

λ_d

A linear λ -calculus for pure, functional memory updates

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We present the λ_d , a linear λ -calculus for pure, functional memory updates. We introduce the syntax, type system, and operational semantics of the destination calculus, and prove type safety formally in the Coq proof assistant.

We show how the principles of the λ_d can form a theoretical ground for destination-passing style programming in functional languages. In particular, we detail how the present work can be applied to Linear Haskell to lift the main restriction of DPS programming in Haskell as developed in [Bagrel 2024]. We illustrate this with a range of pseudo-Haskell examples.

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1 INTRODUCTION

TODO: Redire plein de fois: On introduit de la mutation controlee dans les FP languages sans endommager la purete (comme la laziness peut être vu aussi) + ordre de building flexible + des systemes se sont deja interesses a ca, mais nous on subsume tout ca

Destination-passing style programming takes its root in the early days of imperative programming. In such language, the programmer is responsible for managing memory allocation and deallocation, and thus is it often unpractical for function calls to allocate memory for their results themselves. Instead, the caller allocates memory for the result of the callee, and passes the address of this output memory cell to the callee as an argument. This is called an *out parameter*, *mutable reference*, or even *destination*.

But destination-passing style is not limited to imperative settings; it can be used in functional programming as well. One example is the linear destination-based API for arrays in Haskell [Bernardy et al. 2018], which enables the user to build an array efficiently in a write-once fashion, without sacrificing the language identity and main guarantees. In this context, a destination points to a yet-unfilled memory slot of the array, and is said to be *consumed* as soon as the associated hole is written to. In this paper, we continue on the same line: we present a linear λ -calculus embedding the concept of *destinations* as first-class values, in order to provide a write-once memory scheme for pure, functional programming languages.

Why is it important to have destinations as first-class values? Because it allows the user to store them in arbitrary control or data structures, and thus to build complex data structures in arbitrary order/direction. This is a key feature of first-class DPS APIs, compared to ones in which destinations are inseparable from the structure they point to. In the latter case, the user is still forced to build

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the structure in its canonical order (e.g. from the leaves up to the root of the structure when using data constructors).

2 WORKING WITH DESTINATIONS

TODO: Some introductory words

2.1 Building up a vocabulary

In its simplest form, destination passing, much like continuation passing, is the idea of explicitly receiving a location where to return a value to (we say that the destination is filled when the supplied location is written to). Instead of a function with signature $T \rightarrow U$, in λ_d you would have $T \rightarrow [U] \rightarrow 1$, where $[U]$ is read “destination of type U ”. For instance, here is a destination-passing version of the identity function:

$$\begin{aligned} \text{dId} &: T \rightarrow [T] \rightarrow 1 \\ \text{dId } x \ d &\triangleq d \triangleleft x \end{aligned}$$

We think of a destination as a reference to an uninitialized memory location, and $d \triangleleft x$ (read “fill d with x ”) as writing x to the memory location.

The form $d \triangleleft x$ is the simplest way to use a destination. But we don’t have to fill a destination with a whole value in a single step. Destinations can be filled piecemeal.

$$\begin{aligned} \text{fillWithInl} &: [T \oplus U] \rightarrow [T] \\ \text{fillWithInl } d &\triangleq d \triangleleft \text{Inl} \end{aligned}$$

In this example, we’re building a value of type $T \oplus U$ by setting the outermost constructor to Inl . We think of $d \triangleleft \text{Inl}$ as allocating memory to store a block of the form $\text{Inl } \square$, write the address of that block to the location that d points to, and return a destination pointing to the uninitialized argument of Inl .

Notice that we are constructing the term from the outermost constructor inward: we’ve built a value of the form $\text{Inl } \square$ but we have yet to describe the constructor’s payload. We call such incomplete values “hollow constructors”, where \square represent the hole(s) they contain. This is opposite to how functional programming usually works, where values are built from the innermost constructors outward: first we make a value v and only then can we use Inl to make an $\text{Inl } v$. This will turn out to be a key ingredient in the expressiveness of destination passing.

Yet, everything we’ve shown so far could have been done with continuations. So it’s worth asking: how are destination different from continuations? Part of the answer lies in our intention to represent destinations as pointers to uninitialized memory (see Section 8). But where destinations really differ from continuations is when there are several destinations. Then you can (indeed you must!) fill all the destinations; whereas when you have multiple continuations, you can only return to one of them. Multiple destination arises from filling destination of tuples:

$$\begin{aligned} \text{fillWithAPair} &: [T \otimes U] \rightarrow [T] \otimes [U] \\ \text{fillWithAPair } d &\triangleq d \triangleleft (,) \end{aligned}$$

To fill a destination for a pair, we must fill both the first field and the second field. In plain English, it sounds obvious, but the key remark is that **fillWithAPair** doesn’t exist on continuations.

Structures with holes. Let’s now turn to how we can use the result made by filling destinations. Observe, as a preliminary remark, that while a destination is used to build a structure, the type of the structure being built might be different from the type of the destination. For instance, **fillWithInl**, above, returns a destination $[T]$ while it is used to build a structure of type $T \oplus U$. To represents this, λ_d uses a type $S \ltimes [T]$ for a structure of type S missing a value of type T to be complete; we

Maybe it would be wise to explain the notations for sums and tuples, since the linear-logic notations are less standard than the ccc ones

We probably want to give a reading for the fill-with-a-constructor construction.

Introduce the terminology “hollow constructor” here?

For some reason this v is grey. \rightarrow Thomas : that’s the case for non-terminals in the grammar

Make sure that we clarify early on that when we say “structure” we mean “linked data structure”

then say it has a *hole* of type T . There can be several holes in S , in which case the right-hand side is a tuple of destinations: $S \ltimes ([T] \otimes [U])$.

The form $S \ltimes [T]$ is read “ S ampar destination of T ”. The name “ampar” stands for “asymmetric memory par”; the reasons for this name will become apparent as we get into more details of λ_d in Section 5.2. For now, it’s sufficient to observe that $S \ltimes [T]$ is akin to a $S\&T^\perp$ in linear logic, indeed you can think of $S \ltimes [T]$ as a (linear) function from T to S . That structures with holes could be seen as linear functions was first observed in [Minamide 1998], we elaborate on the value of having a par type rather than a function type in Section 4. A similar connective is called *Incomplete* in [Bagrel 2024].

Destinations always exist within the context of a structure with holes. A hole of type T inside S represents the fact that S contains uninitialized memory that will have to hold a T for S to be readable without errors; it only denotes the absence of a value and thus cannot be manipulated directly. A destination $[T]$, on the other hand, is a first-class value that witnesses the presence of a hole of type T inside S and can be used to complete the structure. To access the destinations, λ_d provides a **map** construction, which lets us apply a function to the right-hand side of an ampar:

$$\begin{array}{ll} \text{fillWithInl}' : S \ltimes [T \oplus U] \rightarrow S \ltimes [T] & \text{fillWithAPair}' : S \ltimes [T \otimes U] \rightarrow S \ltimes ([T] \otimes [U]) \\ \text{fillWithInl}' x \triangleq \text{map } x \text{ with } d \mapsto d \triangleleft \text{Inl} & \text{fillWithAPair}' x \triangleq \text{map } x \text{ with } d \mapsto d \triangleleft (,) \end{array}$$

To tie this up, we need a way to introduce and to eliminate structures with holes. Structures with holes are introduced with **alloc** which creates a value of type $T \ltimes [T]$. **alloc** is a bit like the identity function: it is a hole of type T that needs a structure of type T to be a complete structure of type T . Structures with holes are eliminated with¹ **from'** _{\ltimes} : $S \ltimes 1 \rightarrow S$: if all the destinations have been consumed and only unit remains on the right side, then a structure with holes is really just a normal, complete structure.

Equipped with these, we can, for instance, derive traditional constructors from piecemeal filling. In fact, λ_d doesn’t have primitive constructor forms, they are syntactic sugar. We show here the definition of **Inl** and **(,)**, but the other constructors are derived similarly.

$$\begin{array}{ll} \text{Inl} : T \rightarrow T \oplus U & \\ \text{Inl } x \triangleq \text{from}'_{\ltimes} (\text{map alloc with } d \mapsto d \triangleleft \text{Inl} \triangleleft x) & \\ (,) : T \rightarrow U \rightarrow T \otimes U & \\ (x, y) \triangleq \text{from}'_{\ltimes} (\text{map alloc with } d \mapsto \text{case } (d \triangleleft (,)) \text{ of } (d_1, d_2) \mapsto d_1 \triangleleft x \ ; \ d_2 \triangleleft y) & \end{array}$$

Memory safety and purity. At this point, the reader may be forgiven for feeling distressed at all the talk of using memory mutations as a semantic for destination-filling primitives. How is it consistent with our claim to be building a pure and memory-safe language?

In fact, we build our system on three core principles:

- (1) destinations are linear resources: they have to be used exactly once;
- (2) a structure that still have holes somewhere in its structure cannot be read;
- (3) destinations cannot escape to an older scope than the one they originate from (how we ensure this will be detailed in Section 5).

The first principle ensures that such programs are ruled out:

$$\begin{array}{ll} \text{forget} : T & \\ \text{forget} \triangleq \text{from}'_{\ltimes} (\text{map alloc with } d \mapsto ()) & \\ \text{forget}' : (T_1 \otimes T_2) \ltimes [T_2] & \\ \text{forget}' \triangleq \text{map alloc with } d \mapsto \text{case } (d \triangleleft (,)) \text{ of } (d_1, d_2) \mapsto \text{from}'_{\ltimes} (\text{map alloc with } dd \mapsto dd \triangleleft d_1 \ ; \ dd \triangleleft d_2) & \end{array}$$

¹As the name suggest, there is a more general elimination **from'** _{\ltimes} . It will be discussed in Section 5.

Somewhere around this point it would be good to explain the difference between holes and destinations. → Thomas: see DIFF-HOLE-DEST

DIFF-HOLE-DEST

It may be more readable to have **fillWithInl'** and **fillWithAPair'** side by side. Maybe they're too wide though

Wording slightly awkward. Revisit at some point. Maybe point out that it makes destinations strictly more expressive than traditional constructor. Maybe discuss as Thomas did at some point that this means that the order in which a structure is built is actually arbitrary, not just outside-in.

Ensure that we do claim that

$$\begin{array}{l|l}
\text{List } T \stackrel{\text{rec}}{\triangleq} 1 \oplus (T \otimes (\text{List } T)) & \\
\hline
\triangleleft [] : [\text{List } T] \rightarrow 1 & \triangleleft (::) : [\text{List } T] \rightarrow [T] \otimes [\text{List } T] \\
d \triangleleft [] \triangleq d \triangleleft \text{Inl } \triangleleft () & d \triangleleft (::) \triangleq d \triangleleft \text{Inr } \triangleleft (,)
\end{array}$$

Fig. 1. List implementation in equirecursive λ_d

Here, **forget** claims to be a value of type T , but it's really just a hole, just uninitialized memory, because d hasn't been used. So any attempt to use **forget** will read uninitialized memory.

In the more complex **forget'**, we fill dd twice to drop the first value that it receives into oblivion, even though that value is marked as being consumed. So the hole associated to d_1 can't be filled ever, and that will eventually lead to reading uninitialized memory.

We will see in section 3 why scope escape of destination is also a concern for memory safety.

Purity of the system is ensured by the combination of these principles. The main way to break purity would be to reuse a destination to mutate a structure after that structure has already been read once. But a structure cannot be read while it still has holes, and once it has been completed, the destinations that were used to fill it are no longer accessible nor usable (because of the first and third principles). As a result, in that controlled setting, we can think of destinations as write-once memory locations, and the mutations behind the hood are totally invisible as no read can happen before the (only one allowed) writing is made.

2.2 Functional queues, with destinations

Now that we have an intuition of how destinations work, let's see how they can be used to build usual data structures. For that section, we suppose that λ_d is equipped with equirecursive types and a fixed-point operator, that isn't part of our formally proven fragment.

