

HO unification from object language to meta language

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ABSTRACT

Specifying and implementing a logic from scratch requires significant effort. Logical Frameworks and Higher Order Logic Programming Languages provide dedicated, high-level Meta Languages (ML) to facilitate this task in two key ways: 1) variable binding and substitution are simplified when ML binders represent object logic ones; 2) proof construction, and even proof search, is greatly simplified by leveraging the unification procedure provided by the ML. Notable examples of ML are Elf [13], Twelf [14], λ Prolog [10] and Isabelle [20] which have been utilized to implement various formal systems such as First Order Logic [5], Set Theory [12], Higher Order Logic [11], and even the Calculus of Constuctions [4].

The object logic we are interested in is Coq's [18] Dependent Type Theory (DTT), for which we aim to implement a unification procedure \approx_o using the ML Elpi [3], a dialect of λ Prolog. Elpi's equational theory comprises $\eta\beta$ equivalence and comes equipped with a higher order unification procedure \approx_λ restricted to the pattern fragment [9]. We want \approx_o to be as powerful as \approx_λ but on the object logic DTT. Elpi also comes with an encoding for DTT that works well for meta-programming [17, 16, 7, 6]. Unfortunately this encoding, which we refer to as \mathcal{F}_o , "underuses" \approx_λ by restricting it to first-order unification problems only. To address this issue, we propose a better-behaved encoding, \mathcal{H}_o , demonstrate how to map unification problems in \mathcal{F}_o to related problems in \mathcal{H}_o , and illustrate how to map back the unifiers found by \approx_λ , effectively implementing \approx_o on top of \approx_λ for the encoding \mathcal{F}_o .

We apply this technique to the implementation of a type-class [19] solver for Coq [18]. Type-class solvers are proof search procedures based on unification that back-chain designated lemmas, providing essential automation to widely used Coq libraries such as Stdpp/Iris [8] and TLC [1]. These two libraries constitute our test bed.

KEYWORDS

Logic Programming, Meta-Programming, Higher-Order Unification, Proof Automation

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1 INTRODUCTION

Specifying and implementing a logic from scratch requires significant effort. Logical Frameworks and Higher Order Logic Programming Languages provide dedicated, high-level Meta Languages (ML) to facilitate this task in two key ways: 1) variable binding and substitution are simplified when ML binders represent object logic ones; 2) proof construction, and even proof search, is greatly simplified by leveraging the unification procedure provided by the ML. Notable examples of ML are Elf [13], Twelf [14], λ Prolog [10] and Isabelle [20] which have been utilized to implement various formal systems such as First Order Logic [5], Set Theory [12], Higher Order Logic [11], and even the Calculus of Constuctions [4].

The object logic we are interested in is Coq's [18] Dependent Type Theory (DTT), and we want to code a type-class [19] solver for Coq [18] using the Coq-Elpi [17] meta programming framework. Type-class solvers are unification based proof search procedures that combine a set of designated lemmas in order to providing essential automation to widely used Coq libraries.

As the running example we take the Decide type class, from the Stdpp [8] library. The class identifies predicates equipped with a decision procedure. The following three designated lemmas (called Instances in the type-class jargon) state that: 1) the type `fin n`, of natural numbers smaller than `n` is finite; 2) the predicate `nfact n nf`, linking a natural number `n` to its prime factors `nf`, is decidable; 3) the universal closure of a predicate has a decision procedure if the predicate has and if its domain is finite.

```
Instance fin_fin n : Finite (fin n).          (* r1 *)
Instance nfact_dec n nf : Decision (nfact n nf). (* r2 *)
Instance forall_dec A P : Finite A →          (* r3 *)
  ∀x:A, Decision (P x) → Decision (∀x:A, P x).
```

Under this context of instances a type-class solver is able to prove the following statement automatically by back-chaining.

```
Check _ : Decision (forall y: fin 7, nfact y 3). (g)
```

The encoding of DTT provided by Elpi, that we will discuss at length later in section ?? and ??, is an Higher Order Abstract Syntax (HOAS) datatype `tm` featuring (among others) the following constructors:

```
type lam  tm -> (tm -> tm) -> tm.    % lambda abstraction
type app  list tm -> tm.              % n-ary application
type all  tm -> (tm -> tm) -> tm.    % forall quantifier
type con  string -> tm.               % constants
```

Following standard λ Prolog [10] the concrete syntax to abstract, at the meta level, an expression `e` over a variable `x` is `«x\ e»`, and square brackets denote a list of terms separated by comma. As an example we show the encoding of the Coq term `«∀y:t, nfact y 3»`:

```
all (con"t") y\ app[con"nfact", y, con"3"]
```

We now illustrate the encoding of the three instances above as higher-order logic-programming rules: capital letters denote rule parameters; `:-` separates the rule's head from the premises; `pi w\` introduces a fresh nominal constant `w` for the premise `p`.

```
finite (app[con"fin", N]). (r1)
```

```
decision (app [con"nfact", N, NF]). (r2)
```

```
decision (all A x\ app[P, x]) :- finite A, (r3)
  pi w\ decision (app[P, w]).
```

Unfortunately this translation of rule (r3) uses the predicate `P` as a first order term: for the meta language its type is `tm`. If we try to backchain the rule (r3) on the encoding of the goal (g) given below

```
decision (all (app[con"fin", con"7"]) y\
  app[con"nfact", y, con"3"]).
```

we obtain an unsolvable unification problem (p): the two lists of terms have different lengths!

```
app[con"nfact", y, con"3"] = app[P, y] (p)
```

In this paper we study a more sophisticated encoding of Coq terms allowing us to rephrase the problematic rule (r3) as follows:

```
decision (all A x\ Pm x) :- link Pm P A, finite A, (r3a)
  pi x\ decision (app[P, x]).
```

Since `Pm` is an higher-order unification variable of type `tm` \rightarrow `tm`, with `x` in its scope, the unification problem (p') admits one solution:

```
app[con"nfact", y, con"3"] = Pm y (p')
Pm = x\ app[con"nfact", x, con"3"] % assignment for Pm
A = app[con"fin", con"7"] % assignment for A
```

After unifying the head of rule (r3a) with the goal, Elpi runs the premise `link Pm P A` that is in charge of bringing the assignment for `Pm` back to the domain `tm` of Coq terms:

```
P = lam A a\ app[con"nfact", a, con"3"]
```

This simple example is sufficient to show that the encoding we seek is not trivial and does not only concern the head of rules, but the entire sequence of unification problems that constitute the execution of a logic program. In fact the solution for `P` above generates a (Coq) β -redex in the second premise (the predicate under the `pi w\`):

```
decision (app[lam A (a\ app[con"nfact", a, con"3"]), w])
```

In turn this redex prevents the rule (r2) to backchain properly since the following unification problem has no solution:

```
app[lam A (a\ app[con"nfact", a, con"3"]), x] =
app[con"nfact", N, NF]
```

The root cause of the problems we sketched in the running example is that the unification procedure \approx_λ of the meta language is not aware of the equational theory of the object logic, even if both theories include $\eta\beta$ -conversion and admit most general unifiers for unification problems in the pattern fragment \mathcal{L}_λ [9].

Contributions. In this paper we discuss alternative encodings of Coq in Elpi (Section ??), then we identify a minimal language \mathcal{F}_0 in which the problems sketched here can be fully described. We then detail an encoding `comp` from \mathcal{F}_0 to \mathcal{H}_0 (the language of the meta language) and a decoding `decomp` to relate the unifiers bla

bla.. TODO citare Teyjus. The code discussed in the paper can be accessed at the URL: <https://github.com/FissoreD/paper-ho>.

2 PROBLEM STATEMENT

The equational theory of Coq's Dependent Type Theory is very rich. In addition to the usual $\eta\beta$ -equivalence for functions, terms (hence types) are compared up to proposition unfolding and fix-point unrolling. Still, for efficiency and predictability reasons, most form of automatic proof search employ a unification procedure that captures a simpler one, just $\eta\beta$, and that solves higher-order problems restricted to the pattern fragment \mathcal{L}_λ [9]. We call this unification procedure \approx_o .

The equational theory of the meta language Elpi that we want to use to implement a form of proof automation is strikingly similar, since it it comprises $\eta\beta$ (for the meta language functions), and the unification procedure \approx_λ solves higher-order problems in \mathcal{L}_λ .

In spite of the similarity the link between \approx_λ and \approx_o is not trivial, since the abstraction and application term constructors the two unification procedures deal with are different. For example

$x \setminus f \ x$	$\approx_\lambda \ f$
$\text{lam } A \ x \setminus \text{app}[\text{con} "f", x]$	$\approx_o \ \text{con} "f"$
$\text{lam } A \ x \setminus \text{app}[\text{con} "f", x]$	$\neq_\lambda \ \text{con} "f"$
$P \ x$	$\approx_\lambda \ x$
$\text{app}[P, x]$	$\approx_o \ x$
$\text{app}[P, x]$	$\neq_\lambda \ x$

One could ignore this similarity, and “just” describe the object language unification procedure in the meta language, that is crafting a unif predicate to be used as follows in rule (r3):

```
decision X :- unif X (all A x\ app[P, x]), finite A,
  pi x\ decision (app[P, x]).
```

This choice would underuse the logic programming engine provided by the metalanguage since by removing any datum from the head of rules indexing degenerates. Moreover the unification procedure built in the meta language is likely to be faster than one implemented in it, especially if the meta language is interpreted as Elpi is.

To state precisely the problem we solve we need a \mathcal{F}_0 representation of DTT terms and a \mathcal{H}_0 one. We call $=_o$ the equality over ground terms in \mathcal{F}_0 , $=_\lambda$ the equality over ground terms in \mathcal{H}_0 , \approx_o the unification procedure we want to implement and \approx_λ the one provided by the meta language. TODO extend $=_o$ and $=_\lambda$ with reflexivity on uvars.

We write $t_1 \approx_\lambda t_2 \mapsto \sigma$ when t_1 and t_2 unify with substitution σ ; we write σt for the application of the substitution to t , and $\sigma X = \{\sigma t \mid t \in X\}$ when X is a set; we write $\sigma \subseteq \sigma'$ when σ is more general than σ' . We assume that the unification of our meta language is correct:

$$t_i \in \mathcal{L}_\lambda \Rightarrow t_1 \approx_\lambda t_2 \mapsto \rho \Rightarrow \rho t_1 =_\lambda \rho t_2 \quad (1)$$

$$t_i \in \mathcal{L}_\lambda \Rightarrow \rho t_1 =_\lambda \rho t_2 \Rightarrow \exists \rho', t_1 \approx_\lambda t_2 \mapsto \rho' \wedge \rho' \subseteq \rho \quad (2)$$

We illustrate a compilation $\langle s \rangle \mapsto (t, m, l)$ that maps a term s in \mathcal{F}_0 to a term t in \mathcal{H}_0 , a variable mapping m and list of links l . The variable map connects unification variables in \mathcal{H}_0 with variables in \mathcal{F}_0 and is used to “decompile” the assignment, $\langle \sigma, m, l \rangle^{-1} \mapsto \rho$. Links represent problematic sub-terms which are linked to the

unification variable that stands in their place in the compiled term. These links are checked for or progress XXX improve....

