

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 $\text{fin } n$, of natural numbers smaller than n is finite; 2) the predicate $\text{nfact } n \text{ nf}$, 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 $\llbracket x \backslash e \rrbracket$, and square brackets denote a list of terms separated by comma. As an example we show the encoding of the Coq term $\llbracket \forall y:t, \text{nfact } y \text{ 3} \rrbracket$:

```
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\ p` 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):

```
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 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 A P»` that is in charge of bringing the assignment for `Pm` (that has type `tm -> tm`) back to the domain 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 2, 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.

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 definition unfolding and fixpoint 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

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

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 , $\sigma \subseteq \sigma'$ when σ is more general than σ' , and 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 $\langle s \rangle \mapsto (t, l)$ that maps a term s in \mathcal{F}_0 to a term t in \mathcal{H}_0 and a list of links l . The links connect unification variables in \mathcal{H}_0 with variables in \mathcal{F}_0 and are used to decompile the assignment, $\langle \sigma, l \rangle^{-1} \mapsto \rho$.

Given

$$\langle s_1 \rangle \mapsto (t_1, l_1) \wedge \langle s_2 \rangle \mapsto (t_2, l_2)$$

we define

$$s_1 \approx_o s_2 \mapsto \rho \stackrel{\text{def}}{=} t_1 \approx_\lambda t_2 \mapsto \sigma \wedge \langle \sigma, l_1 + l_2 \rangle^{-1} \mapsto \rho$$

Where $l_1 + l_2$ is the list concatenation of links.

We write $s \in \mathcal{L}_\lambda$ if all unif variables in s are applied to distinct bound variables.

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

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

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

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

Property 5 states that \approx_o is resilient to problems outside \mathcal{L}_λ if a third party provides a (partial) solution for its problem. Since we are interested in using \approx_o in a proof search procedure, made of a sequence of unification problems, not necessarily in \mathcal{L}_λ . In practice it is often the case the order in which these problems are stated matters. A Typical example is the following problem

```
app [F, con"a"] = app[F, con"a", con"a"]
```

preceded by

```
F = lam x\app[const f,x,x]
```

becomes solvable in DTT trivially, since the term is ground (hence in \mathcal{L}_λ), but is one substitutes F in the LHS does not find, structurally, the RHS hence \approx_λ would fail (since \approx_λ does not know about the β rule of DTT). Our compiler takes care of making property 5 hold, see section XXX.

Property 4 is also relevant to use \approx_o for logic programming. In particular we want failures to occur as early as possible, so want the decomp phase to take place immediately after \approx_λ , and fail if need be. This becomes particularly important since compile may introduce two ho variables for the same fo one, leaving the task of unifying the solutions to decomp.

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 know 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 LANGUAGES DESCRIPTION

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.

```
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 nat -> fm.      type uva nat -> list tm -> tm.
```

Figure 1: \mathcal{F}_0 and \mathcal{H}_0 language

In the case of \mathcal{F}_0 unification variables fuva have no explicit scope: Unification variables standing for functions are applied to variables via the fapp constructor. For example in the statement of the instance forall_dec the term $P \ x$ is represented as `fapp[fuva N, x]`, where N is of type nat and x is a bound variable.

In \mathcal{H}_0 the representation of $P \ x$ is instead `uva N [x]`. We say that the unification variable `uva N L` is in \mathcal{L}_λ iff distinct-names L holds.

```
type distinct-names list tm -> o.
distinct-names [].
distinct-names [X|XS] :- name X, not(mem X XS),
distinct-names XS.
```

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

In both languages unification variables are identified by a natural number, which can be seen as a memory address. The memory and its associated operations are described below:

```
typeabbrev memory A (list (option A)).
type set nat -> memory A -> A -> o.
set N S T :- nth N S (some T).
type unset nat -> memory A -> o.
unset N S :- nth N S none.
type assign nat -> memory A -> A -> memory A -> o.
assign z [none|M] T [some T|M].
assign (s N) [X|M] T [X|M1] :- assign N M T M1.
```

If a memory cell is none, then the corresponding unification variable is not set.

Since \mathcal{H}_0 unification variables have a scope, their solution needs to be abstracted over these in order to enables the instantiation of a single solution to different scopes. On the contrary solutions to \mathcal{F}_0 variables are just terms.

```
typeabbrev fsubst (memory ftm).
```

maybe
move
code
to the
appendix
and
keep
only
signatures

```

kind asmt type.
type abs (tm -> asmt) -> asmt.
type val tm -> asmt.
typeabbrev subst (memory asmt).

```

One can see `abs` as a syntax for the lambda abstraction of the meta language.

The memory \mathcal{F}_0 is called `fsubst` while the one of \mathcal{H}_0 is called `subst`. Both have the invariant that they are not cyclic, TODO explain.