Linked lists. For starters, we can define lists as the fixpoint of the functor $X \mapsto 1 \oplus (T \otimes X)$ where T is the type of list items. Following the recipe that we've outline so far, instead of defining the usual “nil” $[]$ and “cons” $(::)$ constructors, we define the more general “fillNil” $\triangleleft []$ and “fillCons” $\triangleleft (::)$ operators, as presented in Figure 1.

Just like we did in Section 2.1 for the primitive constructors, we can recover the “cons” constructor:

$$\begin{array}{l}
(::) : T \otimes (\text{List } T) \rightarrow \text{List } T \\
(::) x xs \triangleq \text{from}'_{\mathbf{x}} (\text{map alloc with } d \mapsto \text{case } (d \triangleleft (::)) \text{ of } (dx, dxs) \mapsto dx \triangleleft x \ ; \ dxs \triangleleft xs)
\end{array}$$

Going from a “fill” operator to the associated constructor is completely generic, and with more metaprogramming tools, we could build this transformation into the language.

Difference lists. While linked lists are optimized for the prepend operation (“cons”), they are not efficient for appending or concatenation, as it requires a full copy (or traversal at least) of the first list before the last cons cell can be changed to point to the head of the second list.

Difference lists are a data structure that allows for efficient concatenation. In functional languages, difference lists are often encoded using a function that take a tail, and returns the previously-unfinished list with the tail appended to it. For example, the difference list $x_1 : x_2 : \dots : x_k : \square$ is represented by the linear function $\lambda xs \mapsto x_1 : x_2 : \dots : x_k : xs$. This encoding shines when list concatenation calls are nested to the left, as the function encoding delays the actual concatenation so that it happens in a more optimal, right-nested fashion than a naive nested list concatenation.

In λ_d , we can go even further, and represent difference lists much like we would do in an imperative programming language (although in a safe setting here), as a pair of an incomplete list who is missing its tail, and a destination pointing to the missing tail's location. The incomplete list

| | |
|--|--|
| <pre> 197 DList $T \triangleq (\text{List } T) \ltimes [\text{List } T]$ 198 append : $\text{DList } T \rightarrow T \rightarrow \text{DList } T$ 199 $ys \text{ append } y \triangleq$ 200 $\text{map } ys \text{ with } dys \mapsto \text{case } (dys \triangleleft (::)) \text{ of}$ 201 $(dy, dys') \mapsto dy \triangleleft y \circ dys'$ 202 concat : $\text{DList } T \rightarrow \text{DList } T \rightarrow \text{DList } T$ 203 $ys \text{ concat } ys' \triangleq \text{map } ys \text{ with } d \mapsto d \triangleleft \bullet ys'$ 204 toList : $\text{DList } T \rightarrow \text{List } T$ 205 $\text{toList } ys \triangleq \text{from}'_{\ltimes} (\text{map } ys \text{ with } d \mapsto d \triangleleft [])$ </pre> | <pre> Queue $T \triangleq (\text{List } T) \otimes (\text{DList } T)$ singleton : $T \rightarrow \text{Queue } T$ singleton $x \triangleq (\text{Inr } (x, \text{Inl } ()), \text{alloc})$ enqueue : $\text{Queue } T \rightarrow T \rightarrow \text{Queue } T$ $q \text{ enqueue } y \triangleq$ $\text{case } q \text{ of } (xs, ys) \mapsto (xs, ys \text{ append } y)$ dequeue : $\text{Queue } T \rightarrow 1 \oplus (T \otimes (\text{Queue } T))$ dequeue $q \triangleq$ $\text{case } q \text{ of } \{$ $(\text{Inr } (x, xs), ys) \mapsto \text{Inr } (x, (xs, ys)),$ $(\text{Inl } (), ys) \mapsto \text{case } (\text{toList } ys) \text{ of } \{$ $\text{Inl } () \mapsto \text{Inl } (),$ $\text{Inr } (x, xs) \mapsto \text{Inr } (x, (xs, \text{alloc}))$ $\}$ $\}$ </pre> |
|--|--|

Fig. 2. Difference list and queue implementation in equirecursive λ_d

is represented by the left side of the ampar, and the destination is represented by its right side. No read on the unfinished list can happen until the destination on the right has been consumed.

Type and operators definitions for difference lists in λ_d are presented on the left of Figure 2.

An empty difference list can be created without the need for a new operator as it is exactly what the `alloc` primitive already does when specialized to type `List T`.

The **append** operator uses “fillCons” to link a new hollow “cons” cell at the end of the list (represented by `dys`), and then handles the two associated destinations `dy` and `dys'`. The former, representing the item slot, is fed with the item to append, while the latter, representing the slot for the tail of the resulting difference list, is returned and so stored back in the right side of the ampar. If that second destination was consumed, and not returned, we would end up with a regular linked list, instead of a difference list.

The **concat** operator concatenates two difference lists by writing the head of the second one to the hole at the end of the first one. This is done using the “fillComp” (\triangleleft) primitive, that here has type $[\text{List } T] \rightarrow \text{DList } T \mapsto [\text{List } T]$. It takes a destination as a first argument and an ampar as its second argument. The left side of the ampar is fed to the destination to be merged with another incomplete structure (the first difference list), while right side of the ampar (the destination for the end of the second difference list) is returned.

Finally, the **toList** operator converts a difference list to a regular list by writing the “nil” constructor to the hole left in the incomplete list using “fillNil”.

We can note that although this example is typical of destination-style programming, it doesn’t use the first-class nature of destinations that our calculus allows, and thus can be implemented in other destination-passing style frameworks such as [Bour et al. 2021] and [Leijen and Lorenzen 2023]. We will see in the next sections what kind of programs can benefit from first-class destinations.

Efficient queue using previously defined structures. The usual functional encoding for a queue is to use a pair of lists, one representing the front of the queue, and keeping the element in order, while the second list represent the back of the queue, and is kept in reverse order (e.g the latest inserted element will be at the front of the second list).

With such a queue implementation, dequeuing the front element is efficient until the first list is depleted. In that case, one now has to transfer elements from the second list to the first one, and so has to reverse the second list beforehand, which is a $O(n)$ operation (although it is amortized).

With access to efficient difference lists, as shown in the previous paragraph, we can replace the second list by a difference list, to remove the need for a reverse operation when the first list get depleted. The corresponding implementation is presented on the left of Figure 2.

The **singleton** operator creates a pair of a list with a single element, and a fresh difference list (obtained via `alloc`).

The **enqueue** operator appends an element to the difference list, while letting the front list unchanged.

The **dequeue** operator first checks if there is one element available in the front list. If there is, it extracts the element x and returns it alongside the rest of the queue (xs , ys). If there isn't, it converts the difference list ys to a normal list, and pattern-matches on it to look for an available element. If none is found again, it returns `Inl ()` to signal that the queue is definitely empty. If an element x is found, then it returns it alongside the updated queue (made of the remaining elements xs paired with a fresh difference list).

3 SCOPE ESCAPE OF DESTINATIONS

Everything described in Section 2 is in fact already possible in destination-passing style for Haskell as presented in [Bagrel 2024]. However, in the aforementioned paper, destinations cannot be stored in destination-based data structures. This restriction is a rather blunt approach to prevent scope escape of destinations that itself pose a great threat to the memory safety of the system. Let's see why.

One core assumption of destination-passing style programming is that once a destination has been linearly consumed, the associated hole has been written to. However, in a realm where destinations $[T]$ can be of arbitrary inner type T , they can in particular be used to store a destination itself when $T = [T']!$

We have to mark the value being fed in a destination as linearly consumed, so that it cannot be both stored away (to be used later) and used in the current context. But that means we have to mark the destination $d : [T']$ as linearly consumed too when it is fed to $dd : [[T']]$ in $dd \triangleleft d$.

As a result, there are in fact two ways to consume a destination: fill it now with a value, or store it away and fill it later. The latter is a much weaker form of consumption, as it doesn't guarantee that the hole associated to the destination has been written to *now*, only that it will be written to later. So our initial assumption above doesn't hold in general case.

The issue is particularly visible when trying to give semantics to the **alloc'** operator:

$\text{alloc}' : ([T] \rightarrow 1) \rightarrow T$
 $\text{alloc}' f \triangleq \text{from}'_{\times} (\text{map } \text{alloc } \text{with } d \mapsto f d)$

With linear store semantics, this is how **alloc'** would behave:

$S \mid \text{alloc}' (\lambda d \mapsto t) \rightarrow S \sqcup \{h := \square\} \mid (t[d := \rightarrow h] \text{ ; } \text{deref} \rightarrow h)$

It works as expected when the function supplied to **alloc'** will indeed use the destination to store a value:

$\begin{array}{ll} \{\} & \mid \text{alloc}' (\lambda d \mapsto d \triangleleft \text{Inl } \triangleleft ()) \\ \rightarrow & \{h := \square\} \mid \rightarrow h \triangleleft \text{Inl } \triangleleft () \text{ ; } \text{deref} \rightarrow h \\ \rightarrow & \{h := \text{Inl } ()\} \mid \text{deref} \rightarrow h \\ \rightarrow & \{\} \mid \text{Inl } () \end{array}$

However this falls short when calls to **alloc'** are nested in the following way (where $dd : [[1]]$ and $d : [1]$):

the mode on the right-most arrow should be $\text{!}\square$, but do we want to show that now?

285
 I'm [Arnaud] really unsure about introducing this one-off notation that we're never using again. Even though I like the use of the underwave to highlight the problem.

295 $\{ \} \mid \text{alloc}' (\lambda dd \mapsto \text{alloc}' (\lambda d \mapsto dd \blacktriangleleft d))$
 296 $\rightarrow \{hd := \square\} \mid \text{alloc}' (\lambda d \mapsto \rightarrow hd \blacktriangleleft d) \ ; \ \text{deref} \rightarrow hd$
 297 $\rightarrow \{hd := \square, h := \square\} \mid \rightarrow hd \blacktriangleleft \rightarrow h \ ; \ \text{deref} \rightarrow h \ ; \ \text{deref} \rightarrow hd$
 298 $\rightarrow \{hd := \rightarrow h, h := \square\} \mid \text{deref} \rightarrow h \ ; \ \text{deref} \rightarrow hd$

299 The original term $\text{alloc}' (\lambda dd \mapsto \text{alloc}' (\lambda d \mapsto dd \blacktriangleleft d))$ is well typed, as the inner call to alloc'
 300 returns a value of type **1** (as d is of type **[1]**) and consumes d linearly. However, the variable d that
 301 stands for destination $\rightarrow h$ isn't filled with a value but instead escapes its scope by being fed to a
 302 destination of destination dd coming from the outer scope (this still counts as a linear consumption).
 303 Hence the associated hole h doesn't receive a value and the reduction get stuck when trying to
 304 dereference $\rightarrow h$.

305 One could argue that the issue comes from the primitive \blacktriangleleft returning a value of type **1** instead of
 306 a dedicated effect type. However, the same issue arise in following program, which is well-typed
 307 even when \blacktriangleleft and the function accepted by alloc' have an arbitrary return type **E**, so we decided
 308 not to introduce yet another type in the system:

309 $\text{alloc}' (\lambda dd \mapsto \text{case } (dd \blacktriangleleft (,)) \text{ of } (dd_1, d_2) \mapsto$
 310 $\text{case } (\text{alloc}' (\lambda d \mapsto dd_1 \blacktriangleleft d)) \text{ of } \{\text{true} \mapsto d_2 \blacktriangleleft \text{true}, \text{false} \mapsto d_2 \blacktriangleleft \text{false}\})$

311 where $dd : [\text{Bool}] \otimes \text{Bool}$, $dd_1 : [\text{Bool}]$, $d_2 : [\text{Bool}]$, $d : [\text{Bool}]$.

312 In the next section, we motivate why being able to store destinations in destinations of des-
 313 tinations is a desirable property of our system that we don't want to give up. In Section 5, we
 314 present a finer type system that prevents scope escape while still allowing to store destinations in
 315 destination-based data structures.
 316

317 4 BREADTH-FIRST TREE TRAVERSAL

318 The core example that showcases the power of destination-passing style programming with first-
 319 class destination — that we borrow from [Bagrel 2024] — is breadth-first tree traversal:

320 Given a tree, create a new one of the same shape, but with the values at the nodes
 321 replaced by the numbers $1 \dots |T|$ in breadth-first order.