We represent a logic program *run* in \mathcal{F}_0 as a list *steps* p of length N . Each made of a unification problem between terms S_{p_l} and S_{p_r} taken from the set of all terms \mathcal{S} . The composition of these steps starting from the empty substitution ρ_0 produces the final substitution ρ_N .¹ The initial here ρ_0 is the empty substitution

$$\begin{aligned} \text{fstep}(\mathcal{S}, p, \rho) &\mapsto \rho'' \stackrel{\text{def}}{=} \rho S_{p_l} \simeq_o \rho S_{p_r} \mapsto \rho' \wedge \rho'' = \rho \cup \rho' \\ \text{frun}(\mathcal{S}, N) &\mapsto \rho_N \stackrel{\text{def}}{=} \bigwedge_{p=1}^N \text{fstep}(\mathcal{S}, p, \rho_{p-1}) \mapsto \rho_p \end{aligned}$$

We simulate each run in \mathcal{F}_0 with a run in \mathcal{H}_0 as follows. Note that σ_0 is the empty substitution.

$$\begin{aligned} \text{hstep}(\mathcal{T}, p, \sigma, \mathbb{L}) &\mapsto \sigma'' \stackrel{\text{def}}{=} \\ &\sigma \mathcal{T}_{p_l} \simeq_\lambda \sigma \mathcal{T}_{p_r} \mapsto \sigma' \wedge \text{check}(\mathbb{L}, \sigma \cup \sigma') \mapsto \sigma'' \\ \text{hrun}(\mathcal{S}, N) &\mapsto \rho_N \stackrel{\text{def}}{=} \\ &\mathcal{T} \times \mathbb{M} \times \mathbb{L} = \{(t_j, m_j, l_j) | s_j \in \mathcal{S}, \langle s_j \rangle \mapsto (t_j, m_j, l_j)\} \\ &\bigwedge_{p=1}^N \text{hstep}(\mathcal{T}, p, \sigma_{p-1}, \mathbb{L}) \mapsto \sigma_p \\ &\langle \sigma_N, \mathbb{M}, \mathbb{L} \rangle^{-1} \mapsto \rho_N \end{aligned}$$

Here *hstep* is made of two sub-steps: a call to \simeq_λ (on the compiled terms) and a call to *check* on the set of links. We claim the following:

PROPOSITION 2.1 (SIMULATION). $\forall \mathcal{S}, \forall N$

$$\text{frun}(\mathcal{S}, N) \mapsto \rho_N \Leftrightarrow \text{hrun}(\mathcal{S}, N) \mapsto \rho_N$$

That is, the two executions give the same result. Moreover:

PROPOSITION 2.2 (SIMULATION FIDELITY). *In the context of* *hrun*, *if* $\mathcal{T} \subseteq \mathcal{L}_\lambda$ *we have that* $\forall p \in 1 \dots N$

$$\text{fstep}(\mathcal{S}, p, \rho_{p-1}) \mapsto \rho_p \Leftrightarrow \text{hstep}(\mathcal{T}, p, \sigma_{p-1}, \mathbb{L}) \mapsto \sigma_p$$

In particular this property guarantees that a *failure* in the \mathcal{F}_0 run is matched by a failure in \mathcal{H}_0 at the same step. We consider this property very important from a practical point of view since it guarantees that the execution traces are strongly related and in turn this enables a user to debug a logic program in \mathcal{F}_0 by looking at its execution trace in \mathcal{H}_0 .

XXX permuting *hrun* does not change the final result if check does not fail eagerly

XXX if we want to apply heuristics, we can apply them in *decomp* to avoid committing to a non MGU too early

We can define $s_1 \simeq_o s_2$ by specializing the code of *hrun* to $\mathcal{S} = \{s_1, s_2\}$ as follows:

$$\begin{aligned} s_1 \simeq_o s_2 &\mapsto \rho \stackrel{\text{def}}{=} \\ &\langle s_1 \rangle \mapsto (t_1, m_1, l_1) \wedge \langle s_2 \rangle \mapsto (t_2, m_2, l_2) \\ &t_1 \simeq_\lambda t_2 \mapsto \sigma' \wedge \text{check}(\{l_1, l_2\}, \sigma') \mapsto \sigma'' \wedge \\ &\langle \sigma'', \{m_1, m_2\}, \{l_1, l_2\} \rangle^{-1} \mapsto \rho \end{aligned}$$

PROPOSITION 2.3 (PROPERTIES OF \simeq_o).

$$s_i \in \mathcal{L}_\lambda \Rightarrow s_1 \simeq_o s_2 \mapsto \rho \Rightarrow \rho s_1 =_o \rho s_2 \quad (3)$$

$$s_i \in \mathcal{L}_\lambda \Rightarrow \rho s_1 =_o \rho s_2 \Rightarrow \exists \rho', s_1 \simeq_o s_2 \mapsto \rho' \wedge \rho' \subseteq \rho \quad (4)$$

$$\rho s_1 =_o \rho s_2 \Rightarrow \rho' \subseteq \rho \Rightarrow \rho' s_i \in \mathcal{L}_\lambda \Rightarrow \rho' s_1 \simeq_o \rho' s_2 \quad (5)$$

¹If the same rule is used multiple time in a run we just consider as many copies as needed of the terms composing the rules, with fresh unification variables each time

Properties 3 and 4 state, respectively, that in \mathcal{L}_λ the implementation of \simeq_o is correct, complete and returns the most general unifier.

Property 5 states that \simeq_o , hence our compilation scheme, is resilient to unification problems outside \mathcal{L}_λ solved by a third party. We believe this property is of practical interest since we want the user to be able to add heuristics via hand written rules to the ones obtained by our compilation scheme. A Typical example is the following problem (*q*) that is outside \mathcal{L}_λ :

$$\begin{aligned} \text{app}[\text{F}, \text{con}["a"]] &= \text{app}[\text{con}["f"], \text{con}["a"], \text{con}["a"]] \quad (q) \\ \text{F} &= \text{lam } x \backslash \text{app}[\text{con}["f"], x, x] \quad (h) \end{aligned}$$

Instead of rejecting it our scheme accepts it and guarantees that if (*h*) is given (after the compilation part of the scheme, as a run time hint) then ...

2.1 The intuition in a nutshell

A term *s* is compiled in a term *t* where every “problematic” sub term *p* is replaced by a fresh unification variable *h* and an accessory link that represent a suspended unification problem $h \simeq_\lambda p$. As a result \simeq_λ is “well behaved” on *t*, that is it does not contradict $=_o$ as it would otherwise do on “problematic” terms. We now define “problematic” and “well behaved” more formally.

Definition 2.4 ($\Diamond\eta$). $\Diamond\eta = \{t \mid \exists \rho, \rho t \text{ is an eta expansion}\}$

An example of term *t* in $\Diamond\eta$ is $\lambda x. \lambda y. F y x$ since the substitution $\rho = \{F \mapsto \lambda a. \lambda b. fba\}$ makes $\rho t = \lambda x. \lambda y. fxy$ that is the eta long form of *f*. This term is problematic since its rigid part, the λ -abstractions, cannot justify a unification failure against, say, a constant.

Definition 2.5 ($\Diamond\beta$). $\Diamond\beta = \{Xt_1 \dots t_n \mid Xt_1 \dots t_n \notin \mathcal{L}_\lambda\}$.

An example of *t* in $\Diamond\beta$ is Fa for a constant *a*. Note however tha an oracle could provide an assignment $\rho = \{F \mapsto \lambda x. x\}$ that makes the resulting term fall outside of $\Diamond\beta$.

Definition 2.6 (Subterms $\mathcal{P}(t)$). The set of sub terms of *t* is the largest set $\mathcal{P}(\sqcup)$ that can be obtained by the following rules.

$$\begin{aligned} t &\in \mathcal{P}(t) \\ t &= f t_1 \dots t_n \Rightarrow \mathcal{P}(t_i) \subseteq \mathcal{P}(t) \wedge f \in \mathcal{P}(t) \\ t &= \lambda x. t' \Rightarrow \mathcal{P}(t') \subseteq \mathcal{P}(t) \end{aligned}$$

We write $\mathcal{P}(X) = \bigcup_{t \in X} \mathcal{P}(t)$ when *X* is a set of terms.

Definition 2.7 (Well behaved set). Given a set of terms $X \subseteq \mathcal{H}_0$,

$$\mathcal{W}(X) \Leftrightarrow \forall t \in \mathcal{P}(X), t \notin (\Diamond\beta \cup \Diamond\eta)$$

PROPOSITION 2.8 (\mathcal{W} -PRESERVATION). $\forall \mathcal{T}, \forall \mathbb{L}, \forall p, \forall \sigma, \forall \sigma'$

$$\mathcal{W}(\sigma \mathcal{T}) \wedge \text{hstep}(\mathcal{T}, p, \sigma, \mathbb{L}) \mapsto \sigma' \Rightarrow \mathcal{W}(\sigma' \mathcal{T})$$

A less formal way to state 2.8 is that *hstep* never “commits” an unneeded λ -abstraction in σ (a λ that could be erased by an η -contraction), nor puts in σ a flexible application outside \mathcal{L}_λ (an application node that could be erased by a β -reduction).

Note that proposition 2.8 does not hold for \simeq_o since *decompila*-tion can introduce (actually restore) terms in $\Diamond\eta$ or $\Diamond\beta$ that were move out of the way (put in \mathbb{L}) during compilation.

3 ALTERNATIVE ENCODINGS AND RELATED WORK

Paper [2] introduces semi-shallow.

Our encoding of DTT may look “semi shallow” since we use the meta-language lambda abstraction but not its application (for the terms of type tm). A fully shallow encoding unfortunately does not fit our use case, although it would make the running example work:

```
finite (fin N).
decision (nfact N NF).
decision (all A x\ P x) :- finite A, pi x\ decision (P x).
```

There are two reasons for dismissing this encoding. The first one is that in DTT it is not always possible to adopt it since the type system of the meta language is too weak to accommodate terms with a variable arity, like the following example:

```
Fixpoint arr T n := if n is S m then T -> arr T m else T.
Definition sum n : arr nat n := ...
Check sum 2 7 8 : nat.
Check sum 3 7 8 9 : nat.
```

The second reason is the encoding for Coq is used for meta programming the system, hence it must accommodate the manipulation of terms that are now known in advance (not even defined in Coq) without using introspection primitives such as Prologs’s functor and arg.

In the literature we could find a few related encoding of DTT. TODO In [4] is related and make the discrepancy between the types of ML and DTT visible. In this case one needs 4 application nodes. Moreover the objective is an encoding of terms, proofs, not proof search. Also note the conv predicate, akin to the unif we rule out.

TODO This other paper [15] should also be cited.

None of the encodings above provide a solution to our problem.

4 PRELIMINARIES: \mathcal{F}_0 AND \mathcal{H}_0

In order to reason about unification we provide a description of the \mathcal{F}_0 and \mathcal{H}_0 languages where unification variables are first class terms, i.e. they have a concrete syntax. We keep these languages minimal, for example, we omit the all quantifier of DTT we used in the example in Section 1 together with the type notation of terms carried by the lam constructor.

```
kind fm type.          kind tm type.
type fapp list fm -> fm. type app list tm -> tm.
type flam (fm -> fm) -> fm. type lam (tm -> tm) -> tm.
type fcon string -> fm.   type con string -> tm.
type fuva addr -> fm.     type uva addr -> list tm -> tm.
```

Figure 1: The \mathcal{F}_0 and \mathcal{H}_0 languages

Unification variables (fuva term constructor) in \mathcal{F}_0 have no explicit scope: the arguments of an higher order variable are given via the fapp constructor. For example the term $P \ x$ is represented as $fapp[fuva \ N, \ x]$, where N is a memory address and x is a bound variable.

In \mathcal{H}_0 the representation of $P \ x$ is instead $uva \ N \ [x]$, since unification variables come equipped with an explicit scope. We say that the unification variable occurrence $uva \ N \ L$ is in \mathcal{L}_λ if and only if

L is made of distinct names. The predicate to test this condition is called pattern-fragment:

```
type pattern-fragment list A -> o.
```

The name builtin predicate tests if a term is a bound variable.²

In both languages unification variables are identified by a natural number representing a memory address. The memory and its associated operations are described below:

```
kind addr type.
type addr nat -> addr.
typeabbrev (mem A) (list (option A)).
```

```
type set? addr -> mem A -> A -> o.
type unset? addr -> mem A -> o.
type assign addr -> mem A -> A -> mem A -> o.
type new mem A -> addr -> mem A -> o.
```

If a memory cell is none, then the corresponding unification variable is not set. assign sets an unset cell to the given value, while new finds the first unused address and sets it to none.

