

# HO unification from object language to meta language

Enrico Tassi

enrico.tassi@inria.fr

Université Côte d'Azur, Inria

France

Davide Fissore

davide.fissore@inria.fr

Université Côte d'Azur, Inria

France

## 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 [12], Twelf [13],  $\lambda$ Prolog [9] and Isabelle [19] which have been utilized to implement various formal systems such as First Order Logic [4], Set Theory [11], Higher Order Logic [10], and even the Calculus of Constuctions [3].

The object logic we are interested in is Coq's [17] Dependent Type Theory (DTT), for which we aim to implement a unification procedure  $\approx_o$  using the ML Elpi [2], a dialect of  $\lambda$ Prolog. Elpi's equational theory comprises  $\eta\beta$  equivalence and comes equipped with a higher order unification procedure  $\approx_\lambda$  restricted to the pattern fragment [8]. We want  $\approx_o$  to be as powerful as  $\approx_\lambda$  but on the object logic DTT. Elpi also comes with an encoding for DTT that works well for meta-programming [16, 15, 6, 5]. Unfortunately this encoding, which we refer to as  $\mathcal{F}_o$ , "underuses"  $\approx_\lambda$  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  $\approx_\lambda$ , effectively implementing  $\approx_o$  on top of  $\approx_\lambda$  for the encoding  $\mathcal{F}_o$ .

We apply this technique to the implementation of a type-class [18] solver for Coq [17]. 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 [7] and TLC [1]. These two libraries constitute our test bed.

## KEYWORDS

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

### ACM Reference Format:

Enrico Tassi and Davide Fissore. XXXX 2024. HO unification from object language to meta language. In *YYY*. ACM, New York, NY, USA, 6 pages. <https://doi.org/ZZZZZZZZZZZZ>

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from [permissions@acm.org](mailto:permissions@acm.org).  
Conference'17, July 2017, Washington, DC, USA

© 2024 Copyright held by the owner/author(s). Publication rights licensed to ACM.  
ACM ISBN 978-x-xxxx-xxxx-x/YY/MM  
<https://doi.org/ZZZZZZZZZZZZ>

## 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 [12], Twelf [13],  $\lambda$ Prolog [9] and Isabelle [19] which have been utilized to implement various formal systems such as First Order Logic [4], Set Theory [11], Higher Order Logic [10], and even the Calculus of Constuctions [3].

The object logic we are interested in is Coq's [17] Dependent Type Theory (DTT), and we want to code a type-class [18] solver for Coq [17] using the Coq-Elpi [16] 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 [7] 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  $\lambda$ Prolog [9] 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\ 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 A P, 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)  $\beta$ -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  $\approx_\lambda$  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  $\mathcal{L}_\lambda$  [8].

*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  $\mathcal{L}_\lambda$  [8]. 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  $\approx_\lambda$  solves higher-order problems in  $\mathcal{L}_\lambda$ .

In spite of the similarity the link between  $\approx_\lambda$  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  $\approx_\lambda$  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  $\sigma$ , we write  $\sigma t$  for the application of the substitution to  $t$ ,  $\sigma \subseteq \sigma'$  when  $\sigma$  is more general than  $\sigma'$ , 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  $\mathcal{L}_\lambda$  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  $\mathcal{L}_\lambda$  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  $\mathcal{L}_\lambda$ . 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  $\mathcal{L}_\lambda$ ), but is one substitutes F in the LHS does not find, structurally, the RHS hence  $\approx_\lambda$  would fail (since  $\approx_\lambda$  does not know about the  $\beta$  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  $\approx_\lambda$ , 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

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 [3] 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 [14] should also be cited.

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

### 4 LANGUAGES DESCRIPTION

In order to reason about unification of the terms of the objet language within the meta language, we start by formally describing the two languages. Employing meta-programming for this purpose, we present in fig. 1 a new type for the terms of the OL.

```
kind tm type.
type app list tm -> tm.
type lam (tm -> tm) -> tm.
type con string -> tm.
```

Figure 1: Common terms

This encoding is very similar to the one introduced in section 1, except for the all constructor. We explicitly neglect it since blabla. Moreover, since we are working with unification variables we need to introduce a new constructor.

In the case of the OL, variables have no scope. For example, the subterm  $P \ x$  from the instance forall\_dec has  $P$  an higher order variables with type  $A \rightarrow \text{Prop}$  and  $x$  as bound variable. However, at the meta level, the translation of  $P \ x$  becomes `app[P, x]`, that is,  $P$  cannot reference  $x$ . In our encoding, we represent the variables of the OL in the following way:

```
type fo_uv nat -> tm.
```

In particular, a variable of the OL is identified by a integer refereeing a memory address. This constructor is prefixed with fo since the variable, having no scope, is a first-order variable. Finally, the memory of the OL is depicted by the following type abbreviation:

```
typeabbrev fo_subst list (option tm).
```

which is a list of optional terms. If a cell is none, then the variable corresponding to this cell is not instantiated.