4.1 equational theory and unification

here we give the functions/signatures to express the properties 3-5 in the problem statement

Together with the description of the terms of the language, we need some auxiliary functions to perform operations like term equality, unification, dereferencing. There predicates are supposed to be implemented in the OL and the ML following respectively their specification. In the following few paragraphs we give a brief definition of them.

Term dereferencing: ρs vs. σt . Since in our encoding we explicitly drag substitution mappings, we need to dereference variables of the two languages. This is particularly useful to check if two terms in the OL (resp. in the ML) are equal. The constructors representing rigid terms, namely `app`, `lam` and `con`, make the dereferencing procedure to recurse over the their subterms. The code below display this behavior for the dereferencing performed by the OL:

```

type fderef fsubst -> fm -> fm -> o.
fderef S (fapp [fuva N|A]) R :- set N S (fapp B),
    append A B C, fderef S (fapp C) R.
fderef S (fapp [fuva N|A]) (fapp [fuva N|B]) :- unset N S,
    forall2 (fderef S) A B.
fderef S (fapp A) (fapp B) :- forall2 (fderef S) A B.
fderef S (flam F) (flam G) :-
    pi x\ fderef S x x => fderef S (F x) (G x).
fderef _ (fcon C) (fcon C).
fderef S (fuva N) R :- set N S T, fderef S T R.
fderef _ (fuva N) (fuva N) :- unset N S.

```

More attention should be paid when the dereferencing encounters a subterm that is unification variable. The following new rules should be added to the previous code snippet to complete the dereferencing of variables of the OL:

A very similar implementation for the dereferencing performed by the ML, given in the appendix, can be encoded respecting the signature:

```

type deref subst -> tm -> tm -> o.
% ... the same
deref S (uva N A) R :- set N S T,
    instantiate T A T', deref S T' R.
deref S (uva N A) (uva N B) :-unset N S,
    forall2 (deref S) A B.

```

In particular, 1) if the variable `fuva N` is assigned to a term `T` in a substitution mapping `S`, we return the result of dereferencing `T`; 2) if the current term is the application of a variable `fuva N` assigned to a list of terms `L` and `uv N` is assigned to a term `T`, we return the

```

type (=o) ftm -> ftm -> o.
% congruence
fapp A =o fapp B :- forall2 (=o) A B.
flam F =o flam G :- pi x\ x =o x => F x =o G x.
fcon C =o fcon C.
fuva N =o fuva N.
% eta
flam F =o T :- pi x\ beta T [x] (T' x),
    x =o x => F x =o T' x.
T =o flam F :- pi x\ beta T [x] (T' x),
    x =o x => T' x =o F x.
% beta
fapp [flam X | TL] =o T :- beta (flam X) TL T', T' =o T. (beta1)
T =o fapp [flam X | TL] :- beta (flam X) TL T', T =o T'. (beta2)

```

Figure 2: Equal predicate OL

```

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

```

Figure 3: Equal predicate ML

result of dereferencing the beta reduction of `T` to `L`. This is due to the semantics of the unification variables within the OL; 3) finally, if `uv N` is not assigned, then the same variable is returned.

A different reasoning is to be addressed to the variables of the ML. Firstly, a meta variable cannot appear in the `app` node as the first element of the list, we will explain why in section 5; secondly, variables in the ML have a scope which should be taken into account. The following few lines of code outline the rules of dereferencing for the ML:

where, 1) if the variable `hov N L` has an assignment `T`, we return the dereferencing of the beta reduction `T` to the scope `L`.

Term equality: $=_o$ vs. $=_\lambda$. We can test if two terms are equal following the equational theory of the language being considered. In fig. 2 we provide an implementation of the $=_o$ predicate. The first four rules check if the two terms are equal regarding the structure of the current node, that is, two terms are equal if they have same head and if recursively each subterm is two by two equal. Moreover, since the theory of the OL accepts η - and β -equivalence, then we implement the corresponding rules.

The equality relation for the ML, accepts $\eta\beta$ -equivalence between terms of the ML. Recall that `abs x\ f x`, is a valid η expansion of the function `f` and that `lam x\ app[f, x]` is not that equivalent to `f` at meta level. However, since we are interested in using the unification procure of the ML, by eq. (1), we can use the \approx_λ relation to test, when needed if two terms are equal in the ML.