Since in \mathcal{H}_0 unification variables have a scope, their solution needs to be abstracted over it to enable the instantiation of a single solution to different scopes. This is obtained via the inctx container, and in particular via its abs binding constructor. On the contrary a solution to a \mathcal{F}_0 variable is a plain term.

```
typeabbrev fsubst (mem fm).
```

```
kind inctx type -> type.
type abs (tm -> inctx A) -> inctx A.
type val A -> inctx A.
typeabbrev assignment (inctx tm).
typeabbrev subst (mem assignment).
```

We call fsubst the memory of \mathcal{F}_0 , while we call subst the one of \mathcal{H}_0 . Both have the invariant that they are not cyclic, TODO explain. Other invariant: the terms in ho_subst never contains eta and beta expansion

```
kind arity type.
type arity nat -> arity.
```

```
kind fvariable type.
type fv addr -> fvariable.
```

```
kind hvariable type.
type hv addr -> arity -> hvariable.
```

```
kind mapping type.
type mapping fvariable -> hvariable -> mapping.
typeabbrev mmap (list mapping).
```

INVARIANT 1 (UNIFICATION VARIABLE ARITY). *Each variable A in \mathcal{H}_0 has a (unique) arity N and each occurrence $(uva \ A \ L)$ is such that $(len \ L \ N)$ holds*

The compiler establishes a mapping between variables of the two languages. In order to preserve invariant 1 we store the arity of

²one could always load name x for every x under a π and get rid of the name builtin

each hvariable in the mapping and we reuse an existing mapping only if the arity matches.

```

type m-alloc fvariable -> hvariable -> mmap -> mmap ->
  subst -> subst -> o.
m-alloc Fv Hv Map Map S S :- mem Map (mapping Fv Hv), !.
m-alloc Fv Hv Map [mapping Fv Hv|Map] S S1 :- Hv = hv N _,
  alloc S N S1.

```

When a single fvariable occurs multiple times with different numbers of arguments the compiler generates multiple mappings for it, on a first approximation, and then makes the mapping bijective by introducing link- η ; this detail is discussed in section 6.1.

As we mentioned in section 2.1 the compiler replaces terms in $\diamond\beta$ and $\diamond\beta$ with fresh variables linked to the problematic terms. Each class of problematic terms has a dedicated link.

```

kind baselink type.
type link-eta tm -> tm -> baselink.
type link-beta tm -> tm -> baselink.
typeabbrev link (inctx baselink).
typeabbrev links (list link).

```

INVARIANT 2 (LINK LEFT HAND SIDE). *The left hand side of a new link is a flexible term.*

The right hand side of a link, the problematic term, can occur under binders. To accommodate this situation the compiler wraps baselink using the inctx container.

4.1 Notational conventions

When we write \mathcal{H}_o terms outside code blocks we follow the usual λ -calculus notation, reserving f, g, a, b for constants, x, y, z for bound variables and X, Y, Z, F, G, H for unification variables. However we need to distinguish between the “application” of a unification variable to its scope and the application of a term to a list of arguments. We write the scope of unification variables in subscript while we use juxtaposition for regular application. Here a few examples:

```

f a      app[con "f", con "a"]
 $\lambda x.F_x a$    lam x\ app[uva F [x], con "a"]
 $\lambda x.\lambda y.F_{xy}$  lam x\ lam y\ uva F [x, y]
 $\lambda x.F_x x$    lam x\ app[uva F [x], x]

```

When detailing examples we write links as equations between terms under a context. The equality sign is subscripted with kind of baselink. For example $x \vdash A =_{\beta} F_x a$ corresponds to:

```
abs x\ val (link-beta (uva A []) (app[uva F [x], con "a"]))
```

4.2 Equational theory and Unification

In order to express properties ?? we need to equip \mathcal{F}_o and \mathcal{H}_o with term equality, substitution application and unification.

Term equality: $=_o$ vs. $=_{\lambda}$. We extend the equational theory over ground terms to the full languages by adding the reflexivity of unification variables (a variable is equal to itself).

The first four rules are common to both equalities and correspond to α -equivalence. In addition to that $=_o$ has rules for η and β -equivalence.

```

type (=o) fm -> fm -> o. (=o)
fcon X =o fcon X.
fapp A =o fapp B :- forall2 (=o) A B.
flam F =o flam G :- pi x\ x =o x => F x =o G x.
fuva N =o fuva N.
flam F =o T :-
  pi x\ beta T [x] (T' x), x =o x => F x =o T' x. ( $\eta_l$ )
T =o flam F :-
  pi x\ beta T [x] (T' x), x =o x => T' x =o F x. ( $\eta_r$ )
fapp [flam X | L] =o T :- beta (flam X) L R, R =o T. ( $\beta_l$ )
T =o fapp [flam X | L] :- beta (flam X) L R, T =o R. ( $\beta_r$ )

type (=λ) tm -> tm -> o.
con C =λ fcon C.
app A =λ fapp B :- forall2 (=λ) A B.
lam F =λ flam G :- pi x\ x =λ x => F x =λ G x.
uva N A =λ fuva N B :- forall2 (=λ) A B.

```

The main point in showing these equality tests is to remark how weaker $=_{\lambda}$ is, and to identify the four rules that need special treatment in the implementation of $=_{\lambda}$.

For reference, (β_r) reduces away lam nodes in head position in T whenever the list A provides a corresponding argument.

```

type beta fm -> list fm -> fm -> o.
beta A [] A.
beta (flam Bo) [H | L] R :- beta (Bo H) L R.
beta (fapp A) L (fapp X) :- append A L X.
beta (fuva N) L (fapp [fuva N | L]).
beta (fcon H) L (fapp [fcon H | L]).
beta N L (fapp [N | L]) :- name N.

```

The name predicate holds only on nominal constants (i.e. bound variables). Elpi provides it as a builtin, but one could implement it by systematically loading the hypothetical rule $\text{name } x$ every time a nominal constant is postulated via $\text{pi } x \backslash$.

Substitution application: ρ_s and σ_t . Applying the substitution corresponds to dereferencing a term with respect to the memory. To ease the comparison we split \mathcal{F}_o dereferencing into a fder step and a napp one. The former step replaces references to memory cells that are set with their values, ans has a corresponding operation in \mathcal{H}_o , namely deref. On the contrary napp, in charge of “flattening” fapp nodes, has no corresponding operation in \mathcal{H}_o . The reasons for this asymmetry is that an fapp node with a flexible head is always mapped to a uva (as per sections ??), preventing nested applications to materialize.

```

type fder fsubst -> fm -> fm -> o.
fder _ (fcon C) (fcon C).
fder S (fapp A) (fapp B) :- map (fder S) A B.
fder S (flam F) (flam G) :-
  pi x\ fder S x x => fder S (F x) (G x).
fder S (fuva N) R :- set? N S T, fder S T R.
fder S (fuva N) (fuva N) :- unset? N S.

```

```

type fderef fsubst -> fm -> fm -> o. ( $\rho_s$ )
fderef S T T2 :- fder S T T1, napp T1 T2.

```

```

type napp fm -> fm -> o.

```

```

581 napp (fcon C) (fcon C).
582 napp (fuva A) (fuva A).
583 napp (flam F) (flam F1) :-
584   pi x\ napp x x => napp (F x) (F1 x).
585 napp (fapp [fapp L1 |L2]) T :- !,
586   append L1 L2 L3, napp (fapp L3) T.
587 napp (fapp L) (fapp L1) :- map napp L L1.

```

TODO: about the cut

```

590 type deref subst -> tm -> tm -> o. (σt)
591 deref _ (con C) (con C).
592 deref S (app A) (app B) :- map (deref S) A B.
593 deref S (lam F) (lam G) :-
594   pi x\ deref S x x => deref S (F x) (G x).
595 deref S (uva N L) R :- set? N S A,
596   move A L T, deref S T R.
597 deref S (uva N A) (uva N B) :- unset? N S,
598   map (deref S) A B.
599
600 type move assignment -> list tm -> tm -> o.
601 move (abs Bo) [H|L] R :- move (Bo H) L R.
602 move (val A) [] A.

```

Note that move strongly relies on invariant 1: the length of the arguments of all occurrences of a unification variable and the number of abstractions in its assignment have to match.

Term unification: \approx_o vs. \approx_λ . In this paper we assume to have an implementation of \approx_λ that satisfies properties 1 and 2. Although we provide an implementation in the appendix (that we used for testing purposes) we only describe its signature here. Elpi is expected to provide this brick, as well as any other implementation of λ Prolog.

```

613 type (≈λ) tm -> tm -> subst -> subst -> o.

```

The only detail worth discussing is the fact that the procedure updates a substitution, rather than just crafting one as presented in section 2. The reason is that the algorithm folds over a term, updating a substitution while it traverses it.

explain
better

5 BASIC SIMULATION OF \mathcal{F}_0 IN \mathcal{H}_0

In this section we describe a basic compilation scheme that we refine later, in the following sections. This scheme is sufficient to implement an \approx_o that respects β -conversion for terms in \mathcal{L}_λ . The extension to $\eta\beta$ -conversion is described in Section 6.1 and the support for terms outside \mathcal{L}_λ in Section 6.2.

5.1 Compilation

The objective of the compilation is to recognize the higher-order variables available in \mathcal{H}_0 when expressed in a first order way in \mathcal{F}_0 . The compiler also generates a map to bring back the substitution from \mathcal{H}_0 to \mathcal{F}_0 .

```

633 type m-alloc fvariable -> hvariable -> mmap -> mmap ->
634   subst -> subst -> o.
635 m-alloc Fv Hv Map Map S S :- mem Map (mapping Fv Hv), !.
636 m-alloc Fv Hv Map [mapping Fv Hv|Map] S S1 :- Hv = hv N _,
637   alloc S N S1.

```

The signature of the comp predicate below allows for the generation of links (suspended unification problems) that play no role in this section but play a major role in Sections 6.1 and 6.2.

```

type comp fm -> tm -> mmap -> mmap -> links -> links ->
  subst -> subst -> o.
comp (fcon C) (con C)      M1 M1 L1 L1 S1 S1.
comp (flam F) (lam F1)     M1 M2 L1 L2 S1 S2 :-
  comp-lam F F1 M1 M2 L1 L2 S1 S2.
comp (fuva A) (uva B [J])  M1 M2 L L S S1 :-
  m-alloc (fv A) (hv B (arity z)) M1 M2 S S1.
comp (fapp [fuva A|Ag]) (uva B Ag1) M1 M2 L1 L1 S1 S2 :-
  pattern-fragment Ag, !,
  fold6 comp Ag Ag1 M1 M1 L1 L1 S1 S1,
  len Ag Arity,
  m-alloc (fv A) (hv B (arity Arity)) M1 M2 S1 S2.
comp (fapp A) (app A1)     M1 M2 L1 L2 S1 S2 :-
  fold6 comp A A1 M1 M2 L1 L2 S1 S2.

```

This preliminary version of comp simply recognizes \mathcal{F}_0 variables applied to a (possibly empty) duplicate free list of names (i.e. pattern-fragment detects variables in \mathcal{L}_λ). Note that compiling Ag cannot create new mappings nor links, see the comp-lam hyp rule.