On the other hand, the terms of the ML have exactly the same shape has the terms of fig. 1. However, since the ML is an Higher Order Programming Language, unification unification variables must have a scope. We represent them in the following way:

```
type ho_uv nat -> list tm -> tm.
```

Of course some attention should be payed when dealing with ho\_uv, since we have to certify that an uv  $i$  remain in the pattern fragment, that is, the list of term in the scope of  $i$  is always a list of distinct names.

Another important implementation should be provided in order to represent the lambda abstractions and the applications of the ML. As outlined in section 2,  $\langle x \setminus f \ x \rangle$  has not the same semantic as  $\langle \text{lam } x \setminus \text{app}[f, x] \rangle$ , since, even though, the two terms represent the same concept, the former is the lambda abstraction of  $f$

say  
we  
do  
not  
care  
about  
types

```

% congruence
type (=o) tm -> tm -> o.
app L1 =o app L2 :- forall2 (=o) L1 L2.
lam F1 =o lam F2 :- pi x\ x =o x => F1 x =o F2 x.
con X =o con X.
fov N =o fov N.
% eta
lam F ==o T :- pi x\ beta T [x] (T' x),
  x ==o x => F x ==o T' x.
T ==o lam F :- pi x\ beta T [x] (T' x),
  x ==o x => T' x ==o F x.
% beta
app [lam X | TL] =o T :- beta (lam X) TL T', T' =o T.
T =o app [lam X | TL] :- beta (lam X) TL T', T =o T'.

```

Figure 2: Equal predicate

applied to the binder in ML, whereas the latter is the same term representation but wrt the OL. We already have defined the nodes `app` and `lam` for the OL, therefore, in the following code snippet, we give their representation in the ML.

```

kind assmt type.
type abs (tm -> assmt) -> assmt.
type val tm -> assmt.

```

In particular, the node `abs` stands for the lambda abstraction. The node `val` contains terms of the object language. The node for variable application is not really necessary, since, using the syntax of the ML, it is defined by putting two terms of the ML side by side. For example, the terms `«x\ f x»` becomes `«abs x\ f x»`.

The memory of the ML, is defined with the following type abbreviation:

```
typeabbrev ho_subst list (option tm).
```

with the invariant that the `tm` inside the cell never contains the node `fo_uv`. Note that, reciprocally, the `fo_subst` does not contain any node of the form `ho_uv`.

#### 4.1 Auxiliary relations

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 equality:*  $=_o$  vs.  $=_\lambda$ .

*Term unification:*  $\approx_o$  vs.  $\approx_\lambda$ .

*Term dereferencing:*  $\rho_s$  vs.  $\sigma_t$ . TODO

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:

Though, this equality relation is to be extended with  $\eta\beta$  reduction rules to mirror the theory of the OL. This mean that new rules for those two redexes are added in the implementation of `fo_equal`.

If `fo_equal` is conceived to manage equality between terms of the OL, the same equality predicate in the ML behave slightly different. By the given definition of the ML, the ML allows  $\eta\beta$  congruence of terms, but, since the node `app` and `abs` are constructor representing the applications and the abstractions of the OL, these two reduction rules cannot applied on them. We build therefore a predicate equal working for terms in the ML which is implemented merely with the rules for the `fo_equal` predicate. For example, if `fo_equal [] (abs x\ [c"f", c]) (c"f")` is true in the object language, `equal [] (abs x\ [c"f", c]) (c"f")` produces a failure.

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.

Mathematically, we what to prove the following property:

```

forall (t u : term_ol) (s : subst_ol)
  (t' u' : term_ml) (s' : subst_ml),
  equal_ol t u s <->
  comp t t' /\ comp u u' /\
  unif_ml t' u' s' /\ links ... /\ decomp s' s.

```

*Math formula*

In the following section we explain how we deal with term (de)compilation and unification variable linking.

## 5 COMPILATION

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

not  
true  
for  
uv

same  
or  
⊇  
or  
⊆



integer 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 1 [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.

- how we transform an `fo_tm` in `tm`
- the role of links
- decomp - esempio che va in questa semplice rappresentazione (from intro) - esempio che non va, multi-var, eta, beta

## 6 UNIFICATION IN ML

- we accept HO unif with PF
- need of multiple vars for a single OL var

## 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 et al. "ELPI: Fast, Embeddable, λProlog 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](http://dx.doi.org/10.1007/978-3-662-48899-7_32).
- [3] 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.
- [4] 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.
- [5] 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>.
- [6] 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>.
- [7] 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.
- [8] 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.
- [9] Dale Miller and Gopalan Nadathur. *Programming with Higher-Order Logic*. Cambridge University Press, 2012. doi: 10.1017/CBO9781139021326.
- [10] 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.
- [11] 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>.
- [12] F. Pfening. "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.
- [13] 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.
- [14] 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.
- [15] 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>.
- [16] Enrico Tassi. "Elpi: an extension language for Coq (Metaprogramming Coq in the Elpi λProlog dialect)". In: *The Fourth International Workshop on Coq for Programming Languages*. Los Angeles (CA), United States, Jan. 2018. URL: <https://inria.hal.science/hal-01637063>.
- [17] The Coq Development Team. *The Coq Reference Manual – Release 8.18.0*. <https://coq.inria.fr/doc/V8.18.0/refman>. 2023.
- [18] 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>.

- [19] 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.