >=> n2a \cdot res)$

**lemma** *fac-acc-body2-body1-eq*:  $fac-acc-body2 = fac-acc-body1$   
 ⟨proof⟩

Apply worker/wrapper.

**definition**

$fac-acc-body3 :: (UNat \rightarrow UNatAcc) \rightarrow UNat \rightarrow UNatAcc$  **where**  
 $fac-acc-body3 \equiv \Lambda r n.$   
*if*  $n = 0$  *then*  $n2a \cdot 1$  *else*  $n2a \cdot n >=> r \cdot (n -\# 1)$

**lemma** *fac-acc-body3-body2*:  $fac-acc-body3 \circo (unwrapA \circo wrapA) = fac-acc-body2$  (**is** *?lhs=?rhs*)  
 ⟨proof⟩

**lemma** *fac-work-final-body3-eq*:  $fac-work-final = wrapA \cdot (fix \cdot fac-acc-body3)$   
 ⟨proof⟩

**definition**

$fac-acc-body-final :: (UNat \rightarrow UNatAcc) \rightarrow UNat \rightarrow UNatAcc$  **where**  
 $fac-acc-body-final \equiv \Lambda r n acc.$   
*if*  $n = 0$  *then*  $up \cdot acc$  *else*  $r \cdot (n -\# 1) \cdot (n *_{\#} acc)$

**definition**

$fac-acc-work-final :: UNat \rightarrow UNat_{\perp}$  **where**  
 $fac-acc-work-final \equiv \Lambda x. fix \cdot fac-acc-body-final \cdot x \cdot 1$

**lemma** *fac-acc-work-final-fac-acc-work3-eq*:  $fac-acc-body-final = fac-acc-body3$  (**is** *?lhs=?rhs*)  
 ⟨proof⟩

**lemma** *fac-acc-work-final-fac-work*:  $fac-acc-work-final = fac-work-final$  (**is** *?lhs=?rhs*)  
 ⟨proof⟩

## 7 Memoisation using streams.

### 7.1 Streams.

The type of infinite streams.



**domain**  $'a \text{ Stream} = \text{stcons} (\text{lazy sthead} :: 'a) (\text{lazy sttail} :: 'a \text{ Stream})$  (**infixr**  $\&\& 65$ )  
 $\langle \text{proof} \rangle$   
**fixrec**  $\text{smap} :: ('a \rightarrow 'b) \rightarrow 'a \text{ Stream} \rightarrow 'b \text{ Stream}$   
**where**  
 $\text{smap}\cdot f\cdot (x \&\& xs) = f\cdot x \&\& \text{smap}\cdot f\cdot xs$   
 $\langle \text{proof} \rangle$   
**lemma**  $\text{smap}\cdot \text{smap}: \text{smap}\cdot f\cdot (\text{smap}\cdot g\cdot xs) = \text{smap}\cdot (f \text{ oo } g)\cdot xs$   $\langle \text{proof} \rangle$   
**fixrec**  $i\text{-th} :: 'a \text{ Stream} \rightarrow \text{Nat} \rightarrow 'a$   
**where**  
 $i\text{-th}\cdot (x \&\& xs) = \text{Nat}\text{-case}\cdot x\cdot (i\text{-th}\cdot xs)$

#### abbreviation

$i\text{-th}\text{-syn} :: 'a \text{ Stream} \Rightarrow \text{Nat} \Rightarrow 'a$  (**infixl**  $!! 100$ ) **where**  
 $s !! i \equiv i\text{-th}\cdot s\cdot i$   
 $\langle \text{proof} \rangle \langle \text{proof} \rangle \langle \text{proof} \rangle \langle \text{proof} \rangle$

The infinite stream of natural numbers.

**fixrec**  $\text{nats} :: \text{Nat} \text{ Stream}$

**where**

$\text{nats} = 0 \&\& \text{smap}\cdot (\lambda x. 1 + x)\cdot \text{nats}$

## 7.2 The wrapper/unwrapper functions.

#### definition

$\text{unwrapS}' :: (\text{Nat} \rightarrow 'a) \rightarrow 'a \text{ Stream}$  **where**  
 $\text{unwrapS}' \equiv \lambda f. \text{smap}\cdot f\cdot \text{nats}$

**lemma**  $\text{unwrapS}'\text{-unfold}: \text{unwrapS}'\cdot f = f\cdot 0 \&\& \text{smap}\cdot (f \text{ oo } (\lambda x. 1 + x))\cdot \text{nats}$   $\langle \text{proof} \rangle$

**fixrec**  $\text{unwrapS} :: (\text{Nat} \rightarrow 'a) \rightarrow 'a \text{ Stream}$

**where**

$\text{unwrapS}\cdot f = f\cdot 0 \&\& \text{unwrapS}\cdot (f \text{ oo } (\lambda x. 1 + x))$

The two versions of  $\text{unwrapS}$  are equivalent. We could try to fold some definitions here but it's easier if the stream constructor is manifest.

**lemma**  $\text{unwrapS}\text{-unwrapS}'\text{-eq}: \text{unwrapS} = \text{unwrapS}'$  (**is**  $?lhs = ?rhs$ )  
 $\langle \text{proof} \rangle$

#### definition

$\text{wrapS} :: 'a \text{ Stream} \rightarrow \text{Nat} \rightarrow 'a$  **where**  
 $\text{wrapS} \equiv \lambda s\ i. s !! i$

Note the identity requires that  $f$  be strict. Gill and Hutton (2009, §6.1) do not make this requirement, an oversight on their part.