322 Indeed, breadth-first traversal implies that the order in which the structure must be populated
 323 (left-to-right, top-to-bottom) is not the same as the structural order of a functional binary tree, that
 324 is, building the leaves first and going up to the root.

325 In the aforementioned paper, the author presents a breadth-first traversal implementation that
 326 relies on first-class destinations so as to build the final tree in a single pass over the input tree. Their
 327 implementation, much like ours, uses a queue to store pairs of an input subtree and a destination
 328 to the corresponding output subtree. This queue is what materialize the breadth-first processing
 329 order: the leading pair (*input subtree*, *dest to output subtree*) of the queue is processed, and pairs of
 330 the same shape for children nodes are appended at the end of the queue.

331 However, as evoked earlier, the API presented in [Bagrel 2024] is not able to store linear data,
 332 and in particular destinations, in destination-based data structures. So they cannot use the efficient,
 333 destination-based queue implementation from Section 2.2 to power up the breadth-first tree traversal
 334 implementation². With λ_d , this is now possible. In fact, our system is self-contained, in the sense
 335 that every possible structure can be built using destination-based primitives (and regular data
 336 constructors can be retrieved from destination-based primitives, as detailed in Figure 5).

337 Figure 3 presents the λ_d implementation of the breadth-first tree traversal. We assume that we
 338 have a binary tree type alias **Tree T** and natural number type alias **Nat** encoded using standard
 339

341 ²This efficient queue implementation can be, and is in fact, implemented in [Bagrel 2024]: see archive.softwareheritage.org/swh:1:cnt:29e9d1fd48d94fa8503023bee0d607d281f512f8. But it cannot store linear data
 342
 343

I remember that we did wonder about that at some point, so it's worth pre-empting the question. Though I'd rather we found a slightly different example that doesn't exploit the return type of fill than a paragraph recounting our life story. Thomas: the second example is too long/complex to show the whole semantics, so I kept the first one in a detailed fashion, and just mentioned the second one.

Rework the next couple of paragraph to flow a little bit better.

```

344 go : ( $S \xrightarrow{100} T_1 \rightarrow (!_{100} S) \otimes T_2$ )  $\omega_{100} \rightarrow S \xrightarrow{100} \text{Queue} (\text{Tree } T_1 \otimes \text{Tree } T_2) \rightarrow (!_{100} S)$ 
345 go  $f \ st \ q \triangleq_{\text{rec}} \text{case } (\text{dequeue } q) \text{ of } \{$ 
346    $\text{Inl } () \mapsto E_{100} \ st,$ 
347    $\text{Inr } ((\text{tree}, \text{dtree}), q') \mapsto \text{case } \text{tree} \text{ of } \{$ 
348      $\text{Inl } () \mapsto \text{dtree} \triangleleft \text{Nil} \ ; \ \text{go } f \ st \ q',$ 
349      $\text{Inr } (x, (tl, tr)) \mapsto \text{case } (\text{dtree} \triangleleft \text{Node}) \text{ of}$ 
350        $(dy, (dtl, dtr)) \mapsto \text{case } (f \ st \ x) \text{ of}$ 
351          $(E_{100} \ st', y) \mapsto$ 
352            $dy \triangleleft y \ ;$ 
353           go  $f \ st' \ (q' \text{ enqueue } (tl, dtl) \text{ enqueue } (tr, dtr))$ 
354      $\}$ 
355    $\}$ 
356 mapAccumBFS : ( $S \xrightarrow{100} T_1 \rightarrow (!_{100} S) \otimes T_2$ )  $\omega_{100} \rightarrow S \xrightarrow{100} \text{Tree } T_1 \xrightarrow{100} \text{Tree } T_2 \otimes (!_{100} S)$ 
357 mapAccumBFS  $f \ st \ \text{tree} \triangleq \text{from}_\kappa (\text{map } \text{alloc } \text{with } \text{dtree} \mapsto \text{go } f \ st \ (\text{singleton } (\text{tree}, \text{dtree})))$ 
358 relabelDPS :  $\text{Tree } 1 \xrightarrow{100} (\text{Tree } \text{Nat}) \otimes (!_{100} (!_{\omega V} \text{Nat}))$ 
359 relabelDPS  $\text{tree} \triangleq \text{mapAccumBFS}$ 
360    $(\lambda ex \xrightarrow{100} \lambda un \mapsto un \ ; \ \text{case } ex \text{ of}$ 
361      $E_{\omega V} \ st \mapsto (E_{100} (E_{\omega V} (\text{succ } st)), st))$ 
362    $(E_{\omega V} (\text{succ } \text{zero}))$ 
363    $\text{tree}$ 
364

```

Fig. 3. Breadth-first tree traversal in destination-passing style

sum and product types. **Tree** T is equipped with operators $\triangleleft \text{Nil}$ and $\triangleleft \text{Node}$, that are implemented in terms of our core destination-filling primitives.

The implementation is as similar as possible to the one from [Bagrel 2024], as to make it easier to spot the few differences between the two systems.

TODO: There is an issue here: because **go** is called after the call to **map**, then every argument is now older, especially **tree** is no longer of the same age as **dtree** (need an exponential probably)

Thomas: Stopped there in the refactor at 17:30 on 02/07/2024.

The first important difference is that in the λ_d implementation, the input tree of type **Tree** T_1 is consumed linearly. The stateful transformer that is applied to each input node to get the output node value is also linear in its two arguments. The state has to be wrapped in an exponential $!_{100}$ so that it can be extracted from the right side of the ampar at the end of the processing (with **from** $_\kappa$). We could imagine a more general version of the traversal, having no constraint on the state type, but necessitating a finalization function $S \rightarrow !_{100} S'$ so that the final state can be returned.

The **go** function is in charge of consuming the queue containing the pairs of input subtrees and destinations to the corresponding output subtrees. It dequeues the first pair, and processes it. If the input subtree is **Nil**, it feeds **Nil** to the destination for the output tree and continues the processing of next elements with unchanged state. If the input subtree is a node, it writes a hollow **Node** constructor to the hole pointed to by the destination, processes the value of the node with the stateful transformer f , and continues the processing of the updated queue where children subtrees and their accompanying destinations have been enqueued.

mapAccumBFS is in charge of spawning the initial memory slot for the output tree together with the associated destination, and preparing the initial queue containing a single pair, made of the whole input tree and the aforementioned destination.

There's way too many mode annotations here. If we are to do that we have to dedicate some space above to explaining the modes and what all the constructions around them mean.


```

393  $t, u ::= v \mid x \mid t' t \mid t \circ t'$ 
394  $\mid \text{case}_m t \text{ of } \{ \text{Inl } x_1 \mapsto u_1, \text{Inr } x_2 \mapsto u_2 \} \mid \text{case}_m t \text{ of } (x_1, x_2) \mapsto u \mid \text{case}_m t \text{ of } E_n x \mapsto u$ 
395  $\mid \text{map } t \text{ with } x \mapsto t' \mid \text{to}_\times t \mid \text{from}_\times t$ 
396  $\mid t \triangleleft () \mid t \triangleleft \text{Inl} \mid t \triangleleft \text{Inr} \mid t \triangleleft () \mid t \triangleleft E_m \mid t \triangleleft (\lambda x_m \mapsto u) \mid t \triangleleft \bullet t'$ 
397
398  $v ::= \boxed{h} \quad (\text{hole})$ 
399  $\mid \rightarrow h \quad (\text{destination})$ 
400  $\mid H^{\langle v_2 \wedge v_1 \rangle} \quad (\text{ampar value form})$ 
401  $\mid () \mid \forall x_m \mapsto u \mid \text{Inl } v \mid \text{Inr } v \mid E_m v \mid (v_1, v_2)$ 
402
403  $T, U, S ::= [{}_m T] \quad (\text{destination})$ 
404  $\mid U \times T \quad (\text{ampar})$ 
405  $\mid 1 \mid T_1 \oplus T_2 \mid T_1 \otimes T_2 \mid !_m T \mid T_m \rightarrow U$ 
406
407  $m, n ::= pa \quad (\text{pair of multiplicity and age})$ 
408  $p ::= 1 \mid \omega$ 
409  $a ::= v \mid \uparrow \mid \infty$ 
410
411  $\Omega, \Gamma, \Theta, \Delta ::= x :_m T \mid \boxed{h} :_n T \mid \rightarrow h :_m [{}_n T]$ 
412  $\mid \Omega_1, \Omega_2 \mid \Omega_1 + \Omega_2 \mid m : \Omega \mid \rightarrow^i \Delta$ 

```

Fig. 4. Grammar of λ_d

relabelDPS is a special case of **mapAccumBFS** that takes the skeleton of a tree (where node values are all unit) and returns a tree of integers, with the same skeleton, but with node values replaced by naturals $1 \dots |T|$ in breadth-first order. The higher-order function passed to **mapAccumBFS** is quite verbose: it must consume the previous node value (unit), using \circ , then extract the state (representing the next natural number to attribute to a node) from its two nested exponential constructors, and finally return a pair, whose left side is the incremented natural wrapped back into its two exponential layers (new state), and whose right side is the plain natural representing the node value for the output subtree.

Two exponentials are needed here. The first one $!_{\infty}$ is part of **from_×** contract, and ensures that the state cannot capture destinations, so that it can be returned at the end of the processing (as **go** runs under a **map** over an ampar). The second one $!_{\omega v}$ allows the natural number to be used in a non-linear fashion: it is used once in **succ st** to serve as the new state, and another time as the value for the output node. With a more general **from_×** operator, we would be able to use just one exponential layer $!_{\omega\infty}$ over the natural number to achieve the same result.

5 LANGUAGE SYNTAX AND TYPE SYSTEM

λ_d is based on simply typed lambda calculus, with a first-order type system, featuring modal function types and modal boxing, in addition to unit (1), product (\otimes) and sum (\oplus) types. It is also equipped with the destination type $[{}_m T]$ and ampar type $S \times T$ that have been previewed in Section 2 to represent DPS structure building. The core grammar of the language is presented in Figure 4. We also provide commonly used syntactic sugar forms for terms in Figure 5.

Modes in λ_d have two axes — multiplicity (i.e. linear/non-linear), and age control — and they take place on variable bindings in typing contexts Ω , and on function arrows, but are not part of the type itself.

We omit the mode annotation m on function arrows and destinations when the mode in question is the multiplicative neutral element $1v$ of the mode semiring (in particular, a function arrow without

To Thomas: didn't you tell me you had plan of making something more general for this very case? I don't remember clearly. If so, don't forget to improve here

I'm [Arnaud] honestly uncomfortable at the quantity of mathematics written in this section without macros and completely uncorrelated from OTT. If we change any

$$\begin{array}{l}
\text{alloc} \triangleq \{1\} \langle \boxed{1} \rangle_{\wedge} \rightarrow 1 \\
t \triangleleft t' \triangleq t \triangleleft \bullet (\text{to}_{\mathbb{K}} t') \\
\text{Inl } t \triangleq \text{from}'_{\mathbb{K}} (\text{map alloc with } d \mapsto \\
\quad d \triangleleft \text{Inl } \triangleleft t \\
\quad) \\
\text{Inr } t \triangleq \text{from}'_{\mathbb{K}} (\text{map alloc with } d \mapsto \\
\quad d \triangleleft \text{Inr } \triangleleft t \\
\quad) \\
E_m t \triangleq \text{from}'_{\mathbb{K}} (\text{map alloc with } d \mapsto \\
\quad d \triangleleft E_m \triangleleft t \\
\quad)
\end{array}
\quad
\begin{array}{l}
\text{from}'_{\mathbb{K}} t \triangleq \\
\quad \text{case } (\text{from}_{\mathbb{K}} (\text{map } t \text{ with } un \mapsto un \circ E_{1\infty} ())) \text{ of} \\
\quad (st, ex) \mapsto \text{case } ex \text{ of} \\
\quad E_{1\infty} un \mapsto un \circ st \\
\lambda x_m \mapsto u \triangleq \text{from}'_{\mathbb{K}} (\text{map alloc with } d \mapsto \\
\quad d \triangleleft (\lambda x_m \mapsto u) \\
\quad) \\
(t_1, t_2) \triangleq \text{from}'_{\mathbb{K}} (\text{map alloc with } d \mapsto \\
\quad \text{case } (d \triangleleft (,)) \text{ of} \\
\quad (d_1, d_2) \mapsto d_1 \triangleleft t_1 \circ d_2 \triangleleft t_2 \\
\quad)
\end{array}$$

Fig. 5. Syntactic sugar forms for terms

annotation is linear by default). A function arrow with multiplicity **1** is equivalent to the linear arrow \multimap from [Girard 1995].