Term unification: \approx_o vs. \approx_λ . The last but not least important relation we should take care of before presenting our full algorithm aiming to unify terms of the OL in the ML and provide the substitution produced in the ML to the OL, is term unification. This procedure is a more powerful version of the equal predicate, since unification checks if two terms can be equal be assigning unification variables. In our representation, variable assignment (or refinement) is performed by modifying the corresponding substitution mapping.

what
about
app
uva?


```

type ( $\approx_\lambda$ ) tm -> tm -> subst -> subst o.
% Congruence
(app A  $\approx_\lambda$  app B) S S1 :- fold2  $\approx_\lambda$  A B S S1.
(lam F  $\approx_\lambda$  lam G) S S1 :-
  pi x\ (pi S\ (x  $\approx_\lambda$  x) S S) => (F x  $\approx_\lambda$  G x) S S1.
 $\approx_\lambda$  (con C) (con C) S S.
% deref
(uva N A  $\approx_\lambda$  T) S S1 :- set N S F,
  beta-abs F A T1, (T1  $\approx_\lambda$  T) S S1.
(T  $\approx_\lambda$  uva N A) S S1 :- set N S F,
  beta-abs F A T1, (T  $\approx_\lambda$  T1) S S1.
% flex-flex
(uva N A  $\approx_\lambda$  uva M B) S S3 :- unset M, unset N,
  pattern-fragment A, pattern-fragment B,
  new S W S1, prune W Args1 B Ass,
  assign N S1 Ass S2, assign M S2 Ass S3.
% assignment
(uva N A  $\approx_\lambda$  T) S S1 :- pattern-fragment A,
  not (T = uva _ _), not_occ N S T,
  bind A T T1, assign N S T1 S1.
(T  $\approx_\lambda$  uva N A) S S1 :- pattern-fragment A,
  not (T = uva _ _), not_occ N S T,
  bind A T T1, assign N S T1 S1.
% Note: (a infix b) c d == (infix) a b c d

```

Figure 4: The \approx_λ predicate // TODO move to the appendix

We will not give an implementation of \approx_o , since we are giving an implementation of it using our algorithm, see ??.

On the other hand, unification in the ML needs to be defined. In fig. 4, we give an implementation of \approx_λ . This predicate has four arguments, the two terms t_1 and t_2 to unify, the old substitution map ρ_1 , and the new substitution map ρ_2 , with the invariant $\rho_1 \subseteq \rho_2$. The first three rules unify terms with same rigid heads, and call the unification relation on the sub-terms. If t_1 (resp. t_2) is an assigned variable, t_1 is dereferenced to t'_1 (resp. t'_2) and the unification is called between t'_1 and t_2 (resp. t_1 and t'_2). If both terms are unification variables, we test that their arguments are in the pattern fragment, we allocate a new variable w in ρ_1 such that w is the pruning of the arguments of t_1 and t_2 , we assign both t_1 and t_2 to w and return the new mapping ρ_2 containing all the new variable assignment. Finally, if only one of the two terms is an unification variable v , after having verified that v does not occur in the other term t , we bind v to t and return the new substitution mapping.

OLD

A key property needed in unification is being able to verify if two terms are equal wrt a given equational theory. This relation allow to compare terms under a certain substitution mapping, so that any time a variable v is assigned in a subterm, a dereferencing of v is performed. After variable dereferencing, the test for equality is continued on the new-created subterm.

The base equality function over terms can be defined as follows:

The solution we are proposing aim to overcome these unification issues by 1) compiling the terms t and u of the OL into an internal version t' and u' in the ML; 2) unifying t' and u' at the meta level instantiating meta variables; 3) decompiling the meta variable into terms of the OL; 4) assigning the variables of the OL with the decompiled version of their corresponding meta variables. We

claim that t and u unify if and only if t' and u' unify and that the substitution in the object language is the same as the one returned by the ML.

In the following section we explain how we deal with term (de)compilation and links between unification variables.

5 COMPILATION

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: $\text{lam } x\ \text{app}[\text{uv } 0, x] \approx_\lambda \text{lam } x\ \text{c}["f"]$

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"]]  $\approx_o$ 
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"]]  $\approx_\lambda$ 
lam x\ app [c"decision", uv 1 [x]]
```

The main difference is the replacement of the subterm $\text{app}[\text{uv } 0, x]$ of the OL with the subterm $\text{uv } 0 [x]$. Variable indexes are chosen by the ML, that is, the index 0 for that unification variable of the OL

same
or
 \supseteq
or
 \subseteq

integer
or
nat?

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.

6 USE OF MULTIVARS

6.1 Problems with η

TODO: The following goal: $X = \lambda m\ x\ \lambda m\ y\ Y\ x\ y$, $X = \lambda m\ x\ f$

TODO: The snd unif pb, we have to unif $\lambda m\ x\ \lambda m\ y\ Y\ x\ y$ with $\lambda m\ x\ f$

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

TODO: An other example:

$\text{@}\lambda m\ x\ \text{@app}[\text{@f}, \text{@app}[\text{@X}, x]] = \text{@Y}, (\text{@}\lambda m\ x\ x) = \text{@X}.$

6.2 Problems with β

TODO: The following goal: $X = \lambda m\ x\ x$, $\text{app}[X, 3] = 3$

TODO: We use links-beta

6.3 Tricky examples

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

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 many rules are we solving?

TODO: Can we do some perf test

10 CONCLUSION

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