In practice all functions worth memoising are strict in the memoised argument.

**lemma** *wrapS-unwrapS-id'*:  
**assumes** *strictF*:  $(f :: \text{Nat} \rightarrow 'a) \cdot \perp = \perp$   
**shows**  $\text{unwrapS} \cdot f \text{ !! } n = f \cdot n$   
 $\langle \text{proof} \rangle$

**lemma** *wrapS-unwrapS-id*:  $f \cdot \perp = \perp \implies (\text{wrapS} \text{ oo } \text{unwrapS}) \cdot f = f$   
 $\langle \text{proof} \rangle$

### 7.3 Fibonacci example.

**definition**  
*fib-body* ::  $(\text{Nat} \rightarrow \text{Nat}) \rightarrow \text{Nat} \rightarrow \text{Nat}$  **where**  
*fib-body*  $\equiv \Lambda r. \text{Nat-case} \cdot 1 \cdot (\text{Nat-case} \cdot 1 \cdot (\Lambda n. r \cdot n + r \cdot (n + 1)))$   
 $\langle \text{proof} \rangle$

**definition**  
*fib* ::  $\text{Nat} \rightarrow \text{Nat}$  **where**  
*fib*  $\equiv \text{fix} \cdot \text{fib-body}$   
 $\langle \text{proof} \rangle$

Apply worker/wrapper.

**definition**  
*fib-work* ::  $\text{Nat Stream}$  **where**  
*fib-work*  $\equiv \text{fix} \cdot (\text{unwrapS} \text{ oo } \text{fib-body} \text{ oo } \text{wrapS})$

**definition**  
*fib-wrap* ::  $\text{Nat} \rightarrow \text{Nat}$  **where**  
*fib-wrap*  $\equiv \text{wrapS} \cdot \text{fib-work}$

**lemma** *wrapS-unwrapS-fib-body*:  $\text{wrapS} \text{ oo } \text{unwrapS} \text{ oo } \text{fib-body} = \text{fib-body}$   
 $\langle \text{proof} \rangle$

**lemma** *fib-ww-eq*:  $\text{fib} = \text{fib-wrap}$   
 $\langle \text{proof} \rangle$

Optimise.

**fixrec**  
*fib-work-final* ::  $\text{Nat Stream}$   
**and**  
*fib-f-final* ::  $\text{Nat} \rightarrow \text{Nat}$   
**where**  
*fib-work-final* =  $\text{smap} \cdot \text{fib-f-final} \cdot \text{nats}$   
 $| \text{fib-f-final} = \text{Nat-case} \cdot 1 \cdot (\text{Nat-case} \cdot 1 \cdot (\Lambda n'. \text{fib-work-final} \text{ !! } n' + \text{fib-work-final} \text{ !! } (n' + 1)))$

**declare** *fib-f-final.simps[simp del]* *fib-work-final.simps[simp del]*

**definition**  
*fib-final* ::  $\text{Nat} \rightarrow \text{Nat}$  **where**  
*fib-final*  $\equiv \Lambda n. \text{fib-work-final} \text{ !! } n$

This proof is only fiddly due to the way mutual recursion is encoded: we need to use Bekić's Theorem (Bekić 1984)<sup>1</sup> to massage the definitions into their final form.

**lemma** *fib-work-final-fib-work-eq*:  $\text{fib-work-final} = \text{fib-work}$  (is ?lhs = ?rhs)  
 ⟨proof⟩

**lemma** *fib-final-fib-eq*:  $\text{fib-final} = \text{fib}$  (is ?lhs = ?rhs)  
 ⟨proof⟩

## 8 Tagless interpreter via double-barreled continuations

**type-synonym**  $'a \text{ Cont} = ('a \rightarrow 'a) \rightarrow 'a$

**definition**

$\text{val2cont} :: 'a \rightarrow 'a \text{ Cont}$  **where**  
 $\text{val2cont} \equiv (\Lambda a c. c \cdot a)$

**definition**

$\text{cont2val} :: 'a \text{ Cont} \rightarrow 'a$  **where**  
 $\text{cont2val} \equiv (\Lambda f. f \cdot \text{ID})$

**lemma** *cont2val-val2cont-id*:  $\text{cont2val} \circ \text{val2cont} = \text{ID}$   
 ⟨proof⟩

**domain**  $\text{Expr} =$

$\text{Val}$  (**lazy**  $\text{val} :: \text{Nat}$ )  
 |  $\text{Add}$  (**lazy**  $\text{addl} :: \text{Expr}$ ) (**lazy**  $\text{addr} :: \text{Expr}$ )  
 |  $\text{Throw}$   
 |  $\text{Catch}$  (**lazy**  $\text{cbody} :: \text{Expr}$ ) (**lazy**  $\text{handler} :: \text{Expr}$ )

**fixrec**  $\text{eval} :: \text{Expr} \rightarrow \text{Nat Maybe}$

**where**

$\text{eval} \cdot (\text{Val} \cdot n) = \text{Just} \cdot n$   
 |  $\text{eval} \cdot (\text{Add} \cdot x \cdot y) = \text{mliftM2} (\Lambda a b. a + b) \cdot (\text{eval} \cdot x) \cdot (\text{eval} \cdot y)$   
 |  $\text{eval} \cdot \text{Throw} = \text{mfail}$   
 |  $\text{eval} \cdot (\text{Catch} \cdot x \cdot y) = \text{mcatch} \cdot (\text{eval} \cdot x) \cdot (\text{eval} \cdot y)$