Let's now introduce age-control, which is a novel feature of this calculus.

5.1 Age-control for bindings to prevent scope escape of destinations

The solution we chose to alleviate scope escape of destinations (detailed in Section 3) is to track the age of destinations (as De-Brujin-like scope indices), and to set age-control restriction on the typing rule of destination-filling primitives.

Age is represented by a commutative semiring, where ν indicates that a destination originates from the current scope, and \uparrow indicates that it originates from the scope just before. We also extend ages to variables (a variable of age a stands for a value of age a). Finally, age ∞ is introduced for variables standing in place of a non-age-controlled value. In particular, destinations can never have age ∞ ; a main role of age ∞ is thus to act as a proof that no destination can be part of the value.

Semiring addition $+$ is used to find the age of a variable or destination that is used in two different branches of a program. Semiring multiplication \cdot corresponds to age composition, and is in fact an integer sum on scope indices. ∞ is absorbing for both addition and multiplication.

Tables for the operations $+$ and \cdot on ages are presented in Figure 6.

We pose $\uparrow^0 = \nu$ and $\uparrow^n = \uparrow \cdot \uparrow^{n-1}$

| | | |
|--------------|--|----------|
| $+$ | \uparrow^n | ∞ |
| \uparrow^m | if $n = m$ then \uparrow^n else ∞ | ∞ |
| ∞ | ∞ | ∞ |

| | | |
|--------------|------------------|----------|
| \cdot | \uparrow^n | ∞ |
| \uparrow^m | \uparrow^{n+m} | ∞ |
| ∞ | ∞ | ∞ |

Fig. 6. Tables for age operations

Age commutative semiring is then combined with the multiplicity commutative semiring from [Bernardy et al. 2018] to form a canonical product commutative semiring that is used to represent the mode of each typing context binding in our final type system.

5.2 Motivation behind the ampar and destination types

Minamide's work[Minamide 1998] is the earliest record we could find of a functional calculus integrating the idea of incomplete data structures (structures with holes) that exist as first class values and can be interacted with by the user.

In that paper, a structure with a hole is named *hole abstraction*. In the body of a hole abstraction, the bound *hole variable* should be used linearly (exactly once), and must only be used as a parameter of a data constructor (it cannot be read). A hole abstraction is thus a weak form of linear lambda abstraction, which just moves a piece of data into a bigger data structure.

Now, in classical linear logic, we know we can transform linear implication $T \multimap S$ into $S \wp T^\perp$. Doing so for the type $(T, S)\mathbf{hfun}$ gives $S \wp [T]$, where $[\cdot]$ is memory negation, and \wp is a memory *par* (it allows less interaction than the CLL *par*, because \mathbf{hfun} is weaker than \multimap).

Transforming the hole abstraction from its original implication form to a *par* form let us consider the *destination* type $[T]$ as a first class component of our calculus. We also get to see the hole abstraction aka. memory *par* as a pair-like structure, where the two sides might be coupled together in a way that prevent using both of them simultaneously.

From memory par \wp to ampar \ltimes . In CLL, thanks to the cut rule, any of the sides S or T of a *par* can be eliminated, by interaction with the opposite type \cdot^\perp , to free up the other side. But in λ_d , we have two types of interaction to consider: interaction between T and $[T]$, and interaction between T and $T \rightarrow \cdot$. The structure that may contain holes, S , can safely interact with $[S]$ (merge it into a bigger structure with holes), but not with $T \rightarrow \cdot$, as it would let the user read an incomplete structure! On the other hand, a complete value of type $T = (\dots [T'] \dots)$ containing destinations (but no holes) can safely interact with a function $T \rightarrow 1$ (in particular, the function can pattern-match on the value of type T to access the destinations), but it is not always safe to fill it into a $[T]$ as that might allow scope escape of destinations $[T']$.

To recover sensible rules for the connective, we decided to make it asymmetric, hence ampar $(S \ltimes T)$ for *asymmetrical memory par*:

- the left side S can contain holes, and can be eliminated by interaction with $[S]$ using “fillComp” (\Leftarrow) to free up the right side T ;
- the right side T cannot contain holes (it might contain destinations), and can be eliminated by interaction with $T \rightarrow 1$ to free up the left side S . At term level, this is done using \mathbf{from}'_{\ltimes} and \mathbf{map} .

5.3 Typing of terms and values

The typing rules for λ_d are highly inspired from[Abel and Bernardy 2020] and Linear Haskell [Bernardy et al. 2018], and are detailed in Figure 7. In particular, they use the same additive/multiplicative approach on contexts for linearity and age enforcement

Destinations and holes are two faces of the same coin, as seen in Section 2.1, and must always be in 1:1 correspondance. Thus, the new idea of our type system is to feature *hole bindings* $[h] :_n T$ and *destination bindings* $\rightarrow h :_m [{}_n T]$ in addition to the variable bindings $x :_m T$ that usually populates typing contexts.

Such bindings mention two distinct classes of names: regular variable names x, y , and *hole names* h, h_1, h_2 which are identifiers for a memory cell that hasn't been written to yet. Hole names are represented by natural numbers under the hood, so they are equipped with addition $h+h'$ and can act both as relative offsets or absolute positions in memory. Typically, when a structure is effectively allocated, its hole (and destination) names are shifted by the maximum hole name encountered

| | | | |
|--|---|---|---|
| $\Theta \vdash t : T$ | (Typing judgment for terms) | | |
| $\frac{\text{TY-TERM-VAL} \quad \text{DisposableOnly } \Theta \quad \Delta \Vdash v : T}{\Theta, \Delta \vdash v : T}$ | $\frac{\text{TY-TERM-VAR} \quad \text{DisposableOnly } \Theta \quad 1v <: m}{\Theta, x : mT \vdash x : T}$ | $\frac{\text{TY-TERM-APP} \quad \Theta_1 \vdash t : T \quad \Theta_2 \vdash t' : T_m \rightarrow U}{m\Theta_1 + \Theta_2 \vdash t' t : U}$ | |
| $\frac{\text{TY-TERM-PATU} \quad \Theta_1 \vdash t : T \quad \Theta_2 \vdash u : U}{\Theta_1 + \Theta_2 \vdash t \text{ ; } u : U}$ | $\frac{\text{TY-TERM-PATS} \quad \Theta_1 \vdash t : T_1 \oplus T_2 \quad \Theta_2, x_1 : mT_1 \vdash u_1 : U \quad \Theta_2, x_2 : mT_2 \vdash u_2 : U}{m\Theta_1 + \Theta_2 \vdash \text{case}_m t \text{ of } \{ \text{Inl } x_1 \mapsto u_1, \text{Inr } x_2 \mapsto u_2 \} : U}$ | | |
| $\frac{\text{TY-TERM-PATP} \quad \Theta_1 \vdash t : T_1 \otimes T_2 \quad \Theta_2, x_1 : mT_1, x_2 : mT_2 \vdash u : U}{m\Theta_1 + \Theta_2 \vdash \text{case}_m t \text{ of } (x_1, x_2) \mapsto u : U}$ | $\frac{\text{TY-TERM-PATE} \quad \Theta_1 \vdash t : !_n T \quad \Theta_2, x : m\cdot nT \vdash u : U}{m\Theta_1 + \Theta_2 \vdash \text{case}_m t \text{ of } E_n x \mapsto u : U}$ | | |
| $\frac{\text{TY-TERM-MAP} \quad \Theta_1 \vdash t : U \times T \quad 1\uparrow \Theta_2, x : 1vT \vdash t' : T'}{\Theta_1 + \Theta_2 \vdash \text{map } t \text{ with } x \mapsto t' : U \times T'}$ | $\frac{\text{TY-TERM-TOA} \quad \Theta \vdash u : U}{\Theta \vdash \text{to}_K u : U \times 1}$ | $\frac{\text{TY-TERM-FROMA} \quad \Theta \vdash t : U \times (!_{100} T)}{\Theta \vdash \text{from}_K t : U \otimes (!_{100} T)}$ | |
| $\frac{\text{TY-TERM-FILLU} \quad \Theta \vdash t : [nT]}{\Theta \vdash t \triangleleft () : 1}$ | $\frac{\text{TY-TERM-FILLL} \quad \Theta \vdash t : [nT_1 \oplus T_2]}{\Theta \vdash t \triangleleft \text{Inl} : [nT_1]}$ | $\frac{\text{TY-TERM-FILLR} \quad \Theta \vdash t : [nT_1 \oplus T_2]}{\Theta \vdash t \triangleleft \text{Inr} : [nT_2]}$ | $\frac{\text{TY-TERM-FILLP} \quad \Theta \vdash t : [nT_1 \otimes T_2]}{\Theta \vdash t \triangleleft (,) : [nT_1] \otimes [nT_2]}$ |
| $\frac{\text{TY-TERM-FILLE} \quad \Theta \vdash t : [n!_{n'}T]}{\Theta \vdash t \triangleleft E_{n'} : [n'\cdot nT]}$ | $\frac{\text{TY-TERM-FILLF} \quad \Theta_1 \vdash t : [nT_m \rightarrow U] \quad \Theta_2, x : mT \vdash u : U}{\Theta_1 + (1\uparrow \cdot n)\Theta_2 \vdash t \triangleleft (\lambda x_m \mapsto u) : 1}$ | $\frac{\text{TY-TERM-FILLCOMP} \quad \Theta_1 \vdash t : [nU] \quad \Theta_2 \vdash t' : U \times T}{\Theta_1 + (1\uparrow \cdot n)\Theta_2 \vdash t \triangleleft \bullet t' : T}$ | |
| $\Theta \vdash t : T$ | (Derived typing judgment for syntactic sugar forms) | | |
| $\frac{\text{TY-STERM-ALLOC} \quad \text{DisposableOnly } \Theta}{\Theta \vdash \text{alloc} : T \times [T]}$ | $\frac{\text{TY-STERM-FROMA}' \quad \Theta \vdash t : T \times 1}{\Theta \vdash \text{from}'_K t : T}$ | $\frac{\text{TY-STERM-FILLLEAF} \quad \Theta_1 \vdash t : [nT] \quad \Theta_2 \vdash t' : T}{\Theta_1 + (1\uparrow \cdot n)\Theta_2 \vdash t \triangleleft t' : 1}$ | |
| $\frac{\text{TY-STERM-FUN} \quad \Theta_2, x : mT \vdash u : U}{\Theta_2 \vdash \lambda x_m \mapsto u : T_m \rightarrow U}$ | $\frac{\text{TY-STERM-LEFT} \quad \Theta_2 \vdash t : T_1}{\Theta_2 \vdash \text{Inl } t : T_1 \oplus T_2}$ | $\frac{\text{TY-STERM-RIGHT} \quad \Theta_2 \vdash t : T_2}{\Theta_2 \vdash \text{Inr } t : T_1 \oplus T_2}$ | $\frac{\text{TY-STERM-EXP} \quad \Theta_2 \vdash t : T}{m\Theta_2 \vdash E_m t : !_m T}$ |
| $\frac{\text{TY-STERM-PROD} \quad \Theta_{21} \vdash t_1 : T_1 \quad \Theta_{22} \vdash t_2 : T_2}{\Theta_{21} + \Theta_{22} \vdash (t_1, t_2) : T_1 \otimes T_2}$ | | | |

Fig. 7. Typing rules for terms and syntactic sugar

so far in the program (denoted $\text{max}(\text{hnames}(C))$); this corresponds to finding the next unused memory cell in which to write new data.