The auxiliary function close-links

```

type comp-lam (fm -> fm) -> (tm -> tm) ->
  mmap -> mmap -> links -> links -> subst -> subst -> o.
comp-lam F F1 M1 M2 L L2 S S1 :-
  pi x y\ (pi M L S\ comp x y M M L L S S) =>
  comp (F x) (F1 y) M1 M2 L (L1 y) S S1,
  close-links L1 L2.

type close-links (tm -> links) -> links -> o.
close-links (_[]) [].
close-links (v[L|XS v]) [L|YS] :- !, close-links XS YS.
close-links (v[(L v)|XS v]) [abs L|YS] :- !,
  close-links XS YS.

```

since we want links to bubble up we use the abs constructor of the inctx data type to bind back the variable just crossed, and we do so only if the variable v occurs in L.

5.2 Execution

5.3 Decompile

5.4 Example

OK

```

Terms [ flam x\ fapp[fcon"g",fapp[fuva z, x]]
      , flam x\ fapp[fcon"g", fcon"a"] ]
Problems = [ pr z (s z) ] % λx.g(Fx) = λx.ga
lam x\ app[con"g",uva z [x]] ≈o lam x\ app[con"g", con"a"]
link z z (s z)
HS = [some (abs x\con"a")]
S = [some (flam x\fcon a)]

```

KO

```

Terms [ flam x\ fapp[fcon"g",fapp[fuva z, x]]
      , flam x\ fapp[fcon"g", fcon"a"] ]
Problems = [ pr 0 1 % A = λx.x

```

```

697     , pr 2 3 ] % Aa = a
698   lam x\ app[con"g",uva z [x]] ≈o lam x\ app[con"g", con"a"]
699   link z z (s z)
700   HS = [some (abs x\con"a")]
701   S = [some (flam x\fcon a)]
702   lam x\ app[f, app[X, x]] = Y,
703     lam x\ x[] = X.

```

TODO: Goal: $s_1 \approx_o s_2$ is compiled into $t_1 \approx_\lambda t_2$

TODO: What is done: uvars fo_uv of OL are replaced into uvars ho_uv of the ML

TODO: Each fo_uv is linked to an ho_uv of the OL

TODO: Example needing the compiler v0 (tra l'altro lo scope è ignorato):

```
lam x\ app[con"g",app[uv 0, x]] ≈o lam x\ app[con"g", c"a"]
```

TODO: Links used to instantiate vars of elpi

TODO: After all links, the solution in links are compacted and given to coq

TODO: It is not so simple, see next sections (multi-vars, eta, beta)

The compilation step is meant to recover the higher-order variables of the OL, expressed in a first order way, by replacing them with higher-order variables in the ML. In particular, every time a variable of the OL is encountered in the original term, it is replaced with a meta variable, and if the OL variable is applied to a list of distinct names L , then this list becomes the scope of the variable. For all the other constructors of tm , the same term constructor is returned and its arguments are recursively compiled. The predicate in charge for term compilation is:

```
type comp tm -> tm -> links -> links -> subst -> subst -> o.
```

where, we take the term of the OL, produce the term of the ML, take a list of link and produce a list of new links, take a substitution and return a new substitution.

In particular, due to programming constraints, we need to drag the old subst and return a new one extended, if needed, with the new declared meta-variables.

The following code

```
kind link type.
type link nat -> nat -> nat -> subst.
```

defines a link, which is a relation between to variables indexes, the first being the index of a OL variable and the second being the index of a ML variable. The third integer is the number of term in the scope of the two variables, or equivalently, in a typed language, their arity.

As an example, let's study the following unification problem (a slightly modified version from section 1):

```
lam x\ app[c"decision", app[c"nfact", x, c"3"]] ≈o
lam x\ app [c"decision", app[uv 0, x]]
```

we have the main unification problem where the nested app nodes have lists of different lengths making the unification to fail. The compilation of these terms produces a new unification problem with the following shape:

```
lam x\ app[c"decision", app[c"nfact", x, c"3"]] ≈λ
lam x\ app [c"decision", uv 1 [x]]
```

The main difference is the replacement of the subterm $app[uv\ 0, x]$ of the OL with the subterm $uv\ 0\ [x]$. Variable indexes are chosen by the ML, that is, the index 0 for that unification variable of the OL term has not the same meaning of the index 0 in the ML. There exists two different substitution mapping, one for the OL and one for the ML and the indexes of variable point to the respective substitution.

decomp che mappa abs verso lam **TODO: An other example:**

```
lam x\ app[f, app[X, x]] = Y, (lam x\ x) = X.
```

6 USE OF MULTIVARS

Se il termine iniziale è della forma

```
app[con"xxx", (lam x\ lam y\ Y y x), (lam x\ f)]
=
app[con"xxx",X,X]
```

allora se non uso due X diverse non ho modo di recuperare il quoziente che mi manca.

a sto punto consideriamo liste di problemi e così da eliminare sta xxx senza perdita di generalità (e facciamo problemi più corti, e modellizziamo anche la sequenza)

6.1 Problems with η

```
comp (flam F) (uva A Scope) M1 M2 L1 L3 S1 S3 :-
(pi x\ maybe-eta x (F x) [x]), !,
alloc S1 A S2,
comp-lam F F1 M1 M2 L1 L2 S2 S3,
get-scope (lam F1) Scope,
L3 = [eval-link-eta (uva A Scope) (lam F1) L2].
```

and aux

```
%% x occurs rigidly in t iff  $\forall \sigma, \forall t', t' =_o \sigma t \Rightarrow x \in \mathcal{P}(t')$ 
%%
```

```
type occurs-rigidly fm -> fm -> o.
```

```
occurs-rigidly N N.
```

```
occurs-rigidly _ (fapp [fuva _]_) :- !, fail.
```

```
occurs-rigidly N (fapp L) :- exists (occurs-rigidly N) L.
```

```
occurs-rigidly N (flam B) :- pi x\ occurs-rigidly N (B x).
```

```
/* maybe-eta N T L succeeds iff T could be an eta expasions for N, that
```

```
%% is  $\exists \sigma, \sigma(\lambda n.t) = \lambda n.t'n$  and n
```

```
%% does not occur rigidly in t'
```

```
type maybe-eta fm -> fm -> list fm -> o.
```

```
maybe-eta N (fapp [fuva _]Args) _ :- !,
```

```
exists (x\ maybe-eta-of [ ] N x) Args, !.
```

```
maybe-eta N (flam B) L :- !, pi x\ maybe-eta N (B x) [x | L].
```

```
maybe-eta _ (fapp [fcon _]Args) L :-
```

```
split-last-n {len L} Args First Last,
```

```
forall1 (x\ forall1 (y\ not (occurs-rigidly x y)) First) L,
```

```
forall2 (maybe-eta-of [ ]) {rev L} Last.
```

```
%% is  $\exists \sigma, \sigma t =_o n$ 
```

```
type maybe-eta-of list fm -> fm -> fm -> o.
```

```
maybe-eta-of _ N N :- !.
```

```
maybe-eta-of L N (fapp [fuva _]Args) :- !,
```

```
forall1 (x\ exists (maybe-eta-of [ ] x) Args) [N|L].
```

```
maybe-eta-of L N (flam B) :- !,
```

integer
or
nat?

```

pi x\ maybe-eta-of [x | L] N (B x).
maybe-eta-of L N (fapp [N|Args]) :-
  last-n {len L} Args R,
  forall12 (maybe-eta-of []) R {rev L}.

```

TODO: The following goal necessita v1 (lo scope è usato):

$$X = \lambda x. \lambda y. Y y x, X = \lambda x. f$$

TODO: The snd unif pb, we have to unif $\text{lam } x \setminus \text{lam } y \setminus Y \ x \ y$
with $\text{lam } x \setminus f$

TODO: It is not doable, with the same elpi var

Invarianti: A destra della eta abbiamo sempre un termine che comincia per $\lambda x.bla$

La deduplicate eta:

- viene chiamata che della forma [variable] -> [eta1] e
↳ [variable] -> [eta2]
(a destra non c'è mai un termine con testa rigida)
- i due termini a dx vengono unificati con la unif e uno
↳ dei due link viene buttato

NOTA!! A dx abbiamo sempre un termine della forma lam
↳ x.VAR x!!!

Altrimenti il link sarebbe stato risolto!!

- dopo l'unificazione rimane un link [variabile] -> [etaX]
- nella progress-eta, se a sx abbiamo una costante o
↳ un'app, allora eta-espandiamo
di uno per poter unificare con il termine di dx.

6.2 Problems with β

β -reduction problems ($\diamond\beta$) appears any time we deal with a subterm $t = X t_1 \dots t_n$, where X is flexible and the list $[t_1 \dots t_n]$ is not in \mathcal{L}_λ . This unification problem is not solvable without loss of generality, since there is not a most general unifier. If we take back the example given in section 2.1, the unification $Fa = a$ admits two solutions for F : $\rho_1 = \{F \mapsto \lambda x.x\}$ and $\rho_2 = \{F \mapsto \lambda_{-}a\}$. Despite this, it is possible to work with $\diamond\beta$ if an oracle provides a substitution ρ such that ρt falls again in the \mathcal{L}_λ .

On the other hand, the \approx_λ is not designed to understand how the β -redexes work in the object language. Therefore, even if we know that F is assigned to $\lambda x.x$, \approx_λ is not able to unify Fa with a . On the other hand, the problem $Fa = G$ is solvable by \approx_λ , but the final result is that G is assigned to $(\lambda x.x)a$ which breaks the invariant saying that the substitution of the meta language does not generate terms outside \mathcal{W} (Property 2.8).

The solution to this problem is to modify the compiler such that any sub-term t considered as a potential β -redex is replaced with a hole h and a new dedicated link, called `link- β` .

```
type link-beta tm -> tm -> link.
```

This link carries two terms, the former representing the variable h for the new created hole and the latter containing the subterm t . As for the link- η , we will call h and t respectively the left hand side (*lhs*) and the right hand side (*rhs*) of the link- β .

In order to build a link- β , we need to adapt the compiler so that it can recognize these “problematic” subterms. The following code snippet illustrate such behavior, we suppose the rule to be added just after ??.

```

comp (fapp [fuva A|Ag]) (uva C Scope) M1 M3 L1 L3 S1 S4 :- !,      871
  pattern-fragment-prefix Ag Pf Extra,                             872
fold6 comp Pf      Scope1 M1 M1 L1 L1 S1 S1,                       873
fold6 comp Extra Extra1 M1 M2 L1 L2 S1 S2,                         874
len Pf Arity,                                                       875
m-alloc (fv A) (hv B (arity Arity)) M2 M3 S2 S3,                 876
Beta = app [uva B Scope1 | Extra1],                                877
get-scope Beta Scope,                                              878
alloc S3 C S4,                                                     879
L3 = [@eval-link-beta (uva C Scope) Beta | L2].                   880

```

A term is $\diamond \beta$ if it has the shape $\text{fapp}[\text{fuva } A | \text{Ag}]$ and $\text{distinct } Ag$ does not hold. In that case, Ag is split in two sublist Pf and Extra such that former is the longest prefix of Ag such that $\text{distinct } Pf$ holds. Extra is the list such that $\text{append } Pf \text{ Extra } Ag$. Next important step is to compile recursively the terms of these lists and allocate a memory adress B from the substitution in order to map the \mathcal{F}_0 variable $\text{fuva } A$ to the \mathcal{H}_0 variable $\text{uva } B$. The link- β to return in the end is given by the term $\text{Beta} = \text{app}[\text{uva } B \text{ Scope1 } | \text{Extra1}]$ constituting the *rhs*, and a fresh variable C having in scope all the free variables occurring in Beta (this is *lhs*). We point out that the *rhs* is intentionally built as an *uva* where Extra1 are not in scope, since by invariant, we want all the variables appearing in \mathcal{H}_0 to be in \mathcal{L}_λ .