**fixrec**  $\text{eval-body} :: (\text{Expr} \rightarrow \text{Nat Maybe}) \rightarrow \text{Expr} \rightarrow \text{Nat Maybe}$

**where**

$\text{eval-body} \cdot r \cdot (\text{Val} \cdot n) = \text{Just} \cdot n$   
 |  $\text{eval-body} \cdot r \cdot (\text{Add} \cdot x \cdot y) = \text{mliftM2} (\Lambda a b. a + b) \cdot (r \cdot x) \cdot (r \cdot y)$   
 |  $\text{eval-body} \cdot r \cdot \text{Throw} = \text{mfail}$   
 |  $\text{eval-body} \cdot r \cdot (\text{Catch} \cdot x \cdot y) = \text{mcatch} \cdot (r \cdot x) \cdot (r \cdot y)$

---

<sup>1</sup>The interested reader can find some historical commentary in Harel (1980); Sangiorgi (2009).

**lemma** *eval-body-strictExpr[simp]*: *eval-body*.*r*. $\perp = \perp$   
 ⟨*proof*⟩

**lemma** *eval-eval-body-eq*: *eval* = *fix*.*eval-body*  
 ⟨*proof*⟩

## 8.1 Worker/wrapper

### definition

*unwrapC* :: (*Expr* → *Nat Maybe*) → (*Expr* → (*Nat* → *Nat Maybe*) → *Nat Maybe* → *Nat Maybe*) **where**  
*unwrapC* ≡  $\Lambda g e s f. \text{case } g \cdot e \text{ of } \text{Nothing} \Rightarrow f \mid \text{Just} \cdot n \Rightarrow s \cdot n$

**lemma** *unwrapC-strict[simp]*: *unwrapC*. $\perp = \perp$   
 ⟨*proof*⟩

### definition

*wrapC* :: (*Expr* → (*Nat* → *Nat Maybe*) → *Nat Maybe* → *Nat Maybe*) → (*Expr* → *Nat Maybe*) **where**  
*wrapC* ≡  $\Lambda g e. g \cdot e \cdot \text{Just} \cdot \text{Nothing}$

**lemma** *wrapC-unwrapC-id*: *wrapC* oo *unwrapC* = *ID*  
 ⟨*proof*⟩

### definition

*eval-work* :: *Expr* → (*Nat* → *Nat Maybe*) → *Nat Maybe* → *Nat Maybe* **where**  
*eval-work* ≡ *fix*.(*unwrapC* oo *eval-body* oo *wrapC*)

### definition

*eval-wrap* :: *Expr* → *Nat Maybe* **where**  
*eval-wrap* ≡ *wrapC*.*eval-work*

**fixrec** *eval-body'* :: (*Expr* → (*Nat* → *Nat Maybe*) → *Nat Maybe* → *Nat Maybe*)  
 → *Expr* → (*Nat* → *Nat Maybe*) → *Nat Maybe* → *Nat Maybe*

### where

*eval-body'*.*r*.(*Val*.*n*).*s*.*f* = *s*.*n*  
 | *eval-body'*.*r*.(*Add*.*x*.*y*).*s*.*f* = (case *wrapC*.*r*.*x* of  
   *Nothing* ⇒ *f*  
   | *Just*.*n* ⇒ (case *wrapC*.*r*.*y* of  
     *Nothing* ⇒ *f*  
     | *Just*.*m* ⇒ *s*.(*n* + *m*)))  
 | *eval-body'*.*r*.*Throw*.*s*.*f* = *f*  
 | *eval-body'*.*r*.(*Catch*.*x*.*y*).*s*.*f* = (case *wrapC*.*r*.*x* of  
   *Nothing* ⇒ (case *wrapC*.*r*.*y* of  
     *Nothing* ⇒ *f*  
     | *Just*.*n* ⇒ *s*.*n*)  
   | *Just*.*n* ⇒ *s*.*n*)

**lemma** *eval-body'-strictExpr[simp]*: *eval-body'*.*r*. $\perp$ .*s*.*f* =  $\perp$

*<proof>*

**definition**

$eval-work' :: Expr \rightarrow (Nat \rightarrow Nat\ Maybe) \rightarrow Nat\ Maybe \rightarrow Nat\ Maybe$  **where**  
 $eval-work' \equiv fix \cdot eval-body'$

This proof is unfortunately quite messy, due to the simplifier's inability to cope with HOLCF's case distinctions.

**lemma**  $eval-body'-eval-body-eq$ :  $eval-body' = unwrapC \circ eval-body \circ wrapC$

*<proof>*

**fixrec**  $eval-body-final :: (Expr \rightarrow (Nat \rightarrow Nat\ Maybe) \rightarrow Nat\ Maybe \rightarrow Nat\ Maybe) \rightarrow Expr \rightarrow (Nat \rightarrow Nat\ Maybe) \rightarrow Nat\ Maybe \rightarrow Nat\ Maybe$

**where**

$eval-body-final \cdot r \cdot (Val \cdot n) \cdot s \cdot f = s \cdot n$   
 $| eval-body-final \cdot r \cdot (Add \cdot x \cdot y) \cdot s \cdot f = r \cdot x \cdot (\Lambda n. r \cdot y \cdot (\Lambda m. s \cdot (n + m))) \cdot f$   
 $| eval-body-final \cdot r \cdot Throw \cdot s \cdot f = f$   
 $| eval-body-final \cdot r \cdot (Catch \cdot x \cdot y) \cdot s \cdot f = r \cdot x \cdot s \cdot (r \cdot y \cdot s \cdot f)$