The mode n of a hole binding $[h] :_n T$ (also present in the corresponding destination type $[nT]$) indicates the mode a value must have to be written to it (that is to say, the mode of bindings that

the value depends on to type correctly).³ We see the mode of a hole coming into play when a hole is located behind an exponential constructor: we should only write a non-linear value to the hole \boxed{h} in $\mathbb{E}_{\omega\nu} \boxed{h}$. In particular, we should not store a destination into this hole, otherwise it could later be extracted and used in a non-linear fashion.

A destination binding $\rightarrow h : \mathbf{m} \lfloor \mathbf{n} \rfloor \mathbf{T}$ mentions two modes, \mathbf{m} and \mathbf{n} ; but only the former (left one, \mathbf{m}) is the actual mode of the binding (in particular, it informs on the age of the destination itself). The latter, \mathbf{n} , is part of the destination's type $\lfloor \mathbf{n} \rfloor \mathbf{T}$ and corresponds to the mode a value has to have to be written to the corresponding hole. In a well-typed, closed program, the mode \mathbf{m} of a destination binding can never be of multiplicity ω or age ∞ in the typing tree; it is always linear and of finite age.

We also extend mode product to a point-wise action on typing contexts:

$$\left\{ \begin{array}{ll} \mathbf{n}' \cdot (x : \mathbf{m} \mathbf{T}) &= x : \mathbf{n}' \cdot \mathbf{m} \mathbf{T} \\ \mathbf{n}' \cdot (\boxed{h} : \mathbf{n} \mathbf{T}) &= \boxed{h} : \mathbf{n}' \cdot \mathbf{n} \mathbf{T} \\ \mathbf{n}' \cdot (\rightarrow h : \mathbf{m} \lfloor \mathbf{n} \rfloor \mathbf{T}) &= \rightarrow h : \mathbf{n}' \cdot \mathbf{m} \lfloor \mathbf{n} \rfloor \mathbf{T} \end{array} \right.$$

Figure 7 presents the typing rules for terms, and rules for syntactic sugar forms that have been derived from term rules and proven formally too. Figure 9 presents the typing rules for values of the language. In every figure,

- Ω denotes an arbitrary typing context, with no particular constraint;
- Γ denotes a typing context made only of hole and destination bindings;
- Θ denotes a typing context made only of destination and variable bindings;
- Δ denotes a typing context made only of destination bindings.

5.3.1 Typing of terms \vdash . A term t always types in a context Θ made only of destination and variable bindings. That being said, typing rules for terms and their syntactic sugar in Figure 7 never explicitly mention a destination binding; only variable bindings. Only at runtime some variables will be substituted by destinations having a matching type and mode (that is why terms cannot type in a context made of variable bindings alone). As a result, the type system the user has to deal with is only slightly more complex than a linear type system *à la* [Bernardy et al. 2018], because of the addition of the age control axis. So at the moment, we can forget about destination and hole bindings specificities.

Let's focus on a few particularities of the type system for terms.

The predicate `DisposableOnly` Θ in rules `TY-TERM-VAL` and `TY-TERM-VAR` says that Θ can only contain variable bindings with multiplicity ω , for which weakening is allowed in linear logic. It is enough to allow weakening at the leaves of the typing tree, that is to say the two aforementioned rules (`TY-TERM-VAL` is indeed a leaf for judgments \vdash , that holds a subtree of judgments $\mathbf{v} \vdash$).

Rule `TY-TERM-VAR`, in addition to weakening, allows for dereliction of the mode for the variable used, with subtyping constraint $1\nu <: \mathbf{m}$ defined as such:

revisit if we allow weakening for dests, as we could replace that by $\omega \mathbf{v} \vdash \Theta$ as in [Bernardy et al. 2018]

³To this day, the only way for a value to have a constraining mode is to capture a destination (otherwise the value has mode $\omega\infty$, meaning it can be used in any possible way), as destinations are the only intrinsically linear values in the calculus, but we will see in Section 8 that other forms of intrinsic linearity can be added to the langage for practical reasons.

$$\begin{aligned}
& pa <: p'a' \iff p <: p' \wedge a <: a' \\
& \left\{ \begin{array}{l} 1 <: 1 \\ p <: \omega \end{array} \right. \\
& \left\{ \begin{array}{l} \uparrow^m <: \uparrow^n \iff m = n \quad (\text{no finite age derelection ; recall that } \uparrow^0 = \nu) \\ a <: \infty \end{array} \right.
\end{aligned}$$

Rule TY-TERM-PATU is elimination (or pattern-matching) for unit, and is also used to chain destination-filling operations.

Pattern-matching with rules TY-TERM-APP, TY-TERM-PATS, TY-TERM-PATP and TY-TERM-PATE is parametrized by a mode m by which the typing context Θ_1 of the scrutinee is multiplied. The variables which bind the subcomponents of the scrutinee then inherit this mode. In particular, this choice crystalize the equivalence $!_{\omega a}(T_1 \otimes T_2) \simeq (!_{\omega a} T_1) \otimes (!_{\omega a} T_2)$, which is not part of intuitionistic linear logic, but valid in Linear Haskell[Bernardy et al. 2018]. We omit the mode annotation on **case** statements and lambda abstractions when the mode in question is the multiplicative neutral element 1ν of the mode semiring.

The Rule TY-TERM-MAP is where most of the safety of the system lies, and it is there where scope control takes place. It opens an ampar t , and binds its right side (containing destinations for holes on the other side, among other things) to variable x and then execute body t' . This lets the user access destinations of an ampar while temporarily forgetting about the structure with holes (being mutated behind the scenes by the destination-filling primitives). Type safety for **map** is based on the idea that a new scope is created for x and t' , so anything coming from the current ambient scope (represented by Θ_2 in the conclusion) appears older when we see it from t' point of view. Indeed, when entering a new scope, the age of every remaining binding from the previous scopes is incremented by \uparrow . That way we can distinguish x from anything else that was already bound using the age of bindings alone. That's why t' types in $\uparrow\uparrow\Theta_2$, $x :_{1\nu}T$ while the global term **map** t with $x \mapsto t'$ types in Θ_1, Θ_2 (notice the absence of shift on Θ_2). A schematic explanation of the scope rules is given in Figure 8.

We see in the schema that the left of an ampar (the structure being built) “takes place” in the ambient scope. The right side however, where destinations are, has its own new, inner scope that is opened when mapped over. When filling a destination (e.g. $x_1 \blacktriangleleft x_0$ in the figure), the right operand must be from a scope one \uparrow older than the destination on the left of the operator, as this value will end up on the left of the ampar (which is thus in a scope \uparrow older than the destination originating from the right side).

The rule TY-TERM-FILLCOMP, or its simpler variant, TY-STERM-FILLLEAF confirm this intuition. The left operand of these operators must be a destination that types in the ambient context (both Θ_1 unchanged in the premise and conclusion of the rules). The right operand, however, is a value that types in a context Θ_2 in the premise, but requires $\uparrow\uparrow\Theta_2$ in the conclusion. This is the opposite of the shift that **map** does: while **map** opens a child scope for its body, “fillComp” (\blacktriangleleft)/“fillLeaf” (\blacktriangleleft) opens a portal to the parent scope for their right operand, as seen in the schema. The same phenomenon happens for the resources captured by the body of a lambda abstraction in TY-TERM-FILLF.

In TY-TERM-ToA, the operator **to κ** embeds an already completed structure in an ampar whose left side is the structure, and right side is unit.

| | | | | | | | |
|---|--|---|--|---|--|---|--|
| $\boxed{\Gamma \vdash v : T}$ | | | | (Typing judgment for values) | | | |
| TY-VAL-HOLE | | TY-VAL-DEST | | TY-VAL-UNIT | | TY-VAL-FUN | |
| $\frac{\boxed{h} :_{1v} T \vdash \boxed{h} : T}{\boxed{h} :_{1v} T \vdash \boxed{h} : T}$ | | $\frac{\rightarrow h :_{1v} [n] T \vdash \rightarrow h : [n] T}{\rightarrow h :_{1v} [n] T \vdash \rightarrow h : [n] T}$ | | $\frac{}{\bullet \vdash () : 1}$ | | $\frac{\Delta, x :_m T \vdash u : U}{\Delta \vdash \lambda x_m. u : T_m \rightarrow U}$ | |
| TY-VAL-LEFT | | TY-VAL-RIGHT | | TY-VAL-PROD | | TY-VAL-EXP | |
| $\frac{\Gamma \vdash v_1 : T_1}{\Gamma \vdash \text{Inl } v_1 : T_1 \oplus T_2}$ | | $\frac{\Gamma \vdash v_2 : T_2}{\Gamma \vdash \text{Inr } v_2 : T_1 \oplus T_2}$ | | $\frac{\Gamma_1 \vdash v_1 : T_1 \quad \Gamma_2 \vdash v_2 : T_2}{\Gamma_1 + \Gamma_2 \vdash (v_1, v_2) : T_1 \otimes T_2}$ | | $\frac{\Gamma \vdash v' : T}{n\Gamma \vdash E_n v' : !_n T}$ | |
| <div style="text-align: center;"> TY-VAL-AMPAR $\text{LinOnly } \Delta_3 \quad \text{FinAgeOnly } \Delta_3$ $\textcolor{violet}{1}\uparrow \Delta_1, \Delta_3 \vdash v_1 : T$ $\Delta_2, (\textcolor{blue}{\rightarrow}^! \Delta_3) \vdash v_2 : U$ <hr/> $\Delta_1, \Delta_2 \vdash \textcolor{red}{hnames}(\Delta_3) \langle v_2 \wedge v_1 \rangle : U \ltimes T$ </div> | | | | | | | |

Fig. 9. Typing rules for values

Hole bindings and destination bindings of the same hole name h are meant to annihilate each other in the typing context given they have a matching base type and mode. That way, the typing context of a term can stay constant during reduction:

- when destination-filling primitives are evaluated to build up data structures, they linearly consume a destination and write to a hole at the same time which makes both disappear, thus the typing context stays balanced;
- when a new hole is created, a matching destination is returned too, so the typing context stays balanced too.

However, the annihilation between a destination and a hole binding having the same name in the typing tree is only allowed to happen around an ampar, as it is the ampar connective that bind the name across the two sides (the names bound are actually stored in a set H on the ampar value $H \langle v_2 \wedge v_1 \rangle$). In fact, an ampar can be seen as a sort of lambda-abstraction, whose body (containing holes instead of variables) and sink are split across two sides, and magically interconnected through the ampar connective.

In most rules, we use a sum $\Gamma_1 + \Gamma_2$ for typing contexts (or the disjoint variant Γ_1, Γ_2). This sum doesn't not allow for annihilation of bindings with the same name; the operation is partial, and in particular it isn't defined if a same hole name is present in the operands in the two different forms (hole binding and destination binding). In particular, a pair $(\boxed{h}, \rightarrow h)$ is not well-typed. A single typing context Γ is not allowed either to contain both a hole binding and a destination binding for the same hole name.

Typing of ampars. As stated above, the core idea of TY-VAL-AMPAR is to act as a binding connective for hole and destinations.

We define a new operator $\rightarrow^!$ to represent the matching hole bindings for a set of destination bindings. It is a partial, point-wise operation on typing bindings of a context where:

$$\rightarrow^! (\rightarrow h :_{1v} [n] T) = \boxed{h} :_n T$$

Only an input context Δ made only of destination bindings, with mode $1v$, results in a valid output context (which is then only composed of hole bindings).

Equipped with this operator, we introduce the annihilation of bindings using Δ_3 to represent destinations on the right side v_1 , and $\rightarrow^{\cdot} \Delta_3$ to represent the matching hole bindings on the left side v_2 (the structure under construction). Those bindings are only present in the premises of the rule but get removed in the conclusion. Those hole names are only local, bound to that ampar and don't affect the outside world nor can be referenced from the outside.

Both sides of the ampar may also contain stored destinations from other scopes, represented by $\uparrow \Delta_1$ and Δ_2 in the respective typing contexts of v_1 and v_2 . All holes introduced by this ampar have to be annihilated by matching destinations; following our naming convention, no hole binding can appear in Δ_1 , Δ_2 in the conclusion.