One created, there exist two main situations waking up a suspended $\text{link-}\beta$. The former is strictly connected to the definition of β -redex and occurs when the head of rhs is materialized by the oracle (see eq. (5)). In this case rhs is safely β -reduced to a new term t' and the result can be unified with lhs . In this scenario the $\text{link-}\beta$ has accomplished its goal and can be removed from \mathbb{L} .

The second circumstance making the link- β to progress is the instantiation of the variables in the `Extra1` making the corresponding arguments to reduce to names. In this case, we want to take the list `Scope1` and append to it the largest prefix of `Extra1` in a new variable `Scope2` such that `Scope2` remains in \mathcal{L}_λ ; we call `Extra2` the suffix of `Extra1` such that the concatenation of `Scope1` and `Extra1` is the same as the concatenation of `Scope2` and `Extra2`.

An example justifying this last link manipulation is given by the following unification problem:

```
f = flam x\ fapp[F, (X x), a] %  $f = \lambda x.F(Xx)a$ 
```

under the substitution $\rho = \{X \mapsto \lambda x.x\}$.

The links generated from this unification problem are:

$$X \mapsto X1^1; F \mapsto X2^0(\text{Themap}) \quad (6)$$

$$\vdash X0 =_{\eta} \lambda x.X3_x \quad (7)$$

$$x \vdash X3_x =_\beta X2 X1_x a \quad (8)$$

where the first link is a link- η between the variable X_0 , representing the right side of the unification problem (it is a $\diamond\eta$) and X_3 ; and a link- β between the variable X_3 and the subterm $\lambda x.X_1 x$ a (it is a $\diamond\beta$). The substitution tells that $x \vdash X_1 x = x$.

We can now represent the hrn execution from this configuration which will, at first, dereference all the links, and then try to solve them. The only link being modified is the second one, which is set to $x \vdash X3 =_{\beta} X2xa$. The *rhs* of the link has now a variable which is partially in the PF, we can therefore remove the original link- β and replace it with the following couple on links:

896 explain
897 why
898
899
900
901
902
903
904
905 A bit
906 too
907 fast,
908 we
909 first
910 com-
911 pile,
912 then
913 unify,
914 then
915
916 oracle,
917 then
918 the
919 ma-
920 nip...


```

  ⊢ X1 =η= x\ `X4 x'
x ⊢ X3 x =β= x\ `X4 x' a

```

By these links we say that $X1$ is now η -linked to a fresh variable $X4$ with arity one. This new variable is used in the new link- β where the name x is in its scope. This allows

6.3 Tricky examples

```

triple ok (@lam x\ @app[@f, @app[@X, x]]) @Y,
triple ok @X (@lam x\ x),
triple ok @Y @f

%ok1 22 [
% triple ok (@lam x\ @lam y\ @app[@Y, y, x]) @X,
% triple ok (@lam x\ @f) @X,
% ].

```

7 FIRST ORDER APPROXIMATION

TODO: Coq can solve this: $f \ 1 \ 2 = x \ 2$, by setting X to $f \ 1$

TODO: We can re-use part of the algo for β given before

8 UNIF ENCODING IN REAL LIFE

TODO: Il ML presentato qui è esattamente elpi

TODO: Il OL presentato qui è esattamente coq

TODO: Come implementiamo tutto ciò nel solver

9 RESULTS: STDPP AND TLC

TODO: How may rule are we solving?

TODO: Can we do some perf test

10 CONCLUSION

REFERENCES

- [1] Arthur Charguéraud. “The Optimal Fixed Point Combinator”. In: *Interactive Theorem Proving*. Ed. by Matt Kaufmann and Lawrence C. Paulson. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 195–210. ISBN: 978-3-642-14052-5.
- [2] Cvetan Dunchev, Claudio Sacerdoti Coen, and Enrico Tassi. “Implementing HOL in an Higher Order Logic Programming Language”. In: *Proceedings of the Eleventh Workshop on Logical Frameworks and Meta-Languages: Theory and Practice*. LFMTTP '16. Porto, Portugal: Association for Computing Machinery, 2016. ISBN: 9781450347778. DOI: 10.1145/2966268.2966272. URL: <https://doi.org/10.1145/2966268.2966272>.
- [3] Cvetan Dunchev et al. “ELPI: Fast, Embeddable, λ Prolog Interpreter”. In: *Logic for Programming, Artificial Intelligence, and Reasoning - 20th International Conference, LPAR-20 2015, Suva, Fiji, November 24-28, 2015, Proceedings*. Ed. by Martin Davis et al. Vol. 9450. 2015, pp. 460–468. DOI: 10.1007/978-3-662-48899-7_32. URL: http://dx.doi.org/10.1007/978-3-662-48899-7_32.
- [4] Amy Felty. “Encoding the Calculus of Constructions in a Higher-Order Logic”. In: ed. by M. Vardi. IEEE, June 1993, pp. 233–244. DOI: 10.1109/LICS.1993.287584.
- [5] Amy Felty and Dale Miller. “Specifying theorem provers in a higher-order logic programming language”. In: *Ninth International Conference on Automated Deduction*. Ed. by Ewing Lusk and Ross Overbeck. 310. Argonne, IL: Springer, May 1988, pp. 61–80. DOI: 10.1007/BFb0012823.
- [6] Davide Fissore and Enrico Tassi. “A new Type-Class solver for Coq in Elpi”. In: *The Coq Workshop 2023*. Bialystok, Poland, July 2023. URL: <https://inria.hal.science/hal-04467855>.
- [7] Benjamin Grégoire, Jean-Christophe L  chenet, and Enrico Tassi. “Practical and sound equality tests, automatically – Deriving eqType instances for Jasmin’s data types with Coq-Elpi”. In: *CPP '23: 12th ACM SIGPLAN International Conference on Certified Programs and Proofs*. CPP 2023: Proceedings of the 12th ACM SIGPLAN International Conference on Certified Programs and Proofs. Boston MA USA, France: ACM, Jan. 2023, pp. 167–181. DOI: 10.1145/3573105.3575683. URL: <https://inria.hal.science/hal-03800154>.
- [8] RALF JUNG et al. “Iris from the ground up: A modular foundation for higher-order concurrent separation logic”. In: *Journal of Functional Programming* 28 (2018), e20. DOI: 10.1017/S0956796818000151.
- [9] Dale Miller. “Unification under a mixed prefix”. In: *Journal of Symbolic Computation* 14.4 (1992), pp. 321–358. DOI: 10.1016/0747-7171(92)90011-R.
- [10] Dale Miller and Gopalan Nadathur. *Programming with Higher-Order Logic*. Cambridge University Press, 2012. DOI: 10.1017/CBO9781139021326.
- [11] Tobias Nipkow, Lawrence C. Paulson, and Markus Wenzel. *Isabelle/HOL - A Proof Assistant for Higher-Order Logic*. Vol. 2283. Lecture Notes in Computer Science. Springer, 2002. ISBN: 3-540-43376-7.
- [12] Lawrence C. Paulson. “Set theory for verification. I: from foundations to functions”. In: *J. Autom. Reason.* 11.3 (Dec. 1993), pp. 353–389. ISSN: 0168-7433. DOI: 10.1007/BF00881873. URL: <https://doi.org/10.1007/BF00881873>.
- [13] F. Pfenning. “Elf: a language for logic definition and verified metaprogramming”. In: *Proceedings of the Fourth Annual Symposium on Logic in Computer Science*. Pacific Grove, California, USA: IEEE Press, 1989, pp. 313–322. ISBN: 0818619546.
- [14] Frank Pfenning and Carsten Sch  rmann. “System Description: Twelf – A Meta-Logical Framework for Deductive Systems”. In: *Automated Deduction – CADE-16*. Berlin, Heidelberg: Springer Berlin Heidelberg, 1999, pp. 202–206. ISBN: 978-3-540-48660-2.
- [15] Colin Rothgang, Florian Rabe, and Christoph Benzm  ller. “Theorem Proving in Dependently-Typed Higher-Order Logic”. In: *Automated Deduction – CADE 29*. Ed. by Brigitte Pientka and Cesare Tinelli. Cham: Springer Nature Switzerland, 2023, pp. 438–455. ISBN: 978-3-031-38499-8.
- [16] Enrico Tassi. “Deriving proved equality tests in Coq-elpi: Stronger induction principles for containers in Coq”. In: *ITP 2019 - 10th International Conference on Interactive Theorem Proving*. Portland, United States, Sept. 2019. DOI: 10.4230/LIPIcs.CVIT.2016.23. URL: <https://inria.hal.science/hal-01897468>.
- [17] Enrico Tassi. “Elpi: an extension language for Coq (Metaprogramming Coq in the Elpi λ Prolog dialect)”. In: *The Fourth*

- [18] The Coq Development Team. *The Coq Reference Manual – Release 8.18.0*. <https://coq.inria.fr/doc/V8.18.0/refman>. 2023.
- [19] P. Wadler and S. Blott. “How to Make Ad-Hoc Polymorphism Less Ad Hoc”. In: *Proceedings of the 16th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*. POPL ’89. Austin, Texas, USA: Association for Computing Machinery, 1989, pp. 60–76. ISBN: 0897912942. DOI: 10.1145/75277.75283. URL: <https://doi.org/10.1145/75277.75283>.
- [20] Makarius Wenzel, Lawrence C. Paulson, and Tobias Nipkow. “The Isabelle Framework”. In: *Theorem Proving in Higher Order Logics*. Ed. by Otmane Ait Mohamed, César Muñoz, and Sofiène Tahar. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 33–38. ISBN: 978-3-540-71067-7.

APPENDIX

This appendix contains the entire code described in this paper. The code can also be accessed at the URL: <https://github.com/FissoreD/paper-ho>

Note that (a infix b) c d de-sugars to (infix) a b c d.

Explain builtin name (can be implemented by loading name after each pi)

11 THE MEMORY

```

kind addr type.
type addr nat -> addr.
typeabbrev (mem A) (list (option A)).

type set? addr -> mem A -> A -> o.
set? (addr A) Mem Val :- get A Mem Val.

type unset? addr -> mem A -> o.
unset? Addr Mem :- not (set? Addr Mem _).

type assign-aux nat -> mem A -> A -> mem A -> o.
assign-aux z (none :: L) Y (some Y :: L).
assign-aux (s N) (X :: L) Y (X :: L1) :- assign-aux N L Y L1.

type assign addr -> mem A -> A -> mem A -> o.
assign (addr A) Mem1 Val Mem2 :- assign-aux A Mem1 Val Mem2.

type get nat -> mem A -> A -> o.
get z (some Y :: _) Y.
get (s N) (_ :: L) X :- get N L X.

type alloc-aux nat -> mem A -> mem A -> o.
alloc-aux z [] [none] :- !.
alloc-aux z L L.
alloc-aux (s N) [] [none | M] :- alloc-aux N [] M.
alloc-aux (s N) [X | L] [X | M] :- alloc-aux N L M.

type alloc addr -> mem A -> mem A -> o.
alloc (addr A as Ad) Mem1 Mem2 :- unset? Ad Mem1,
  alloc-aux A Mem1 Mem2.

type new-aux mem A -> nat -> mem A -> o.
new-aux [] z [none].
new-aux [A | As] (s N) [A | Bs] :- new-aux As N Bs.

type new mem A -> addr -> mem A -> o.
new Mem1 (addr Ad) Mem2 :- new-aux Mem1 Ad Mem2.

```

12 THE OBJECT LANGUAGE

```

kind fm type.
type fapp list fm -> fm.
type flam (fm -> fm) -> fm.
type fcon string -> fm.
type fuva addr -> fm.

typeabbrev fsubst (mem fm).