**lemma**  $eval-body-final-strictExpr[simp]$ :  $eval-body-final \cdot r \cdot \perp \cdot s \cdot f = \perp$

*<proof>*

**lemma**  $eval-body'-eval-body-final-eq$ :  $eval-body-final \circ unwrapC \circ wrapC = eval-body'$

*<proof>*

**definition**

$eval-work-final :: Expr \rightarrow (Nat \rightarrow Nat\ Maybe) \rightarrow Nat\ Maybe \rightarrow Nat\ Maybe$

**where**

$eval-work-final \equiv fix \cdot eval-body-final$

**definition**

$eval-final :: Expr \rightarrow Nat\ Maybe$  **where**  
 $eval-final \equiv (\Lambda e. eval-work-final \cdot e \cdot Just \cdot Nothing)$

**lemma**  $eval = eval-final$

*<proof>*

## 9 Backtracking using lazy lists and continuations

To illustrate the utility of worker/wrapper fusion to programming language semantics, we consider here the first-order part of a higher-order backtracking language by Wand and Vaillancourt (2004); see also Danvy et al. (2001). We refer the reader to these papers for a broader motivation for these languages.

As syntax is typically considered to be inductively generated, with each syntactic object taken to be finite and completely defined, we define the syntax for our language using a HOL datatype:

**datatype**  $expr = const\ nat \mid add\ expr\ expr \mid disj\ expr\ expr \mid fail\langle proof \rangle\langle proof \rangle\langle proof \rangle$

The language consists of constants, an addition function, a disjunctive choice between expressions, and failure. We give it a direct semantics using the monad of lazy lists of natural numbers, with the goal of deriving an an extensionally-equivalent evaluator that uses double-barrelled continuations. Our theory of lazy lists is entirely standard.

**default-sort**  $predomain$

**domain**  $'a\ llist =$   
 $nil$   
 $\mid lcons\ (lazy\ 'a)\ (lazy\ 'a\ llist)$

By relaxing the default sort of type variables to  $predomain$ , our polymorphic definitions can be used at concrete types that do not contain  $\perp$ . These include those constructed from HOL types using the discrete ordering type constructor  $'a\ discr$ , and in particular our interpretation  $nat\ discr$  of the natural numbers.

The following standard list functions underpin the monadic infrastructure:

**fixrec**  $lappend :: 'a\ llist \rightarrow 'a\ llist \rightarrow 'a\ llist$  **where**  
 $lappend\ nil\ ys = ys$   
 $\mid lappend\ (lcons\ x\ xs)\ ys = lcons\ x\ (lappend\ xs\ ys)$

**fixrec**  $lconcat :: 'a\ llist\ llist \rightarrow 'a\ llist$  **where**  
 $lconcat\ nil = nil$   
 $\mid lconcat\ (lcons\ x\ xs) = lappend\ x\ (lconcat\ xs)$

**fixrec**  $lmap :: ('a \rightarrow 'b) \rightarrow 'a\ llist \rightarrow 'b\ llist$  **where**  
 $lmap\ f\ nil = nil$   
 $\mid lmap\ f\ (lcons\ x\ xs) = lcons\ (f\ x)\ (lmap\ f\ xs)\langle proof \rangle\langle proof \rangle\langle proof \rangle$

We define the lazy list monad  $S$  in the traditional fashion:

**type-synonym**  $S = nat\ discr\ llist$

**definition**  $returnS :: nat\ discr \rightarrow S$  **where**  
 $returnS = (\Lambda x. lcons\ x\ nil)$

**definition**  $bindS :: S \rightarrow (nat\ discr \rightarrow S) \rightarrow S$  **where**  
 $bindS = (\Lambda x\ g. lconcat\ (lmap\ g\ x))$

Unfortunately the lack of higher-order polymorphism in HOL prevents us from providing the general typing one would expect a monad to have in Haskell.

The evaluator uses the following extra constants:

**definition**  $addS :: S \rightarrow S \rightarrow S$  **where**  
 $addS \equiv (\Lambda x\ y. bindS\ x\ (\Lambda xv. bindS\ y\ (\Lambda yv. returnS\ (xv + yv))))$

**definition**  $disjS :: S \rightarrow S \rightarrow S$  **where**

$disjS \equiv lappend$

**definition**  $failS :: S$  **where**

$failS \equiv lnil$

We interpret our language using these combinators in the obvious way. The only complication is that, even though our evaluator is primitive recursive, we must explicitly use the fixed point operator as the worker/wrapper technique requires us to talk about the body of the recursive definition.

**definition**

$evalS\text{-}body :: (expr\ discr \rightarrow nat\ discr\ llist)$   
 $\rightarrow (expr\ discr \rightarrow nat\ discr\ llist)$

**where**

$evalS\text{-}body \equiv \Lambda r\ e.\ case\ undiscr\ e\ of$   
 $const\ n \Rightarrow returnS.(Discr\ n)$   
 $| add\ e1\ e2 \Rightarrow addS.(r.(Discr\ e1)).(r.(Discr\ e2))$   
 $| disj\ e1\ e2 \Rightarrow disjS.(r.(Discr\ e1)).(r.(Discr\ e2))$   
 $| fail \Rightarrow failS$

**abbreviation**  $evalS :: expr\ discr \rightarrow nat\ discr\ llist$  **where**

$evalS \equiv fix.\ evalS\text{-}body$

We aim to transform this evaluator into one using double-barrelled continuations; one will serve as a "success" context, taking a natural number into "the rest of the computation", and the other outright failure.