The properties $\text{LinOnly } \Delta_3$ and $\text{FinAgeOnly } \Delta_3$ are true given that $\rightarrow^{\cdot} \Delta_3$ is a valid typing context, so are not really a new restriction on Δ_3 . They are mostly used to ease the mechanical proof of type safety for the system.

Other notable typing rules for values. Rules TY-VAL-HOLE and TY-VAL-DEST indicates that a hole or destination must have mode $1v$ in the typing context to be used (except when a destination is stored away, as we will see later).

Rules for unit, left and right variants, and product are straightforward.

Rule TY-VAL-EXP is rather classic too: we multiply the dependencies Γ of the value by the mode n of the exponential. The intuition is that if v uses a resource v' twice, then $E_2 v$, that corresponds to two uses of v (in a system with such a mode), will use v' four times.

Rule TY-VAL-FUN indicates that (value level) lambda abstractions cannot have holes inside. In other terms, a function value cannot be built piecemeal like other data structures, its whole body must be a complete term right from the beginning. It cannot contain free variables either, as the body of the function must type in context Δ , $x :_m T$ where Δ is made only of destination bindings. One might wonder, how can we represent a curried function $\lambda x \mapsto \lambda y \mapsto x \text{ concat } y$ as the value level, as the inner abstraction captures the free variable x ? The answer is that such a function, at value level, is encoded as $\lambda x \mapsto \text{from}'_{\times} (\text{map alloc with } d \mapsto d \triangleleft (\lambda y \mapsto x \text{ concat } y))$, where the inner closure is not yet in value form, but pending to be built into a value. As the form $d \triangleleft (\lambda y \mapsto t)$ is part of term syntax, and not value syntax, we allow free variable captures in it.

6 EVALUATION CONTEXTS AND SEMANTICS

The semantics of λ_d are given using small-step reductions on a pair $C[t]$ of an evaluation context C (represented by a stack) determining a focusing path, and a term t under focus. Such a pair $C[t]$ is called a *command*, and represents a running program.

6.1 Evaluation contexts forms

The grammar of evaluation contexts is given in Figure 10. An evaluation context C is the composition of an arbitrary number of focusing components $c_1, c_2 \dots$. We chose to represent this composition explicitly using a stack, instead of a meta-operation that would only let us access its final result. As a result, focusing and defocusing operations are made explicit in the semantics, resulting in a more verbose but simpler proof. It is also easier to imagine how to build a stack-based interpreter for such a language.

Focusing components are all directly derived from the term syntax, except for the “open ampar” focus $\text{op}_H \langle v_2 \wedge \square \rangle$. This focus component indicates that an ampar is currently being mapped on, with its left-hand side v_2 (the structure being built) being attached to the “open ampar” focus component, while its right-hand side (containing destinations) is either in subsequent focus components, or in the term under focus.

Not sure whether we should explain why Δ_1 is offset by \uparrow in the premise but not in conclusion. The reason is “because it is needed” more than having a good intuition narrative behind it.

revisit this if we allow weakening for dests

| | | | |
|-----|--|---|---|
| 883 | $\boxed{\Delta \vdash C : T \rightarrow U_0}$ | | (Typing judgment for evaluation contexts) |
| 884 | | TY-ECTXS-APP-FOC1 | TY-ECTXS-APP-FOC2 |
| 885 | | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ |
| 886 | | $\Delta_2 \vdash t' : T_m \rightarrow U$ | $\Delta_1 \vdash v : T$ |
| 887 | TY-ECTXS-ID | $\Delta_1 \vdash C \circ (t' \square) : T \rightarrow U_0$ | $\Delta_2 \vdash C \circ (\square v) : (T_m \rightarrow U) \rightarrow U_0$ |
| 888 | $\vdash \square : U_0 \rightarrow U_0$ | | |
| 889 | | TY-ECTXS-PATS-FOC | |
| 890 | TY-ECTXS-PATU-FOC | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ |
| 891 | $\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ | $\Delta_2, x_1 : mT_1 \vdash u_1 : U$ | $\Delta_2, x_2 : mT_2 \vdash u_2 : U$ |
| 892 | $\Delta_2 \vdash u : U$ | | |
| 893 | $\Delta_1 \vdash C \circ (\square \circ u) : 1 \rightarrow U_0$ | $\Delta_1 \vdash C \circ (\text{case}_m \square \text{ of } \{ \text{Inl } x_1 \mapsto u_1, \text{Inr } x_2 \mapsto u_2 \}) : (T_1 \oplus T_2) \rightarrow U_0$ | |
| 894 | TY-ECTXS-PATP-FOC | | TY-ECTXS-PATE-FOC |
| 895 | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ | | $m\Delta_1, \Delta_2 \vdash C : U \rightarrow U_0$ |
| 896 | $\Delta_2, x_1 : mT_1, x_2 : mT_2 \vdash u : U$ | | $\Delta_2, x : m-m' T \vdash u : U$ |
| 897 | $\Delta_1 \vdash C \circ (\text{case}_m \square \text{ of } (x_1, x_2) \mapsto u) : (T_1 \otimes T_2) \rightarrow U_0$ | | $\Delta_1 \vdash C \circ (\text{case}_m \square \text{ of } E_{m'} x \mapsto u) : !_{m'} T \rightarrow U_0$ |
| 898 | | | |
| 899 | TY-ECTXS-MAP-FOC | | TY-ECTXS-TOA-FOC |
| 900 | $\Delta_1, \Delta_2 \vdash C : U \times T' \rightarrow U_0$ | | $\Delta \vdash C : (U \times 1) \rightarrow U_0$ |
| 901 | $\uparrow \Delta_2, x : !_{1'} T \vdash t' : T'$ | | $\Delta \vdash C \circ (\text{to}_K \square) : U \rightarrow U_0$ |
| 902 | $\Delta_1 \vdash C \circ (\text{map } \square \text{ of } x \mapsto t') : (U \times T) \rightarrow U_0$ | | |
| 903 | | | |
| 904 | TY-ECTXS-FROMA-FOC | | TY-ECTXS-FILLU-FOC |
| 905 | $\Delta \vdash C : (U \otimes (!_{100} T)) \rightarrow U_0$ | | $\Delta \vdash C : 1 \rightarrow U_0$ |
| 906 | $\Delta \vdash C \circ (\text{from}_K \square) : (U \times (!_{100} T)) \rightarrow U_0$ | | $\Delta \vdash C \circ (\square \triangleleft ()) : [n] 1 \rightarrow U_0$ |
| 907 | | | |
| 908 | TY-ECTXS-FILLL-FOC | | TY-ECTXS-FILLR-FOC |
| 909 | $\Delta \vdash C : [n] T_1 \rightarrow U_0$ | | $\Delta \vdash C : [n] T_2 \rightarrow U_0$ |
| 910 | $\Delta \vdash C \circ (\square \triangleleft \text{Inl}) : [n] T_1 \oplus T_2 \rightarrow U_0$ | | $\Delta \vdash C \circ (\square \triangleleft \text{Inr}) : [n] T_1 \oplus T_2 \rightarrow U_0$ |
| 911 | | | |
| 912 | TY-ECTXS-FILLP-FOC | | TY-ECTXS-FILLE-FOC |
| 913 | $\Delta \vdash C : ([n] T_1 \otimes [n] T_2) \rightarrow U_0$ | | $\Delta \vdash C : [m-n] T \rightarrow U_0$ |
| 914 | $\Delta \vdash C \circ (\square \triangleleft (,)) : [n] T_1 \otimes T_2 \rightarrow U_0$ | | $\Delta \vdash C \circ (\square \triangleleft E_m) : [n] !m T \rightarrow U_0$ |
| 915 | | | |
| 916 | TY-ECTXS-FILLF-FOC | | TY-ECTXS-FILLCOMP-FOC1 |
| 917 | $\Delta_1, (!_{1'} n) \Delta_2 \vdash C : 1 \rightarrow U_0$ | | $\Delta_1, (!_{1'} n) \Delta_2 \vdash C : T \rightarrow U_0$ |
| 918 | $\Delta_2, x : m T \vdash u : U$ | | $\Delta_2 \vdash t' : U \times T$ |
| 919 | $\Delta_1 \vdash C \circ (\square \triangleleft (\lambda x_m \mapsto u)) : [n] T_m \rightarrow U \rightarrow U_0$ | | $\Delta_1 \vdash C \circ (\square \triangleleft \bullet t') : [n] U \rightarrow U_0$ |
| 920 | | | |
| 921 | TY-ECTXS-FILLCOMP-FOC2 | TY-ECTXS-OPENAMPAR-FOC | |
| 922 | $\Delta_1, (!_{1'} n) \Delta_2 \vdash C : T \rightarrow U_0$ | $\text{LinOnly } \Delta_3 \quad \text{FinAgeOnly } \Delta_3$ | |
| 923 | $\Delta_1 \vdash v : [n] U$ | $\text{hnames}(C) \quad \# \# \quad \text{hnames}(\Delta_3)$ | |
| 924 | $\Delta_2 \vdash C \circ (v \triangleleft \bullet \square) : U \times T \rightarrow U_0$ | $\Delta_1, \Delta_2 \vdash C : (U \times T') \rightarrow U_0$ | |
| 925 | | $\Delta_2, \rightarrow \cdot \Delta_3 \quad \forall v_2 : U$ | |
| 926 | $\boxed{\vdash C[t] : T}$ | $\uparrow \Delta_1, \Delta_3 \vdash C \circ (\overset{\text{op}}{\text{hnames}}(\Delta_3) \langle v_2 \wedge \square \rangle) : T' \rightarrow U_0$ | |
| 927 | | | (Typing judgment for commands) |
| 928 | | TY-CMD | |
| 929 | | $\Delta \vdash C : T \rightarrow U_0 \quad \Delta \vdash t : T$ | |
| 930 | | $\vdash C[t] : U_0$ | |
| 931 | | | |

Fig. 11. Typing rules for evaluation contexts and commands

Composing an evaluation context of pseudo-type $T \rightarrow U_0$ with a new focus component never affects the type U_0 of the future command ; only the type T of what can be put in the box is altered.

All typing rules for evaluation contexts can be derived from the ones for the corresponding term (except for the rule TY-ECTXS-OPENAMPAR-FOC that is the truly new form). Let's take the rule TY-ECTXS-PATP-FOC as an example:

- the typing context $m\Delta_1 + \Delta_2$ in the premise for C corresponds to $m\Theta_1 + \Theta_2$ in the conclusion of TY-TERM-PATP in Figure 7;
- the typing context $\Delta_2, x_1 : mT_1, x_2 : mT_2$ in the premise for term u corresponds to the typing context $\Theta_2, x_1 : mT_1, x_2 : mT_2$ for the same term in TY-TERM-PATP;
- the typing context Δ_1 in the conclusion for $C \circ (\text{case}_m \square \text{ of } (x_1, x_2) \mapsto u)$ corresponds to the typing context Θ_1 in the premise for t in TY-TERM-PATP (the term t is located where the box \square is in TY-ECTXS-OPENAMPAR-FOC).

In a way, the typing rule for an evaluation context is a “rotation” of the typing rule for the associated term, where the typing contexts of one premise and the conclusion are swapped, and the typing context of the other potential premise is kept unchanged (with the added difference that free variables cannot appear in typing contexts of evaluation contexts, so any Θ becomes a Δ).

As we see at the bottom of the figure, a command $C[t]$ (i.e. a pair of an evaluation context and a term) is well typed when the evaluation context C provides a typing context Δ that is exactly one in which t is well typed. We can always embed a well-typed, closed term $\bullet \vdash t : T$ as a well-typed command using the identity evaluation context: $t \approx \square[t]$ and we thus have $\vdash \square[t] : T$ where $\Delta = \bullet$ (the empty context).

6.3 Small-step semantics

TODO: Mention why we don't use store semantics as showcased in Section 3

We equip λ_d with small-step semantics. There are three types of semantic rules:

- focus rules, where we remove a layer from term t (which cannot be a value) and push a corresponding focus component on the stack C ;
- unfocus rules, where t is a value and thus we pop a focus component from the stack C and transform it back to a term, so that a redex appears (or so that another focus/unfocus rule can be triggered);
- reduction rules, where the actual computation logic takes place.