```

```

type fder fsubst -> fm -> fm -> o.
fder _ (fcon C) (fcon C).
fder S (fapp A) (fapp B) :- map (fder S) A B.
fder S (flam F) (flam G) :-
  pi x\ fder S x x => fder S (F x) (G x).
fder S (fuva N) R :- set? N S T, fder S T R.
fder S (fuva N) (fuva N) :- unset? N S.

type fderef fsubst -> fm -> fm -> o. (ps)
fderef S T T2 :- fder S T T1, napp T1 T2.

```

```

type napp fm -> fm -> o.
napp (fcon C) (fcon C).
napp (fuva A) (fuva A).
napp (flam F) (flam F1) :-
  pi x\ napp x x => napp (F x) (F1 x).
napp (fapp [fapp L1 | L2]) T :- !,
  append L1 L2 L3, napp (fapp L3) T.
napp (fapp L) (fapp L1) :- map napp L L1.

```

```

type (=o) fm -> fm -> o. (=o)
fcon X =o fcon X.
fapp A =o fapp B :- forall2 (=o) A B.
flam F =o flam G :- pi x\ x =o x => F x =o G x.
fuva N =o fuva N.
flam F =o T :- (eta)
  pi x\ beta T [x] (T' x), x =o x => F x =o T' x.
T =o flam F :- (eta_r)
  pi x\ beta T [x] (T' x), x =o x => T' x =o F x.
fapp [flam X | L] =o T :- beta (flam X) L R, R =o T. (beta_l)
T =o fapp [flam X | L] :- beta (flam X) L R, T =o R. (beta_r)

```

```

type extend-subst fm -> fsubst -> fsubst -> o.
extend-subst (fuva N) S S' :- mem.alloc N S S'.
extend-subst (flam F) S S' :-
  pi x\ (pi S\ extend-subst x S S) => extend-subst (F x) S S'.
extend-subst (fcon _) S S.
extend-subst (fapp L) S S1 :- fold extend-subst L S S1.

```

```

type beta fm -> list fm -> fm -> o.
beta A [] A.
beta (flam Bo) [H | L] R :- beta (Bo H) L R.
beta (fapp A) L (fapp X) :- append A L X.
beta (fuva N) L (fapp [fuva N | L]).
beta (fcon H) L (fapp [fcon H | L]).
beta N L (fapp [N | L]) :- name N.

```

```

type mk-app fm -> list fm -> fm -> o.
mk-app T L S :- beta T L S.

```

```

type eta-contract fm -> fm -> o.
eta-contract (fcon X) (fcon X).
eta-contract (fapp L) (fapp L1) :- map eta-contract L L1.
eta-contract (flam F) T :- eta-contract-aux [] (flam F) T.
eta-contract (flam F) (flam F1) :-
  pi x\ eta-contract x x => eta-contract (F x) (F1 x).

```

13 THE META LANGUAGE

```

1277 eta-contract (fuva X) (fuva X).
1278 eta-contract X X := name X.
1279
1280 type eta-contract-aux list fm -> fm -> fm -> o.
1281 eta-contract-aux L (flam F) T :-
1282   pi x\ eta-contract-aux [x|L] (F x) T. % also checks H Prefix does not x
1283 eta-contract-aux L (fapp [H|Args]) T :-
1284   rev L LRev, append Prefix LRev Args,
1285   if (Prefix = []) (T = H) (T = fapp [H|Prefix]).
1286
1287
1288
1289 kind inctx type -> type.
1290 type abs (tm -> inctx A) -> inctx A.
1291 type val A -> inctx A.
1292 typeabbrev assignment (inctx tm).
1293 typeabbrev subst (mem assignment).
1294
1295 kind tm type.
1296 type app list tm -> tm.
1297 type lam (tm -> tm) -> tm.
1298 type con string -> tm.
1299 type uva addr -> list tm -> tm.
1300
1301 type (≈λ) tm -> tm -> subst -> subst -> o.
1302 (con C ≈λ con C) S S1.
1303 (app L1 ≈λ app L2) S S1 :- fold2 (≈λ) L1 L2 S S1.
1304 (lam F1 ≈λ lam F2) S S1 :-
1305   pi x\ (pi S\ (x ≈λ x) S S) => (F1 x ≈λ F2 x) S S1.
1306 (uva N Args ≈λ T) S S1 :-
1307   set? N S F,!, move F Args T1, (T1 ≈λ T) S S1.
1308 (T ≈λ uva N Args) S S1 :-
1309   set? N S F,!, move F Args T1, (T ≈λ T1) S S1.
1310 (uva M A1 ≈λ uva N A2) S1 S2 :- !,
1311   pattern-fragment A1, pattern-fragment A2,
1312   prune! M A1 N A2 S1 S2.
1313 (uva N Args ≈λ T) S S1 :- not_occ N S T, pattern-fragment Args,
1314   bind T Args T1, assign N S T1 S1.
1315 (T ≈λ uva N Args) S S1 :- not_occ N S T, pattern-fragment Args,
1316   bind T Args T1, assign N S T1 S1.
1317
1318 type prune! addr -> list tm -> addr ->
1319   list tm -> subst -> subst -> o.
1320
1321 /* no pruning needed */
1322 prune! N A N A S S :- !.
1323 prune! M A N A S1 S2 :- !, bind (uva M A) A Ass,
1324   assign N S1 Ass S2.
1325 /* prune different arguments */
1326 prune! N A1 N A2 S1 S3 :- !,
1327   new S1 W S2, prune-same-variable W A1 A2 [] Ass,
1328   assign N S2 Ass S3.
1329 /* prune to the intersection of scopes */
1330 prune! N A1 M A2 S1 S4 :- !,
1331   new S1 W S2, prune-diff-variables W A1 A2 Ass1 Ass2,
1332   assign N S2 Ass1 S3,
1333   assign M S3 Ass2 S4.
1334
1335 type prune-same-variable addr -> list tm -> list tm ->
1336   list tm -> assignment -> o.
1337 prune-same-variable N [] [] ACC (val (uva N Args)) :-
1338   rev ACC Args.
1339 prune-same-variable N [X|XS] [X|YS] ACC (abs F) :-
1340   pi x\ prune-same-variable N XS YS [x|ACC] (F x).
1341 prune-same-variable N [_|XS] [_|YS] ACC (abs F) :-
1342   pi x\ prune-same-variable N XS YS ACC (F x).
1343
1344 type permute list nat -> list tm -> list tm -> o.
1345 permute [] _ [].
1346 permute [P|PS] Args [T|TS] :-
1347   nth P Args T,
1348   permute PS Args TS.
1349
1350 type build-perm-assign addr -> list tm -> list bool ->
1351   list nat -> assignment -> o.
1352 build-perm-assign N ArgsR [] Perm (val (uva N PermutedArgs)) :-
1353   rev ArgsR Args, permute Perm Args PermutedArgs.
1354 build-perm-assign N Acc [tt|L] Perm (abs T) :-
1355   pi x\ build-perm-assign N [x|Acc] L Perm (T x).
1356 build-perm-assign N Acc [ff|L] Perm (abs T) :-
1357   pi x\ build-perm-assign N Acc L Perm (T x).
1358
1359 type keep list A -> A -> bool -> o.
1360 keep L A tt :- mem L A, !.
1361 keep _ _ ff.
1362
1363 type prune-diff-variables addr -> list tm -> list tm ->
1364   assignment -> assignment -> o.
1365 prune-diff-variables N Args1 Args2 Ass1 Ass2 :-
1366   map (keep Args2) Args1 Bits1,
1367   map (keep Args1) Args2 Bits2,
1368   filter Args1 (mem Args2) ToKeep1,
1369   filter Args2 (mem Args1) ToKeep2,
1370   map (index ToKeep1) ToKeep1 IdPerm,
1371   map (index ToKeep1) ToKeep2 Perm21,
1372   build-perm-assign N [] Bits1 IdPerm Ass1,
1373   build-perm-assign N [] Bits2 Perm21 Ass2.
1374
1375 type beta tm -> list tm -> tm -> o.
1376 beta A [] A.
1377 beta (lam Bo) [H | L] R :- beta (Bo H) L R.
1378 beta (app A) L (app X) :- append A L X.
1379 beta (con H) L (app [con H | L]).
1380 beta X L (app [X|L]) :- name X.
1381
1382 /* occur check for N before crossing a functor */
1383 type not_occ addr -> subst -> tm -> o.
1384 not_occ N S (uva M Args) :- set? M S F,
1385   move F Args T, not_occ N S T.
1386 not_occ N S (uva M Args) :- unset? M S, not (M = N),
1387   forall1 (not_occ_aux N S) Args.
1388 not_occ _ _ (con _).
1389 not_occ N S (app L) :- not_occ_aux N S (app L).
1390 /* Note: lam is a functor for the meta language! */
1391 not_occ N S (lam L) :- pi x\ not_occ_aux N S (L x).
1392

```



```

1393 not_occ _ _ X :- name X.
1394 /* finding N is ok */
1395 not_occ N _ (uva N _).
1396
1397 /* occur check for X after crossing a functor */
1398 type not_occ_aux addr -> subst -> tm -> o.
1399 not_occ_aux N S (uva M _) :- unset? M S, not (N = M).
1400 not_occ_aux N S (uva M Args) :- set? M S F,
1401   move F Args T, not_occ_aux N S T.
1402 not_occ_aux N S (app L) :- forall1 (not_occ_aux N S) L.
1403 not_occ_aux N S (lam F) :- pi x\ not_occ_aux N S (F x).
1404 not_occ_aux _ _ (con _).
1405 not_occ_aux _ _ X :- name X.
1406 /* finding N is ko, hence no rule */
1407
1408 /* copy T T' vails if T contains a free variable, i.e. it
1409   performs scope checking for bind */
1410 type copy tm -> tm -> o.
1411 copy (con C) (con C).
1412 copy (app L) (app L') :- map copy L L'.
1413 copy (lam T) (lam T') :- pi x\ copy x x => copy (T x) (T' x).
1414 copy (uva A L) (uva A L') :- map copy L L'.
1415
1416 type bind tm -> list tm -> assignment -> o.
1417 bind T [] (val T') :- copy T T'.
1418 bind T [X | TL] (abs T') :- pi x\ copy X x => bind T TL (T' x).
1419
1420 type deref subst -> tm -> tm -> o. (σt)
1421 deref _ (con C) (con C).
1422 deref S (app A) (app B) :- map (deref S) A B.
1423 deref S (lam F) (lam G) :-
1424   pi x\ deref S x x => deref S (F x) (G x).
1425 deref S (uva N L) R :- set? N S A,
1426   move A L T, deref S T R.
1427 deref S (uva N A) (uva N B) :- unset? N S,
1428   map (deref S) A B.
1429
1430 type move assignment -> list tm -> tm -> o.
1431 move (abs Bo) [H|L] R :- move (Bo H) L R.
1432 move (val A) [] A.
1433
1434 type deref-assmt subst -> assignment -> assignment -> o.
1435 deref-assmt S (abs T) (abs R) :- pi x\ deref-assmt S (T x) (R x).
1436 deref-assmt S (val T) (val R) :- deref S T R.

```

14 THE COMPILER

```

1441 kind arity type.
1442 type arity nat -> arity.
1443
1444 kind fvariable type.
1445 type fv addr -> fvariable.
1446
1447 kind hvariable type.
1448 type hv addr -> arity -> hvariable.