In general we could work with an arbitrary observation type ala [Reynolds \(1974\)](#), but for convenience we use the clearly adequate concrete type  $nat\ discr\ llist$ .

**type-synonym**  $Obs = nat\ discr\ llist$

**type-synonym**  $Failure = Obs$

**type-synonym**  $Success = nat\ discr \rightarrow Failure \rightarrow Obs$

**type-synonym**  $K = Success \rightarrow Failure \rightarrow Obs$

To ease our development we adopt what [Wand and Vaillancourt \(2004, §5\)](#) call a "failure computation" instead of a failure continuation, which would have the type  $unit \rightarrow Obs$ .

The monad over the continuation type  $K$  is as follows:

**definition**  $returnK :: nat\ discr \rightarrow K$  **where**

$returnK \equiv (\Lambda x.\ \Lambda s\ f.\ s.x.f)$

**definition**  $bindK :: K \rightarrow (nat\ discr \rightarrow K) \rightarrow K$  **where**

$bindK \equiv \Lambda x\ g.\ \Lambda s\ f.\ x.( \Lambda xv\ f'.\ g.xv.s.f').f$

Our extra constants are defined as follows:

**definition**  $addK :: K \rightarrow K \rightarrow K$  **where**

$$addK \equiv (\Lambda x y. bindK \cdot x \cdot (\Lambda xv. bindK \cdot y \cdot (\Lambda yv. returnK \cdot (xv + yv))))$$

**definition**  $disjK :: K \rightarrow K \rightarrow K$  **where**

$$disjK \equiv (\Lambda g h. \Lambda s f. g \cdot s \cdot (h \cdot s \cdot f))$$

**definition**  $failK :: K$  **where**

$$failK \equiv \Lambda s f. f$$

The continuation semantics is again straightforward:

**definition**

$$evalK\text{-body} :: (expr\ discr \rightarrow K) \rightarrow (expr\ discr \rightarrow K)$$

**where**

$$\begin{aligned} evalK\text{-body} &\equiv \Lambda r e. \text{case } undiscr\ e \text{ of} \\ &\quad const\ n \Rightarrow returnK \cdot (Discr\ n) \\ &\quad | add\ e1\ e2 \Rightarrow addK \cdot (r \cdot (Discr\ e1)) \cdot (r \cdot (Discr\ e2)) \\ &\quad | disj\ e1\ e2 \Rightarrow disjK \cdot (r \cdot (Discr\ e1)) \cdot (r \cdot (Discr\ e2)) \\ &\quad | fail \Rightarrow failK \end{aligned}$$

**abbreviation**  $evalK :: expr\ discr \rightarrow K$  **where**

$$evalK \equiv fix \cdot evalK\text{-body}$$

We now set up a worker/wrapper relation between these two semantics.

The kernel of  $unwrap$  is the following function that converts a lazy list into an equivalent continuation representation.

**fixrec**  $SK :: S \rightarrow K$  **where**

$$\begin{aligned} SK \cdot lnil &= failK \\ | SK \cdot (lcons \cdot x \cdot xs) &= (\Lambda s f. s \cdot x \cdot (SK \cdot xs \cdot s \cdot f)) \end{aligned}$$

**definition**

$$unwrap :: (expr\ discr \rightarrow nat\ discr\ llist) \rightarrow (expr\ discr \rightarrow K)$$

**where**

$$unwrap \equiv \Lambda r e. SK \cdot (r \cdot e) \langle proof \rangle \langle proof \rangle$$

Symmetrically  $wrap$  converts an evaluator using continuations into one generating lazy lists by passing it the right continuations.

**definition**  $KS :: K \rightarrow S$  **where**

$$KS \equiv (\Lambda k. k \cdot lcons \cdot lnil)$$

**definition**  $wrap :: (expr\ discr \rightarrow K) \rightarrow (expr\ discr \rightarrow nat\ discr\ llist)$  **where**

$$wrap \equiv \Lambda r e. KS \cdot (r \cdot e) \langle proof \rangle \langle proof \rangle$$

The worker/wrapper condition follows directly from these definitions.

**lemma**  $KS\text{-}SK\text{-}id$ :

$$\begin{aligned} KS \cdot (SK \cdot xs) &= xs \\ \langle proof \rangle \end{aligned}$$

**lemma**  $wrap\text{-}unwrap\text{-}id$ :

$$wrap \circ unwrap = ID$$



*<proof>*

The worker/wrapper transformation is only non-trivial if *wrap* and *unwrap* do not witness an isomorphism. In this case we can show that we do not even have a Galois connection.