Here is the whole set of rules for PATP:

$$\begin{array}{c}
 \text{SEM-PATP-FOC} \quad \frac{\text{NotVal } t}{C[\text{case}_m t \text{ of } (x_1, x_2) \mapsto u] \longrightarrow (C \circ (\text{case}_m \square \text{ of } (x_1, x_2) \mapsto u))[t]} \\
 \text{SEM-PATP-UNFOC} \quad \frac{}{(C \circ (\text{case}_m \square \text{ of } (x_1, x_2) \mapsto u))[v] \longrightarrow C[\text{case}_m v \text{ of } (x_1, x_2) \mapsto u]} \\
 \text{SEM-PATP-RED} \quad \frac{}{C[\text{case}_m (v_1, v_2) \text{ of } (x_1, x_2) \mapsto u] \longrightarrow C[u[x_1 := v_1][x_2 := v_2]]}
 \end{array}$$

Rules are triggered in a purely deterministic fashion; once a subterm is a value, it cannot be focused again. As focusing and defocusing rules are entirely mechanical (they are just a matter of pushing and popping a focus component on the stack), we only present the set of reduction rules for the system in Figure 12.

The reduction rules for function application, pattern-matching, **to_κ** and **from_κ** are straightforward.

| | | |
|------|--|--|
| 981 | $C[t] \longrightarrow C'[t']$ | (Small-step evaluation of commands) |
| 982 | SEM-APP-RED | SEM-PATU-RED |
| 983 | $C[(\lambda x_{\mathfrak{m}} \mapsto u) v] \longrightarrow C[u[x := v]]$ | $C[(\circledast u)] \longrightarrow C[u]$ |
| 984 | | |
| 985 | SEM-PATL-RED | |
| 986 | $C[\text{case}_{\mathfrak{m}} (\text{Inl } v_1) \text{ of } \{\text{Inl } x_1 \mapsto u_1, \text{Inr } x_2 \mapsto u_2\}] \longrightarrow C[u_1[x_1 := v_1]]$ | |
| 987 | | |
| 988 | SEM-PATR-RED | |
| 989 | $C[\text{case}_{\mathfrak{m}} (\text{Inr } v_2) \text{ of } \{\text{Inl } x_1 \mapsto u_1, \text{Inr } x_2 \mapsto u_2\}] \longrightarrow C[u_2[x_2 := v_2]]$ | |
| 990 | | |
| 991 | SEM-PATP-RED | |
| 992 | $C[\text{case}_{\mathfrak{m}} (v_1, v_2) \text{ of } (x_1, x_2) \mapsto u] \longrightarrow C[u[x_1 := v_1][x_2 := v_2]]$ | |
| 993 | | |
| 994 | SEM-PATE-RED | SEM-TOA-RED |
| 995 | $C[\text{case}_{\mathfrak{m}} E_{\mathfrak{n}} v' \text{ of } E_{\mathfrak{n}} x \mapsto u] \longrightarrow C[u[x := v']]$ | $C[\text{to}_{\mathfrak{K}} v_2] \longrightarrow C[\langle \{v_2 \wedge ()\} \rangle]$ |
| 996 | | |
| 997 | SEM-FROMA-RED | SEM-FILLU-RED |
| 998 | $C[\text{from}_{\mathfrak{K}} \{ \} \langle v_2 \wedge E_{\mathfrak{lo}} v_1 \rangle] \longrightarrow C[(v_2, E_{\mathfrak{lo}} v_1)]$ | $C[\rightarrow h \triangleleft ()] \longrightarrow C[h := \{ \} ()][()]$ |
| 999 | | |
| 1000 | SEM-FILLF-RED | |
| 1001 | $C[\rightarrow h \triangleleft (\lambda x_{\mathfrak{m}} \mapsto u)] \longrightarrow C[h := \{ \} \lambda x_{\mathfrak{m}} \mapsto u][()]$ | |
| 1002 | | |
| 1003 | SEM-FILLR-RED | SEM-FILLR-RED |
| 1004 | $h' = \max(\text{hnames}(C) \cup \{h\}) + 1$ | $h' = \max(\text{hnames}(C) \cup \{h\}) + 1$ |
| 1005 | $C[\rightarrow h \triangleleft \text{Inl}] \longrightarrow C[h := \{h'+1\} \text{Inl} [\overline{h'+1}]] [\rightarrow h'+1]$ | $C[\rightarrow h \triangleleft \text{Inr}] \longrightarrow C[h := \{h'+1\} \text{Inr} [\overline{h'+1}]] [\rightarrow h'+1]$ |
| 1006 | | |
| 1007 | SEM-FILLE-RED | |
| 1008 | $h' = \max(\text{hnames}(C) \cup \{h\}) + 1$ | |
| 1009 | $C[\rightarrow h \triangleleft E_{\mathfrak{m}}] \longrightarrow C[h := \{h'+1\} E_{\mathfrak{m}} [\overline{h'+1}]] [\rightarrow h'+1]$ | |
| 1010 | | |
| 1011 | SEM-FILLP-RED | |
| 1012 | $h' = \max(\text{hnames}(C) \cup \{h\}) + 1$ | |
| 1013 | $C[\rightarrow h \triangleleft (.)] \longrightarrow C[h := \{h'+1, h'+2\} (\overline{h'+1}, \overline{h'+2})][(\rightarrow h'+1, \rightarrow h'+2)]$ | |
| 1014 | | |
| 1015 | SEM-FILLCOMP-RED | |
| 1016 | $h' = \max(\text{hnames}(C) \cup \{h\}) + 1$ | |
| 1017 | $C[\rightarrow h \triangleleft \bullet_H \langle v_2 \wedge v_1 \rangle] \longrightarrow C[h := (H \pm h') v_2 [H \pm h']][v_1 [H \pm h']]$ | |
| 1018 | | |
| 1019 | SEM-MAP-RED-OPENAMPAR-FOC | |
| 1020 | $h' = \max(\text{hnames}(C)) + 1$ | |
| 1021 | $C[\text{map } H \langle v_2 \wedge v_1 \rangle \text{ with } x \mapsto t'] \longrightarrow (C \circ \overset{\text{op}}{H \pm h'} \langle v_2 [H \pm h'] \wedge \square \rangle)[t' [x := v_1 [H \pm h']]]$ | |
| 1022 | | |
| 1023 | SEM-OPENAMPAR-UNFOC | |
| 1024 | $(C \circ \overset{\text{op}}{H} \langle v_2 \wedge \square \rangle)[v_1] \longrightarrow C[H \langle v_2 \wedge v_1 \rangle]$ | |
| 1025 | | |
| 1026 | | |
| 1027 | | |
| 1028 | | |
| 1029 | | |

Fig. 12. Small-step semantics

All reduction rules for destination-filling primitives trigger a substitution $C[h :=_H v]$ on the evaluation context C that corresponds to a memory update of a hole $[h]$. SEM-FILLU-RED and SEM-FILLF-RED do not create any new hole; they only write a value to an existing one. On the other hand, rules SEM-FILL-RED, SEM-FILLR-RED, SEM-FILLE-RED and SEM-FILLP-RED all write a hollow constructor to the hole h , that is to say a value containing holes itself. Thus, we need to generate fresh names for these new holes, and also return a destination for each new hole with a matching name.

Obtaining a fresh name is represented by the statement $h' = \max(hnames(C) \cup \{h\}) + 1$ in the premises of these rules. The implicit invariant of the system is that we always rename hole names inside an ampar to fresh names when that ampar is **mapped** on. Names bound by a closed ampar — represented by the set of hole names H that it carries — are only local, and thus can shadow already existing names (that's why `alloc` is allowed to reuse the same hole name `1` at each invocation: it doesn't matter as it desugars to a closed ampar). Thus we only need to take into account the names of already opened ampars — all part of the evaluation context — when we want fresh names (either for new holes, or for ampar renaming).

For that, we introduce hole name shifting. Shifting all hole names in a set H by a given offset h' is denoted $H \pm h'$. We extend this notation to define a conditional shift operation $[H \pm h']$ which shifts each hole name appearing in the operand to the left of the brackets by h' if this hole name is also member of H . This conditional shift can be used on a single hole name, a value, or a typing context.

In rule SEM-FILLCOMP-RED, we write the left-hand side v_2 of a closed ampar $_H \langle v_2 \wedge v_1 \rangle$ to a hole $[h]$ that is part of some focus fragment $^{op}_{H'} \langle v'_2 \wedge \square \rangle$ in the evaluation context C . That fragment is not mentioned explicitly in the rule, as the destination $\rightarrow h$ is enough to target it. This results in the composition of two structures with holes v'_2 and v_2 through filling of $\rightarrow h$. Because we split open the ampar $_H \langle v_2 \wedge v_1 \rangle$ (its left-hand side gets written to a hole, while its right hand side is returned), we need to rename any hole name that it contains to a fresh one, as we do when an ampar is opened in the **map** rule. The renaming is carried out by the conditional shift $[H \pm h']$ on v_2 and v_1 (only hole names local to the ampar, represented by the set H , gets renamed).

Last but not least, rules SEM-MAP-RED-OPENAMPAR-FOC and SEM-OPENAMPAR-UNFOC dictates how and when a closed ampar (a term) is converted to an open ampar (a focusing fragment) and vice-versa.

With SEM-MAP-RED-OPENAMPAR-FOC, the local hole names of the ampar gets renamed to fresh ones, and the left-hand side gets attached to the focusing fragment $^{op}_{H \pm h'} \langle v_2 [H \pm h'] \wedge \square \rangle$ while the right-hand side (containing destinations) is substituted in the body of the **map** statement (which becomes the new term under focus). This effectively allows the right-hand side of an ampar to be a term instead of a value for a limited time.

The rule SEM-OPENAMPAR-UNFOC triggers when the body of a **map** statement has reduced to a value. In that case, we can close the ampar, by popping the focus fragment from the stack C and merging back with v_1 to reform a closed ampar.

Type safety. With the semantics now defined, we can state the usual type safety theorems:

THEOREM 6.1 (TYPE PRESERVATION). *If $\vdash C[t] : T$ and $C[t] \rightarrow C'[t']$ then $\vdash C'[t'] : T$.*

THEOREM 6.2 (PROGRESS). *If $\vdash C[t] : T$ and $\forall v, C[t] \neq \square[v]$ then $\exists C', t'. C[t] \rightarrow C'[t']$.*

A command of the form $\square[v]$ cannot be reduced further, as it only contains a fully determined value, and no pending computation. This it is the expected stopping point of the reduction, and any well-typed command is supposed to reach such a form at some point.

7 REMARKS ON THE FORMAL PROOFS

We've proved type preservation and progress theorems with the Coq proof assistant. At time of writing, we have assumed, rather than proved, the substitution lemmas. The choice of turning to a proof assistant was a pragmatic choice: the context handling in λ_d can be quite finicky, and it was hard, without computer assistance, to make sure that we hadn't made mistakes in our proofs. The version of λ_d that we've proved is written in Ott, the same Ott file is used as a source for this article, making sure that we've proved the same system as we're presenting; some visual simplification is applied by a script to produce the version in the article.

We probably want to make sure that the statement of these two lemmas is stated in the type system section

a citation maybe

Most of the proof was done by an author with little prior experience with Coq. This goes to show that Coq is reasonably approachable even for non-trivial development. The proof is about 6000 lines long, and contains nearly 350 lemmas. Many of the cases of the type preservation and progress lemmas are similar, to handle such repetitive cases using of a large-language-model based autocompletion system has been quite effective.

Binders are the biggest problem. We've largely manage to make the proof to be only about closed terms, to avoid any complication with binders. This worked up until the substitution lemmas, which is the reason why we haven't proved them in Coq yet (that and the fact that it's much easier to be confident in our pen-and-paper proofs for those). There are backends to generate locally nameless representations from Ott definitions; we haven't tried them yet, but the unusual binding nature of ampars may be too much for them to handle.

citation

The proofs aren't very elegant. For instance, we don't have any abstract formalization of semirings: since our semirings are finite it was more expedient to brute-force the properties we needed by hand. We've observed up to 232 simultaneous goals, but a computer makes short work of this: it was solved by a single call to the congruence tactic. Nevertheless there are a few points of interest.