```

```

1451 kind mapping type.
1452 type mapping fvariable -> hvariable -> mapping.
1453 typeabbrev mmap (list mapping).
1454
1455 typeabbrev scope (list tm).
1456 typeabbrev inctx ho.inctx.
1457 kind baselink type.
1458 type link-eta tm -> tm -> baselink.
1459 type link-beta tm -> tm -> baselink.
1460 typeabbrev link (inctx baselink).
1461 typeabbrev links (list link).
1462
1463 macro @val-link-eta T1 T2 :- ho.val (link-eta T1 T2).
1464 macro @val-link-beta T1 T2 :- ho.val (link-beta T1 T2).
1465
1466 %% x occurs rigidly in t iff  $\forall \sigma, \forall t', t' =_{\sigma} \sigma t \Rightarrow x \in \mathcal{P}(t')$ 
1467 %%
1468 type occurs-rigidly fm -> fm -> o.
1469 occurs-rigidly N N.
1470 occurs-rigidly _ (fapp [fuva _|_] ) :- !, fail.
1471 occurs-rigidly N (fapp L) :- exists (occurs-rigidly N) L.
1472 occurs-rigidly N (flam B) :- pi x\ occurs-rigidly N (B x).
1473
1474 /* maybe-eta N T L succeeds iff T could be an eta expasions for N, that
1475   is  $\exists \sigma, \sigma(\lambda n.t) = \lambda n.t'n$  and n
1476   does not occur rigidly in t'
1477 type maybe-eta fm -> fm -> list fm -> o.
1478 maybe-eta N (fapp [fuva _|Args] ) :- !,
1479   exists (x\ maybe-eta-of [] N x) Args, !.
1480 maybe-eta N (flam B) L :- !, pi x\ maybe-eta N (B x) [x | L].
1481 maybe-eta _ (fapp [fcon _|Args] ) L :-
1482   split-last-n {len L} Args First Last,
1483   forall1 (x\ forall1 (y\ not (occurs-rigidly x y)) First) L,
1484   forall2 (maybe-eta-of [] ) {rev L} Last.
1485
1486 %% is  $\exists \sigma, \sigma t =_{\sigma} n$ 
1487 type maybe-eta-of list fm -> fm -> fm -> o.
1488 maybe-eta-of _ N N :- !.
1489 maybe-eta-of L N (fapp [fuva _|Args] ) :- !,
1490   forall1 (x\ exists (maybe-eta-of [] x) Args) [N|L].
1491 maybe-eta-of L N (flam B) :- !,
1492   pi x\ maybe-eta-of [x | L] N (B x).
1493 maybe-eta-of L N (fapp [N|Args] ) :-
1494   last-n {len L} Args R,
1495   forall2 (maybe-eta-of [] ) R {rev L}.
1496
1497 type locally-bound tm -> o.
1498 type get-scope-aux tm -> list tm -> o.
1499 get-scope-aux (con _) [].
1500 get-scope-aux (uva _ L) L1 :-
1501   forall2 get-scope-aux L R,
1502   flatten R L1.
1503 get-scope-aux (lam B) L1 :-
1504   pi x\ locally-bound x => get-scope-aux (B x) L1.

```

```

1509   get-scope-aux (app L) L1 :-
1510     forall2 get-scope-aux L R,
1511     flatten R L1.
1512   get-scope-aux X [X] :- name X, not (locally-bound X).
1513   get-scope-aux X [] :- name X, (locally-bound X).
1514
1515   %% TODO: scrivere undup
1516   type get-scope tm -> list tm -> o.
1517   get-scope T Scope :-
1518     get-scope-aux T ScopeDuplicata,
1519     names N, filter N (mem ScopeDuplicata) Scope.
1520   type rigid fm -> o.
1521   rigid X :- not (X = fuva _).
1522
1523   type comp-lam (fm -> fm) -> (tm -> tm) ->
1524     mmap -> mmap -> links -> links -> subst -> subst -> o.
1525   comp-lam F F1 M1 M2 L L2 S S1 :-
1526     pi x y\ (pi M L S\ comp x y M M L L S S) =>
1527       comp (F x) (F1 y) M1 M2 L (L1 y) S S1,
1528       close-links L1 L2.
1529
1530   type close-links (tm -> links) -> links -> o.
1531   close-links (_\[]) [].
1532   close-links (v\[L|XS v]) [L|YS] :- !, close-links XS YS.
1533   close-links (v\[L v]|XS v]) [abs L|YS] :- !,
1534     close-links XS YS.
1535   type comp fm -> tm -> mmap -> mmap -> links -> links ->
1536     subst -> subst -> o.
1537   comp (fcon C) (con C) M1 M1 L1 L1 S1 S1.
1538   comp (flam F) (uva A Scope) M1 M2 L1 L3 S1 S3 :-
1539     (pi x\ maybe-eta x (F x) [x]), !,
1540     alloc S1 A S2,
1541     comp-lam F F1 M1 M2 L1 L2 S2 S3,
1542     get-scope (lam F1) Scope,
1543     L3 = [@eval-link-eta (uva A Scope) (lam F1)| L2].
1544   comp (flam F) (lam F1) M1 M2 L1 L2 S1 S2 :-
1545     comp-lam F F1 M1 M2 L1 L2 S1 S2.
1546   comp (fuva A) (uva B []) M1 M2 L L S S1 :-
1547     m-alloc (fv A) (hv B (arity z)) M1 M2 S S1.
1548   comp (fapp [fuva A|Ag]) (uva B Ag1) M1 M2 L1 L1 S1 S2 :-
1549     pattern-fragment Ag, !,
1550     fold6 comp Ag Ag1 M1 M1 L1 L1 S1 S1,
1551     len Ag Arity,
1552     m-alloc (fv A) (hv B (arity Arity)) M1 M2 S1 S2.
1553   comp (fapp [fuva A|Ag]) (uva C Scope) M1 M3 L1 L3 S1 S4 :- !,
1554     pattern-fragment-prefix Ag Pf Extra,
1555     fold6 comp Pf Scope1 M1 M1 L1 L1 S1 S1,
1556     fold6 comp Extra Extra1 M1 M2 L1 L2 S1 S2,
1557     len Pf Arity,
1558     m-alloc (fv A) (hv B (arity Arity)) M2 M3 S2 S3,
1559     Beta = app [uva B Scope1 | Extra1],
1560     get-scope Beta Scope,
1561     alloc S3 C S4,
1562     L3 = [@eval-link-beta (uva C Scope) Beta | L2].
1563   comp (fapp A) (app A1) M1 M2 L1 L2 S1 S2 :-
1564     fold6 comp A A1 M1 M2 L1 L2 S1 S2.
1565
1566   type alloc mem A -> addr -> mem A -> o.
1567   alloc S N S1 :- mem.new S N S1.
1568
1569   type compile-terms-diagnostic
1570     triple diagnostic fm fm ->
1571     triple diagnostic tm tm ->
1572     mmap -> mmap ->
1573     links -> links ->
1574     subst -> subst -> o.
1575   compile-terms-diagnostic (triple D F01 F02) (triple D H01 H02) M1 M3 L1
1576     comp F01 H01 M1 M2 L1 L2 S1 S2,
1577     comp F02 H02 M2 M3 L2 L3 S2 S3.
1578
1579   type compile-terms
1580     list (triple diagnostic fm fm) ->
1581     list (triple diagnostic tm tm) ->
1582     mmap -> links -> subst -> o.
1583   compile-terms T H M L S :-
1584     fold6 compile-terms-diagnostic T H [] M_ [] L_ [] S_,
1585     deduplicate-map M_ M S_ S L_ L.
1586
1587   type make-eta-link-aux nat -> addr -> addr ->
1588     list tm -> links -> subst -> subst -> o.
1589   make-eta-link-aux z Ad1 Ad2 Scope1 L H1 H1 :-
1590     rev Scope1 Scope, eta-expand (uva Ad2 Scope) @one T1,
1591     L = [@eval-link-eta (uva Ad1 Scope) T1].
1592   make-eta-link-aux (s N) Ad1 Ad2 Scope1 L H1 H3 :-
1593     rev Scope1 Scope, alloc H1 Ad H2,
1594     eta-expand (uva Ad Scope) @one T2,
1595     (pi x\ make-eta-link-aux N Ad Ad2 [x|Scope1] (L1 x) H2 H3),
1596     close-links L1 L2,
1597     L = [@eval-link-eta (uva Ad1 Scope) T2 | L2].
1598
1599   type make-eta-link nat -> nat -> addr -> addr ->
1600     list tm -> links -> subst -> subst -> o.
1601   make-eta-link (s N) z Ad1 Ad2 Vars L H H1 :-
1602     make-eta-link-aux N Ad2 Ad1 Vars L H H1.
1603   make-eta-link z (s N) Ad1 Ad2 Vars L H H1 :-
1604     make-eta-link-aux N Ad1 Ad2 Vars L H H1.
1605   make-eta-link (s N) (s M) Ad1 Ad2 Vars Links H H1 :-
1606     (pi x\ make-eta-link N M Ad1 Ad2 [x|Vars] (L x) H H1),
1607     close-links L Links.
1608
1609   type deduplicate-map mmap -> mmap ->
1610     subst -> subst -> links -> links -> o.
1611   deduplicate-map [] [] H H L L.
1612   deduplicate-map [(mapping (fv 0) (hv M (arity LenM))) as X1] | Map1 Map2
1613     take-list Map1 (mapping (fv 0) (hv M' (arity LenM'))), !,
1614     std.assert! (not (LenM = LenM')) "Deduplicate map, there is a bug",
1615     print "arity-fix links:" {ppmapping X1} "~!~" {ppmapping (mapping (fv
1616     make-eta-link LenM LenM' M M' [] New H1 H2,
1617     print "new eta link" {pplinks New},
1618     append New L1 L2,
1619     deduplicate-map Map1 Map2 H2 H3 L2 L3.
1620   deduplicate-map [A|As] [A|Bs] H1 H2 L1 L2 :-
1621     deduplicate-map As Bs H1 H2 L1 L2, !.
1622
1623
1624