**lemma** *cfun-not-below*:

$$f \cdot x \not\sqsubseteq g \cdot x \implies f \not\sqsubseteq g$$

*<proof>*

**lemma** *unwrap-wrap-not-under-id*:

$$\text{unwrap} \circ \text{wrap} \not\sqsubseteq \text{ID}$$

*<proof>*

We now apply `worker_wrapper_id`:

**definition** *eval-work* :: *expr discr* → *K* **where**

$$\text{eval-work} \equiv \text{fix} \cdot (\text{unwrap} \circ \text{evalS-body} \circ \text{wrap})$$

**definition** *eval-ww* :: *expr discr* → *nat discr llist* **where**

$$\text{eval-ww} \equiv \text{wrap} \cdot \text{eval-work}$$

**lemma** *evalS = eval-ww*

*<proof>*

We now show how the monadic operations correspond by showing that *SK* witnesses a *monad morphism* (Wadler 1992, §6). As required by Danvy et al. (2001, Definition 2.1), the mapping needs to hold for our specific operations in addition to the common monadic scaffolding.

**lemma** *SK-returnS-returnK*:

$$SK \cdot (\text{returnS} \cdot x) = \text{returnK} \cdot x$$

*<proof>*

**lemma** *SK-lappend-distrib*:

$$SK \cdot (\text{lappend} \cdot xs \cdot ys) \cdot s \cdot f = SK \cdot xs \cdot s \cdot (SK \cdot ys \cdot s \cdot f)$$

*<proof>*

**lemma** *SK-bindS-bindK*:

$$SK \cdot (\text{bindS} \cdot x \cdot g) = \text{bindK} \cdot (SK \cdot x) \cdot (SK \circ g)$$

*<proof>*

**lemma** *SK-addS-distrib*:

$$SK \cdot (\text{addS} \cdot x \cdot y) = \text{addK} \cdot (SK \cdot x) \cdot (SK \cdot y)$$

*<proof>*

**lemma** *SK-disjS-disjK*:

$$SK \cdot (\text{disjS} \cdot xs \cdot ys) = \text{disjK} \cdot (SK \cdot xs) \cdot (SK \cdot ys)$$

*<proof>*

**lemma** *SK-failS-failK*:

$SK \cdot \text{fail}S = \text{fail}K$   
 ⟨proof⟩

These lemmas directly establish the precondition for our all-in-one worker/wrapper and fusion rule:

**lemma** *evalS-body-evalK-body*:  
 $\text{unwrap} \circ \text{eval}S\text{-body} \circ \text{wrap} = \text{eval}K\text{-body} \circ \text{unwrap} \circ \text{wrap}$   
 ⟨proof⟩

**theorem** *evalS-evalK*:  
 $\text{eval}S = \text{wrap} \cdot \text{eval}K$   
 ⟨proof⟩

This proof can be considered an instance of the approach of [Hutton et al. \(2010\)](#), which uses the worker/wrapper machinery to relate two algebras.

This result could be obtained by a structural induction over the syntax of the language. However our goal here is to show how such a transformation can be achieved by purely equational means; this has the advantage that our proof can be locally extended, e.g. to the full language of [Danvy et al. \(2001\)](#) simply by proving extra equations. In contrast the higher-order language of [Wand and Vaillancourt \(2004\)](#) is beyond the reach of this approach.

## 10 Transforming $O(n^2)$ *nub* into an $O(n \lg n)$ one

Andy Gill's solution, mechanised.

### 10.1 The *nub* function.

**fixrec** *nub* ::  $\text{Nat list} \rightarrow \text{Nat list}$   
**where**  
 $\text{nub} \cdot \text{nil} = \text{nil}$   
 $|\ \text{nub} \cdot (x :@ xs) = x :@ \text{nub} \cdot (\text{lfilter} \cdot (\text{neg} \circ (\lambda y. x =_B y))) \cdot xs$

**lemma** *nub-strict[simp]*:  $\text{nub} \cdot \perp = \perp$   
 ⟨proof⟩

**fixrec** *nub-body* ::  $(\text{Nat list} \rightarrow \text{Nat list}) \rightarrow \text{Nat list} \rightarrow \text{Nat list}$   
**where**  
 $\text{nub-body} \cdot f \cdot \text{nil} = \text{nil}$   
 $|\ \text{nub-body} \cdot f \cdot (x :@ xs) = x :@ f \cdot (\text{lfilter} \cdot (\text{neg} \circ (\lambda y. x =_B y))) \cdot xs$

**lemma** *nub-nub-body-eq*:  $\text{nub} = \text{fix} \cdot \text{nub-body}$   
 ⟨proof⟩

## 10.2 Optimised data type.

Implement sets using lazy lists for now. Lifting up HOL's 'a set type causes continuity grief.

**type-synonym**  $NatSet = Nat\ llist$

### definition

$SetEmpty :: NatSet$  **where**  
 $SetEmpty \equiv lnil$

### definition

$SetInsert :: Nat \rightarrow NatSet \rightarrow NatSet$  **where**  
 $SetInsert \equiv lcons$

### definition

$SetMem :: Nat \rightarrow NatSet \rightarrow tr$  **where**  
 $SetMem \equiv lmember.(bpred (=))$

**lemma**  $SetMem\text{-}strict[simp]: SetMem.x.\perp = \perp$   $\langle proof \rangle$

**lemma**  $SetMem\text{-}SetEmpty[simp]: SetMem.x.SetEmpty = FF$   
 $\langle proof \rangle$

**lemma**  $SetMem\text{-}SetInsert: SetMem.v.(SetInsert.x.s) = (SetMem.v.s\ orelse\ x =_B\ v)$   
 $\langle proof \rangle$

AndyG's new type.