- We represent context as finite-domain functions, rather than as syntactic lists. This works much better when defining sums of context. There are a bunch of finite-function libraries in the ecosystem, but we needed finite dependent functions (because the type of binders depend on whether we're binding a variable name or a hole name). This didn't exist, but for our limited purpose, it ended up not being too costly rolling our own. About 1000 lines of proofs. The underlying data type is actual functions, this was simpler to develop, but equality is more complex than with a bespoke data type.
- We make the mode semiring total by adding an invalid mode. This prevents us from having to deal with partiality at all. The cost is that contexts can contain binders with invalid mode. Proofs are written so as to rule out this case.

The inference rules produced by Ott aren't conducive to using setoid equality. This turned out to be a problem with our type for finite function:

```
Record T A B := {
  underlying :> forall x:A, option (B x);
  supported : exists l : list A, Support l underlying;
}.
```

where `Support l f` means that `l` contains the domain of `f`. To make the equality of finite function be strict equality `eq`, we assumed functional extensionality and proof irrelevance. In some circumstances, we've also needed to list the finite functions' domains. But in the definition, the domain is sealed behind a proposition, so we also assumed classical logic as well as indefinite description

```
Axiom constructive_indefinite_description :
  forall (A : Type) (P : A->Prop), (exists x, P x) -> { x : A | P x }.
```

together, they let us extract the domain from the proposition. Again this isn't particularly elegant, we could have avoided some of these axioms at the price of more complex development. But for the sake of this article, we decided to favor expediency over elegance.

8 IMPLEMENTATION OF λ_d USING IN-PLACE MEMORY MUTATIONS

The formal language presented in Sections 5 and 6 is not meant to be implemented as-is.

First, λ_d misses a form of recursion, but we believe that adding equirecursive types and a fix-point operator wouldn't compromise the safety of the system.

Secondly, ampars are not managed linearly in λ_d ; only destinations are. That is to say that an ampar can be wrapped in an exponential, e.g. $\mathbb{E}_{\omega V} \{h\} \langle \text{Inr} (\text{Inl } ()), \boxed{h} \rangle_{\wedge} \rightarrow h$ (representing a non-linear difference list $\mathbb{E}_{\omega V} (0 :: \square)$), and then used twice, each time in a different way:

```

case  $\mathbb{E}_{\omega V} \{h\} \langle \text{Inr} (\text{Inl } ()), \boxed{h} \rangle_{\wedge} \rightarrow h$  of  $\mathbb{E}_{\omega V} x \mapsto$ 
  let  $x_1 := x$  append (succ zero) in
  let  $x_2 := x$  append (succ (succ zero)) in
  toList ( $x_1$  concat  $x_2$ )
   $\longrightarrow * 0 :: 1 :: 0 :: 2 :: []$ 

```

It may seem counter-intuitive at first, but this program is valid and safe in λ_d . Thanks to the renaming discipline we detailed in Section 6.3, every time an ampar is **mapped** over, its hole names are renamed to fresh ones. So when we call **append** to build x_1 (which is implemented in terms of **map**), we sort of allocate a new copy of the ampar before mutating it, effectively achieving a copy-on-write memory scheme. Thus it is safe to operate on x again to build x_2 .

In the introduction of the article, we announced a safe framework for in-place memory mutation, so we will uphold this promise now. The key to go from a copy-on-write scheme to an in-place mutation scheme is to force ampars to be linearly managed too. For that we introduce a new type **Token**, together with primitives **dup** and **drop** (remember that unqualified arrows have mode **1v**, so are linear):

```

dup : Token  $\rightarrow$  Token $\otimes$ Token
drop : Token  $\rightarrow$  1
 $\text{alloc}_{\text{cow}}$  : T  $\ltimes$  [T]
 $\text{alloc}_{\text{ip}}$  : Token  $\rightarrow$  T  $\ltimes$  [T]

```

We now have two possible versions of **alloc**: the new one with an in-place mutation memory model (**ip**), that has to be managed linearly, and the old one that doesn't have to be used linearly, and features a copy-on-write (**cow**) memory model.

We use the **Token** type as an intrinsic source of linearity that infects the ampar returned by alloc_{ip} . Such a token can be duplicated using **dup**, but as soon as it is used to create an ampar, that ampar cannot be duplicated itself. In the system featuring the **Token** type and alloc_{ip} , that we call $\lambda_d \text{ip}$, "closed" programs now typecheck in the non-empty context $\{tok_0 : {}_{100}\text{Token}\}$ containing a token variable that the user can **duplicate** and **drop** freely to give birth to an arbitrary number of ampars, that will then have to be managed linearly.

Having closed programs to typecheck in non-empty context $\{tok_0 : {}_{100}\text{Token}\}$ is very similar to having a primitive function **withToken** : $(\text{Token } {}_{100} \rightarrow !_{\omega\infty} \text{T}) \rightarrow !_{\omega\infty} \text{T}$ as it is done in [Bagrel 2024].

In $\lambda_d \text{ip}$, as ampars are managed linearly, we can change the allocation and renaming mechanisms:

- the hole name for a new ampar can be chosen fresh right from the start (this corresponds to a new heap allocation);
- adding a new hollow constructor still require fresh freshness/renaming for its hole names (this corresponds to a new heap allocation too);

I don't think we need to write this: methodology: assume a lot of lemmas, prove main theorem, prove assumptions, some wrong, fix. A number of wrong lemma initially assumed, but replacing them by correct variant was always easy to fix in proofs.

- **mapping** over an ampar and filling destinations or composing two ampars using “fillComp” (\Leftarrow) no longer require any renaming: we have the guarantee that the names are globally fresh, and thus we can do in-place memory updates.

We decided to omit the linearity aspect of ampars in λ_d as it clearly obfuscate the presentation of the system without adding much to the understanding of the latter. We believe that the system is still sound with this linearity aspect, and articles such as [Spiwack et al. 2022] gives a pretty clear view on how to implement the linearity requirement for ampars in practice without too much noise for the user.

9 RELATED WORK

9.1 Destination-passing style for efficient memory management

In [Shaikhha et al. 2017], the authors present a destination-based intermediate language for a functional array programming language. They develop a system of destination-specific optimizations and boast near-C performance.

This is the most comprehensive evidence to date of the benefit of destination-passing style for performance in functional programming languages. Although their work is on array programming, while this article focuses on linked data structure. They can therefore benefit of optimizations that are perhaps less valuable for us, such as allocating one contiguous memory chunk for several arrays.

The main difference between their work and ours is that their language is solely an intermediate language: it would be unsound to program in it manually. We, on the other hand, are proposing a type system to make it sound for the programmer to program directly with destinations.

We consider that these two aspects complement each other: good compiler optimization are important to alleviate the burden from the programmer and allowing high-level abstraction; having the possibility to use destinations in code affords the programmer more control would they need it.

9.2 Tail modulo constructor

Another example of destinations in a compiler’s optimizer is [Bour et al. 2021]. It’s meant to address the perennial problem that the map function on linked lists isn’t tail-recursive, hence consumes stack space. The observation is that there’s a systematic transformation of functions where the only recursive call is under a constructor to a destination-passing tail-recursive implementation.

Here again, there’s no destination in user land, only in the intermediate representation. However, there is a programmatic interface: the programmer annotates a function like

```
let[@tail_mod_cons] rec map =
```

to ask the compiler to perform the translation. The compiler will then throw an error if it can’t. This way, contrary to the optimizations in [Shaikhha et al. 2017], this optimization is entirely predictable.

This has been available in OCaml since version 4.14. This is the one example we know of of destinations built in a production-grade compiler. Our λ_d makes it possible to express the result tail-modulo-constructor in a typed language. It can be used to write programs directly in that style, or it could serve as a typed target language for and automatic transformation. On the flip-side, tail modulo constructor is too weak to handle our difference lists or breadth-first traversal examples.

9.3 A functional representation of data structures with a hole

The idea of using linear types to safely represent structures with holes dates back to [Minamide 1998]. Our system is strongly inspired by theirs. In their system, we can only compose functions

Subsection for each work seems a little heavy-weight. On the other hand the italic paragraphs seem too light-weight. I’m longing for the days of paragraph heading in bold.

that represent data structures with holes, we can't pattern-match on the result; just like in our system we cannot act on the left-hand side of $S \ltimes T$, only the right hand part.

In [Minamide 1998], it's only ever possible to represent structures with a single hole. But this is a rather superficial restriction. The author doesn't comment on this, but we believe that this restriction only exists for convenience of the exposition: the language is lowered to a language without function abstraction and where composition is performed by combinators. While it's easy to write a combinator for single-argument-function composition, it's cumbersome to write combinators for functions with multiple arguments. But having multiple-hole data structures wouldn't have changed their system in any profound way.

The more important difference is that while their system is based on a type of linear functions, our is based on the linear logic's par combinator. This, in turns, lets us define a type of destinations which are representations of holes in values, which [Minamide 1998] doesn't have. This means that [Minamide 1998] can implement our examples with difference lists and queues from Section 2.2, but it can't do our breadth-first traversal example from Section 4, since storing destinations in a data structure is the essential ingredient of this example.

This ability to store destination does come at a cost though: the system needs this additional notion of ages to ensure that destinations are use soundly. On the other hand, our system is strictly more general, in that the system from [Minamide 1998] can be embedded in λ_d , and if one stays in this fragment, we're never confronted with ages. Ages only show up when writing programs that go beyond Minamide's system.

9.4 Tail modulo context

9.5 Destination-passing style programming: a Haskell implementation

In [Bagrel 2024], the author proposes a system much like ours: it has a par-like construct (that they call *Incomplete*), where only the right-hand side can be modified, and a destination type. The main difference is that in their system, $d \triangleleft t$ requires t to be unrestricted, while in λ_d , t can be linear.

The consequence is that in [Bagrel 2024], destinations can be stored in data structures but not in data structures with holes. In order to do a breadth-first search algorithm like in Section 4, they can't use improved queues like we do, they have to use regular functional queues.

However, unlike λ_d , [Bagrel 2024] is implemented in Haskell, which features linear types. Our λ_d , with the age modes, needs more than what Haskell provides. Our system subsumes theirs, however, ages will appear in the typing rules for that fragment.

9.6 Semi-axiomatic sequent calculus

In, the author develop a system where constructors return to a destination rather than allocating memory. It is very unlike the other systems described in this section in that it's completely founded in the Curry-Howard isomorphism. Specifically it gives an interpretation of a sequent calculus which mixes Gentzen-style deduction rules and Hilbert-style axioms. As a consequence, the par connective is completely symmetric, and, unlike our $[T]$ type, their dualization connective is involutive.

The cost of this elegance is that computations may try to pattern-match on a hole, in which case they must wait for the hole to be filled. So the semantic of holes is that of a future or a promise. In turns this requires the semantic of their calculus to be fully concurrent. Which is a very different point in the design space.

You'll [Thomas] have to do this section, because I'm not familiar enough with that work

More of these greys I don't know why that is.

Add citation

10 CONCLUSION AND FUTURE WORK

Using a system of ages in addition to linearity, λ_d is a purely functional calculus which supports destination in a very flexible way. It subsumes existing calculi from the literature for destination passing, allowing both composition of data structures with holes and storing destinations in data structures. Data structures are allowed to have multiple holes, and destinations can be stored in data structures that, themselves, have holes. The latter is the main reason to introduce ages and is key to λ_d 's flexibility.

We don't anticipate that a system of ages like λ_d will actually be used in a programming language: it's unlikely that destination are so central to the design of a programming language that it's worth baking them so deeply in the type system. Perhaps a compiler that makes heavy use of destinations in its optimizer could use λ_d as a typed intermediate representation. But, more realistically, our expectation is that λ_d can be used as a theoretical framework to analyze destination-passing systems: if an API can be defined in λ_d then it's sound.

In fact, we plan to use this very strategy to design an API for destination passing in Haskell, leveraging only the existing linear types, but retaining the possibility of storing destinations in data structures with holes.

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