```

15 THE PROGRESS FUNCTION

```

1625 deduplicate-map [A|_] _ H _ _ :- ((ho.uva V Scope) ==1 T1) S1 S2.
1626 halt "deduplicating mapping error" {ppmapping A} {ho.ppsubst H}.
1627
1628
1629
1630 macro @one :- s z.
1631
1632 type contract-rigid list ho.tm -> ho.tm -> ho.tm -> o.
1633 contract-rigid L (ho.lam F) T :-
1634   pi x\ contract-rigid [x|L] (F x) T. % also checks H Prefix does not make eta-link
1635 contract-rigid L (ho.app [H|Args]) T :-
1636   rev L LRev, append Prefix LRev Args,
1637   if (Prefix = []) (T = H) (T = ho.app [H|Prefix]).
1638
1639 type progress-eta-link ho.tm -> ho.tm -> ho.subst -> ho.subst -> link -> link -> o.
1640 progress-eta-link (ho.app _ as T) (ho.lam x\ _ as T1) H H1 [] :- !, not (T1 = ho.uva _), !, fail.
1641 ({eta-expand T @one} ==1 T1) H H1.
1642 progress-eta-link (ho.con _ as T) (ho.lam x\ _ as T1) H H1 [] :- !
1643 ({eta-expand T @one} ==1 T1) H H1.
1644 progress-eta-link (ho.lam _ as T) T1 H H1 [] :- !,
1645 (T ==1 T1) H H1.
1646 progress-eta-link (ho.uva _ _ as X) T H H1 [] :-
1647   contract-rigid [] T T1, !, (X ==1 T1) H H1.
1648 progress-eta-link (ho.uva Ad _ as T1) T2 H H [@eval-link-eta T1 T2] :- !,
1649   if (ho.not_occ Ad H T2) true fail.
1650
1651 type is-in-pf ho.tm -> o.
1652 is-in-pf (ho.app [ho.uva _ _ | _]) :- !, fail.
1653 is-in-pf (ho.lam B) :- !, pi x\ is-in-pf (B x).
1654 is-in-pf (ho.con _).
1655 is-in-pf (ho.app L) :- forall1 is-in-pf L.
1656 is-in-pf N :- name N.
1657 is-in-pf (ho.uva _ L) :- pattern-fragment L.
1658
1659 type arity ho.tm -> nat -> o.
1660 arity (ho.con _) z.
1661 arity (ho.app L) A :- len L A.
1662
1663 type occur-check-err ho.tm -> ho.tm -> ho.subst -> o.
1664 occur-check-err (ho.con _) _ _ :- !.
1665 occur-check-err (ho.app _) _ _ :- !.
1666 occur-check-err (ho.lam _) _ _ :- !.
1667 occur-check-err (ho.uva Ad _) T S :-
1668   not (ho.not_occ Ad S T).
1669
1670 type progress-beta-link-aux ho.tm -> ho.tm ->
1671   ho.subst -> ho.subst -> links -> o.
1672 progress-beta-link-aux T1 T2 S1 S2 [] :- is-in-pf T2, !,
1673   (T1 ==1 T2) S1 S2.
1674 progress-beta-link-aux T1 T2 S S [@eval-link-beta T1 T2] :- !.
1675
1676 type progress-beta-link ho.tm -> ho.tm -> ho.subst ->
1677   ho.subst -> links -> o.
1678 progress-beta-link T (ho.app[ho.uva V Scope | L] as T2) S S2 [@eval-link-beta T T2] :- !,
1679   arity T Arity, len L ArgsNb, ArgsNb >n Arity, !,
1680   minus ArgsNb Arity Diff, mem.new S V1 S1,
1681   eta-expand (ho.uva V1 Scope) Diff T1,
1682
1683   ((ho.uva V Scope) ==1 T1) S1 S2.
1684
1685 progress-beta-link (ho.uva _ _ as T) (ho.app[ho.uva Ad1 Scope1 | L1] as T2) S1 S2 :- !,
1686   append Scope1 L1 Scope1L,
1687   pattern-fragment-prefix Scope1L Scope2 L2,
1688   not (Scope1 = Scope2), !,
1689   mem.new S1 Ad2 S2,
1690   len Scope1 Scope1Len,
1691   len Scope2 Scope2Len,
1692   make-eta-link Scope1Len Scope2Len Ad1 Ad2 [] LinkEta S2 S3,
1693   if (L2 = []) (NewLinks = LinkEta, T2 = ho.uva Ad2 Scope2)
1694   (T2 = ho.app [ho.uva Ad2 Scope2 | L2],
1695    NewLinks = [@eval-link-beta T T2 | LinkEta]).
1696
1697 progress-beta-link T1 (ho.app[ho.uva _ _ | _] as T2) _ _ :- !,
1698   progress-beta-link (ho.uva _ _ as T) (ho.app[ho.uva _ _ | _] as T2) S1 S2 :- !,
1699   occur-check-err T T2 S1, !, fail.
1700
1701 progress-beta-link T1 (ho.app[ho.uva _ _ | _] as T2) H H [@eval-link-beta T T2] :- !,
1702   progress-beta-link T1 (ho.app [Hd | T1]) S1 S2 B :- !,
1703   ho.lbeta Hd T1 T3,
1704   progress-beta-link-aux T1 T3 S1 S2 B.
1705
1706 type solve-link-abs link -> links -> ho.subst -> ho.subst -> o.
1707 solve-link-abs (ho.abs X) R H H1 :-
1708   pi x\ ho.copy x x => (pi S\ ho.deref S x x) =>
1709   solve-link-abs (X x) (R' x) H H1,
1710   close-links R' R.
1711
1712 solve-link-abs (@eval-link-eta A B) NewLinks S S1 :- !,
1713   progress-eta-link A B S S1 NewLinks.
1714
1715 solve-link-abs (@eval-link-beta A B) NewLinks S S1 :- !,
1716   progress-beta-link A B S S1 NewLinks.
1717
1718 type take-link link -> links -> link -> links -> o.
1719 take-link A [B|XS] B XS :- link-abs-same-lhs A B, !.
1720 take-link A [L|XS] B [L|YS] :- take-link A XS B YS.
1721
1722 type link-abs-same-lhs link -> link -> o.
1723 link-abs-same-lhs (ho.abs F) B :-
1724   pi x\ link-abs-same-lhs (F x) B.
1725 link-abs-same-lhs A (ho.abs G) :-
1726   pi x\ link-abs-same-lhs A (G x).
1727 link-abs-same-lhs (@eval-link-eta (ho.uva N _) _) (@eval-link-eta (ho.uva N _) _) :- !.
1728
1729 type same-link-eta link -> link -> ho.subst -> ho.subst -> o.
1730 same-link-eta (ho.abs F) B H H1 :- !, pi x\ same-link-eta (F x) B H H1.
1731 same-link-eta A (ho.abs G) H H1 :- !, pi x\ same-link-eta A (G x) H H1.
1732 same-link-eta (@eval-link-eta (ho.uva N S1) A) (@eval-link-eta (ho.uva N S2) B) H H1 :-
1733   std.map2 S1 S2 (x\y\r\ r = ho.copy x y) Perm,
1734   Perm => ho.copy A A',
1735   (A' ==1 B) H H1.
1736
1737
1738
1739
1740

```

```

1741
1742 type solve-links links -> links -> ho.subst -> ho.subst -> o.
1743 solve-links [] [] X X.
1744 solve-links [A|L1] [A|L3] S S2 :- take-link A L1 B L2, !,
1745     same-link-eta A B S S1,
1746     solve-links L2 L3 S1 S2.
1747 solve-links [L0|L1] L3 S S2 :- deref-link S L0 L,
1748     solve-link-abs L R S S1, !,
1749     solve-links L1 L2 S1 S2, append R L2 L3.
1750

```

16 THE DECOMPILER

```

1751
1752 type abs->lam ho.assignment -> ho.tm -> o.
1753 abs->lam (ho.abs T) (ho.lam R) :- !, pi x\ abs->lam (T x) (R x).
1754 abs->lam (ho.val A) A.
1755
1756 type commit-links-aux link -> ho.subst -> ho.subst -> o.
1757 commit-links-aux (@val-link-eta T1 T2) H1 H2 :-
1758     ho.deref H1 T1 T1', ho.deref H1 T2 T2',
1759     (T1' ==1 T2') H1 H2.
1760 commit-links-aux (@val-link-beta T1 T2) H1 H2 :-
1761     ho.deref H1 T1 T1', ho.deref H1 T2 T2',
1762     (T1' ==1 T2') H1 H2.
1763 commit-links-aux (ho.abs B) H H1 :-
1764     pi x\ commit-links-aux (B x) H H1.
1765
1766 type commit-links links -> links -> ho.subst -> ho.subst -> o.
1767 commit-links [] [] H H.
1768 commit-links [Abs | Links] L H H2 :-
1769     commit-links-aux Abs H H1, !, commit-links Links L H1 H2.
1770
1771 type decomp-subst map -> map -> ho.subst ->
1772     fo.fsubst -> fo.fsubst -> o.
1773 decomp-subst _ [A|_] _ _ _ :- fail.
1774 decomp-subst _ [] _ F F.
1775 decomp-subst Map [mapping (fv V0) (hv VM _)|T1] H F F2 :-
1776     mem.set? VM H T, !,
1777     ho.deref-assmt H T TTT,
1778     abs->lam TTT T', tm->fm Map T' T1,
1779     fo.eta-contract T1 T2, mem.assign V0 F T2 F1,
1780     decomp-subst Map T1 H F1 F2.
1781 decomp-subst Map [mapping _ (hv VM _)|T1] H F F2 :-
1782     mem.unset? VM H, decomp-subst Map T1 H F F2.
1783
1784 type tm->fm map -> ho.tm -> fo.fm -> o.
1785 tm->fm _ (ho.con C) (fo.fcon C).
1786 tm->fm L (ho.lam B1) (fo.flam B2) :-
1787     pi x y\ tm->fm _ x y => tm->fm L (B1 x) (B2 y).
1788 tm->fm L (ho.app L1) T :- map (tm->fm L) L1 [Hd|T1],
1789     fo.mk-app Hd T1 T.
1790 tm->fm L (ho.uva VM TL) T :- mem L (mapping (fv V0) (hv VM _)),
1791     map (tm->fm L) TL T1, fo.mk-app (fo.fuva V0) T1 T.
1792
1793 type add-new-map-aux ho.subst -> list ho.tm -> map ->
1794     map -> fo.fsubst -> fo.fsubst -> o.
1795 add-new-map-aux _ [] _ [] S S.
1796 add-new-map-aux H [T|Ts] L L2 S S2 :-

```

```

1797     add-new-map H T L L1 S S1,
1798     add-new-map-aux H Ts L1 L2 S1 S2.
1799
1800 type add-new-map ho.subst -> ho.tm -> map ->
1801     map -> fo.fsubst -> fo.fsubst -> o.
1802 add-new-map _ (ho.uva N _) Map [] F1 F1 :-
1803     mem Map (mapping _ (hv N _)), !.
1804 add-new-map H (ho.uva N L) Map [Map1 | MapL] F1 F3 :-
1805     mem.new F1 M F2,
1806     len L Arity, Map1 = mapping (fv M) (hv N (arity Arity)),
1807     add-new-map H (ho.app L) [Map1 | MapL] MapL F2 F3.
1808 add-new-map H (ho.lam B) Map NewMap F1 F2 :-
1809     pi x\ add-new-map H (B x) Map NewMap F1 F2.
1810 add-new-map H (ho.app L) Map NewMap F1 F3 :-
1811     add-new-map-aux H L Map NewMap F1 F3.
1812 add-new-map _ (ho.con _) _ [] F F :- !.
1813 add-new-map _ N _ [] F F :- name N.
1814
1815 type complete-mapping-under-ass ho.subst -> ho.assignment ->
1816     map -> map -> fo.fsubst -> fo.fsubst -> o.
1817 complete-mapping-under-ass H (ho.val Val) Map1 Map2 F1 F2 :-
1818     add-new-map H Val Map1 Map2 F1 F2.
1819 complete-mapping-under-ass H (ho.abs Abs) Map1 Map2 F1 F2 :-
1820     pi x\ complete-mapping-under-ass H (Abs x) Map1 Map2 F1 F2.
1821
1822 type complete-mapping ho.subst -> ho.subst ->
1823     map -> map -> fo.fsubst -> fo.fsubst -> o.
1824 complete-mapping _ [] L L F F.
1825 complete-mapping H [none | T1] L1 L2 F1 F2 :-
1826     complete-mapping H T1 L1 L2 F1 F2.
1827 complete-mapping H [some T0 | T1] L1 L3 F1 F3 :-
1828     ho.deref-assmt H T0 T,
1829     complete-mapping-under-ass H T L1 L2 F1 F2,
1830     append L1 L2 LAll,
1831     complete-mapping H T1 LAll L3 F2 F3.
1832
1833 type decompile map -> links -> ho.subst ->
1834     fo.fsubst -> fo.fsubst -> o.
1835 decompile Map1 L H0 F0 F02 :-
1836     commit-links L L1_ H0 H01, !,
1837     complete-mapping H01 H01 Map1 Map2 F0 F01,
1838     decomp-subst Map2 Map2 H01 F01 F02.
1839

```

17 AUXILIARY FUNCTIONS

```

1840 type fold4 (A -> A1 -> B -> B -> C -> C -> o) -> list A ->
1841     list A1 -> B -> B -> C -> C -> o.
1842 fold4 _ [] [] A A B B.
1843 fold4 F [X|XS] [Y|YS] A A1 B B1 :- F X Y A A0 B B0,
1844     fold4 F XS YS A0 A1 B0 B1.
1845
1846 type len list A -> nat -> o.
1847 len [] z.
1848 len [_|L] (s X) :- len L X.
1849

```