**domain**  $R = R$  (**lazy**  $resultR :: Nat\ llist$ ) (**lazy**  $exceptR :: NatSet$ )

### definition

$nextR :: R \rightarrow (Nat * R)\ Maybe$  **where**  
 $nextR = (\Lambda r.\ case\ ldropWhile.\ (\Lambda x.\ SetMem.x.(exceptR.r)).(resultR.r)\ of$   
 $\quad\quad\quad lnil \Rightarrow Nothing$   
 $\quad\quad\quad | x :@ xs \Rightarrow Just.(x,\ R.xs.(exceptR.r))$

**lemma**  $nextR\text{-}strict1[simp]: nextR.\perp = \perp$   $\langle proof \rangle$

**lemma**  $nextR\text{-}strict2[simp]: nextR.(R.\perp.S) = \perp$   $\langle proof \rangle$

**lemma**  $nextR\text{-}lnil[simp]: nextR.(R.lnil.S) = Nothing$   $\langle proof \rangle$

### definition

$filterR :: Nat \rightarrow R \rightarrow R$  **where**  
 $filterR \equiv (\Lambda v\ r.\ R.(resultR.r).(SetInsert.v.(exceptR.r)))$

### definition

$c2a :: Nat\ llist \rightarrow R$  **where**  
 $c2a \equiv \Lambda xs.\ R.xs.SetEmpty$

### definition

$a2c :: R \rightarrow Nat\ llist$  **where**

$a2c \equiv \Lambda r. \text{lfilter} \cdot (\Lambda v. \text{neg} \cdot (\text{SetMem} \cdot v \cdot (\text{exceptR} \cdot r))) \cdot (\text{resultR} \cdot r)$

**lemma**  $a2c\text{-strict}[simp]: a2c \cdot \perp = \perp$   $\langle \text{proof} \rangle$

**lemma**  $a2c\text{-}c2a\text{-id}: a2c \text{ oo } c2a = ID$   
 $\langle \text{proof} \rangle$

**definition**

$\text{wrap} :: (R \rightarrow \text{Nat llist}) \rightarrow \text{Nat llist} \rightarrow \text{Nat llist}$  **where**  
 $\text{wrap} \equiv \Lambda f \text{ xs}. f \cdot (c2a \cdot \text{xs})$

**definition**

$\text{unwrap} :: (\text{Nat llist} \rightarrow \text{Nat llist}) \rightarrow R \rightarrow \text{Nat llist}$  **where**  
 $\text{unwrap} \equiv \Lambda f \text{ r}. f \cdot (a2c \cdot r)$

**lemma**  $\text{unwrap-strict}[simp]: \text{unwrap} \cdot \perp = \perp$   
 $\langle \text{proof} \rangle$

**lemma**  $\text{wrap-unwrap-id}: \text{wrap} \text{ oo } \text{unwrap} = ID$   
 $\langle \text{proof} \rangle$

Equivalences needed for later.

**lemma**  $TR\text{-deMorgan}: \text{neg} \cdot (x \text{ orlse } y) = (\text{neg} \cdot x \text{ andalso } \text{neg} \cdot y)$   
 $\langle \text{proof} \rangle$

**lemma**  $\text{case-maybe-case}$ :

$(\text{case } ( \text{case } L \text{ of } \text{lnil} \Rightarrow \text{Nothing} \mid x :@ \text{xs} \Rightarrow \text{Just} \cdot (h \cdot x \cdot \text{xs}) ) \text{ of}$   
 $\text{Nothing} \Rightarrow f \mid \text{Just} \cdot (a, b) \Rightarrow g \cdot a \cdot b)$   
 $=$   
 $(\text{case } L \text{ of } \text{lnil} \Rightarrow f \mid x :@ \text{xs} \Rightarrow g \cdot (\text{fst } (h \cdot x \cdot \text{xs})) \cdot (\text{snd } (h \cdot x \cdot \text{xs})))$   
 $\langle \text{proof} \rangle$

**lemma**  $\text{case-a2c-case-caseR}$ :

$(\text{case } a2c \cdot w \text{ of } \text{lnil} \Rightarrow f \mid x :@ \text{xs} \Rightarrow g \cdot x \cdot \text{xs})$   
 $= (\text{case } \text{nextR} \cdot w \text{ of } \text{Nothing} \Rightarrow f \mid \text{Just} \cdot (x, r) \Rightarrow g \cdot x \cdot (a2c \cdot r))$  (**is**  $?lhs = ?rhs$ )  
 $\langle \text{proof} \rangle$

**lemma**  $\text{filter-filterR}: \text{lfilter} \cdot (\text{neg} \text{ oo } (\Lambda y. x =_B y)) \cdot (a2c \cdot r) = a2c \cdot (\text{filterR} \cdot x \cdot r)$   
 $\langle \text{proof} \rangle$

Apply worker/wrapper. Unlike Gill/Hutton, we manipulate the body of the worker into the right form then apply the lemma.

**definition**

$\text{nub-body}' :: (R \rightarrow \text{Nat llist}) \rightarrow R \rightarrow \text{Nat llist}$  **where**  
 $\text{nub-body}' \equiv \Lambda f \text{ r}. \text{case } a2c \cdot r \text{ of } \text{lnil} \Rightarrow \text{lnil}$   
 $\mid x :@ \text{xs} \Rightarrow x :@ f \cdot (c2a \cdot (\text{lfilter} \cdot (\text{neg} \text{ oo } (\Lambda y. x =_B y)) \cdot \text{xs}))$

**lemma**  $\text{nub-body-nub-body}'\text{-eq}: \text{unwrap} \text{ oo } \text{nub-body} \text{ oo } \text{wrap} = \text{nub-body}'$

$\langle \text{proof} \rangle$

**definition**

$nub\text{-}body'' :: (R \rightarrow Nat\ llist) \rightarrow R \rightarrow Nat\ llist$  **where**  
 $nub\text{-}body'' \equiv \Lambda f\ r.\ case\ nextR.r\ of\ Nothing \Rightarrow lnil$   
 $\quad | Just.(x, xs) \Rightarrow x :@ f.(c2a.(lfilter.(neg\ oo\ (\Lambda y.\ x$   
 $=_B\ y)).(a2c.xs)))$

**lemma**  $nub\text{-}body'\text{-}nub\text{-}body''\text{-}eq$ :  $nub\text{-}body' = nub\text{-}body''$

$\langle \text{proof} \rangle$

**definition**

$nub\text{-}body''' :: (R \rightarrow Nat\ llist) \rightarrow R \rightarrow Nat\ llist$  **where**  
 $nub\text{-}body''' \equiv (\Lambda f\ r.\ case\ nextR.r\ of\ Nothing \Rightarrow lnil$   
 $\quad | Just.(x, xs) \Rightarrow x :@ f.(filterR.x.xs))$

**lemma**  $nub\text{-}body''\text{-}nub\text{-}body'''\text{-}eq$ :  $nub\text{-}body'' = nub\text{-}body''' \text{ oo } (unwrap\ oo\ wrap)$

$\langle \text{proof} \rangle$

Finally glue it all together.

**lemma**  $nub\text{-}wrap\text{-}nub\text{-}body'''$ :  $nub = wrap.(fix.nub\text{-}body''')$

$\langle \text{proof} \rangle$

**end**

## 11 Optimise “last”.

Andy Gill’s solution, mechanised. No fusion, works fine using their rule.

### 11.1 The last function.

**fixrec**  $llast :: 'a\ llist \rightarrow 'a$

**where**

$llast.(x :@ yys) = (case\ yys\ of\ lnil \Rightarrow x \mid y :@ ys \Rightarrow llast.yys)$

**lemma**  $llast\text{-}strict[simp]$ :  $llast.\perp = \perp$

$\langle \text{proof} \rangle$

**fixrec**  $llast\text{-}body :: ('a\ llist \rightarrow 'a) \rightarrow 'a\ llist \rightarrow 'a$

**where**

$llast\text{-}body.f.(x :@ yys) = (case\ yys\ of\ lnil \Rightarrow x \mid y :@ ys \Rightarrow f.yys)$

**lemma**  $llast\text{-}llast\text{-}body$ :  $llast = fix.llast\text{-}body$

$\langle \text{proof} \rangle$

**definition**  $wrap :: ('a \rightarrow 'a\ llist \rightarrow 'a) \rightarrow ('a\ llist \rightarrow 'a)$  **where**

$wrap \equiv \Lambda f\ (x :@ xs).\ f.x.xs$

**definition**  $unwrap :: ('a\ llist \rightarrow 'a) \rightarrow ('a \rightarrow 'a\ llist \rightarrow 'a)$  **where**  
 $unwrap \equiv \Lambda f\ x\ xs. f \cdot (x :@ xs)$

**lemma**  $unwrap\text{-}strict[simp]$ :  $unwrap \cdot \perp = \perp$   
 $\langle proof \rangle$

**lemma**  $wrap\text{-}unwrap\text{-}ID$ :  $wrap\ oo\ unwrap\ oo\ llast\text{-}body = llast\text{-}body$   
 $\langle proof \rangle$

**definition**  $llast\text{-}worker :: ('a \rightarrow 'a\ llist \rightarrow 'a) \rightarrow 'a \rightarrow 'a\ llist \rightarrow 'a$  **where**  
 $llast\text{-}worker \equiv \Lambda r\ x\ yys. case\ yys\ of\ lnil \Rightarrow x \mid y :@ ys \Rightarrow r \cdot y \cdot ys$

**definition**  $llast' :: 'a\ llist \rightarrow 'a$  **where**  
 $llast' \equiv wrap \cdot (fix \cdot llast\text{-}worker)$

**lemma**  $llast\text{-}worker\text{-}llast\text{-}body$ :  $llast\text{-}worker = unwrap\ oo\ llast\text{-}body\ oo\ wrap$   
 $\langle proof \rangle$

**lemma**  $llast'\text{-}llast$ :  $llast' = llast$  (**is**  $?lhs = ?rhs$ )  
 $\langle proof \rangle$

**end**

## 12 Concluding remarks

Gill and Hutton provide two examples of fusion: accumulator introduction in their §4, and the transformation in their §7 of an interpreter for a language with exceptions into one employing continuations. Both involve strict *unwraps* and are indeed totally correct.

The example in their §5 demonstrates the unboxing of numerical computations using a different worker/wrapper rule and does not require fusion. In their §6 a non-strict *unwrap* is used to memoise functions over the natural numbers using the rule considered here. It should in fact use the same rule as the unboxing example as the scheme only correctly memoises strict functions. We can see this by considering a base case missing from their inductive proof, viz that if  $f :: Nat \rightarrow a$  is not strict – in fact constant, as  $Nat$  is a flat domain – then  $f \perp \neq \perp = (map\ f\ [0..]) !! \perp$ , where  $xs !! n$  is the  $n$ th element of  $xs$ .

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