

Operational semantics for Prolog with Cut in Rocq and its application to determinacy analysis

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Abstract

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12 **2012 ACM Subject Classification** Replace ccsdesc macro with valid one

13 **Keywords and phrases** Dummy keyword

14 **Digital Object Identifier** 10.4230/LIPIcs.CVIT.2016.23

15 **Funding Jane Open Access:** (Optional) author-specific funding acknowledgements

16 **Joan R. Public:** [funding]

17 **Acknowledgements** I want to thank ...

1 Introduction

19 ELPI is a dialect of λ PROLOG (see [14, 15, 7, 12]) used as an extension language for the ROCQ
20 prover (formerly the Coq proof assistant). ELPI has become an important infrastructure
21 component: several projects and libraries depend on it [13, 3, 4, 19, 8, 9]. Examples include
22 the Hierarchy-Builder library-structuring tool [5] and Derive [17, 18, 11], a program-and-proof
23 synthesis framework with industrial applications at SkyLabs AI.

24 Starting with version 3, ELPI gained a static analysis for determinacy [10] to help users
25 tame backtracking. ROCQ users are familiar with functional programming but not necessarily
26 with logic programming and uncontrolled backtracking is a common source of inefficiency
27 and makes debugging harder. The determinacy checkers identifies predicates that behave
28 like functions, i.e., predicates that commit to their first solution and leave no *choice points*
29 (places where backtracking could resume).

30 This paper reports our first steps towards a mechanization, in the ROCQ prover, of the
31 determinacy analysis from [10]. We focus on the control operator *cut*, which is useful to
32 restrict backtracking but makes the semantic depart from a pure logical reading.

33 We formalize two operational semantics for PROLOG with cut. The first is a stack-
34 based semantics that closely models ELPI's implementation and is similar to the semantics
35 mechanized by Pusch in ISABELLE/HOL [16] and to the model of Debray and Mishra [6,
36 Sec. 4.3]. This stack-based semantics is a good starting point to study further optimizations
37 used by standard PROLOG abstract machines [20, 1], but it makes reasoning about the scope
38 of *cut* difficult. To address that limitation we introduce a tree-based semantics in which the
39 branches pruned by *cut* are explicit and we prove the two semantics equivalent. Using the

¹ Optional footnote, e.g. to mark corresponding author



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42nd Conference on Very Important Topics (CVIT 2016).

Editors: John Q. Open and Joan R. Access; Article No. 23; pp. 23:1–23:13

 Leibniz International Proceedings in Informatics

Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

23:2 Operational semantics for Prolog with Cut in Rocq and its application to determinacy analysis

```

Inductive P := IP of nat. Inductive D := ID of nat. Inductive V := IV of nat.

Inductive Tm :=
| Tm_P of P      | Tm_D   of D      | Callable_P of P
| Tm_V of V      | Tm_App of Tm & Tm. | Callable_App of Callable & Tm.

```

Figure 1 Tm and Callable types

40 tree-based semantics we then show that if every rule of a predicate passes the determinacy
41 analysis, the call to a deterministic predicate does not leave any choice points.

2 Common code: the language

put unif and pros
gram in variable@
hides from types
46 the them. The smallest unit of code that we can use in the langauge is an atom. The atom
inductive (see Type 1) is either a cut or a call. A call carries a callable term (see Figure 1).
A term (Tm) is either a predicate, a datum, a variable or the binary application of a term to
another. A Callable is a term accepting predicates only predicates as functors.

```

48 Inductive A := cut | call : Callable → A.                               (1)
49 Record R := mkR { head : Callable; premises : list A }.             (2)
50 Record P := { rules : seq R; sig : sigT }.                           (3)
51 Definition Σ := { fmap V → Tm}.                                       (4)
52 Definition bc : Unif → P → FU → Callable →
Σ → FU * seq (Σ * seq A) :=                                         (5)

```

!!!: controllare il
tipo di bc nel
testo
55 atoms. A program (see Type 3) is made by a list of rules and a mapping from predicates to
their signatures. The type sigT is the classic type from the simply typed lambda calculus, i.e.
56 it is either a base type or an arrow. We decorate arrows to know the mode of the lhs type.

57 A substitution (see Type 4) is a mapping from variables to terms. It is the output of a
58 successful query and is often called the output of a query.

```

Record Unif := {
  unify : Tm → Tm → Σ → option Σ;
  matching : Tm → Tm → Σ → option Σ;
}.

```

59 The backchain function (bc, see Type 5) filters the rules in the program that can be
60 used on a given query. It takes: a unificator U which explains how to unify terms up to
61 standard unification (for output terms) or matching (for input terms); a program P to explore
62 and filter; a set S of free variable (fvS) allowing to fresh the program P by renaming the
63 its variables; a query q ; and the substitution σ in which the query q lives. The result of a
64 backchain operation is couple made of an extension of S containing the new variables that
65 have been allocated during the unification phase and a list of filtered rules r accompagnate
66 by their a substition. This substitution is the result of the unification of q with the head of
67 each rule in r .

68 In Figure 2, we have an example of a simple ELPI program which will be used in the
69 following section of the paper as an example to show how backtracking and the cut operator
70 works in the semantcis we propose. The translation of these rules in the ROCQ representation
71 is straightforward.

```
f 1 2.    f 2 3.    r 2 4.    r 2 8.
g X X.          % r1
g X Z :- r X Z, !.   % r2
g X Z :- f X Y, f Y Z.   % r3
```

Figure 2 Small ELPI program example

2.1 The cut operator

The semantics of the cut operator adopted in the ELPI language corresponds to the *hard cut* operator of standard SWI-PROLOG. This operator has two primary purposes. First, it eliminates all alternatives that are created either simultaneously with, or after, the introduction of the cut into the execution state.

To illustrate this high-level description, consider the program shown in Figure 2 and the query $q = g 2 Z$. All three rules for g can be used on the query q . They are tried according to their order of appearance in the program: rule r_1 is tried first, followed by r_2 , and r_3 .

The first rule has no premises and immediately returns the assignment $Z = 2$. However, the computation does not terminate at this point, since two additional unexplored alternatives remain, corresponding to the premises of rules r_2 and r_3 .

The premises of rule r_2 are $r 2 Z, !$. At this stage, the role of the cut becomes apparent. If the premise $r 2 Z$ succeeds, the cut commits to this choice and removes the premises of rule r_3 from the alternative list, as they were generated at the same point as the cut. Moreover, if the call $r 2 Z$ itself produces multiple alternatives, only the first one is committed, while the remaining alternatives are discarded. This is because such alternatives have been created at a deeper depth in the search tree than the cut.

Concretely, the call $r 2 Z$ yields two solutions, assigning Z the values 4 and 8, respectively. The second solution is eliminated by the cut, and only the first assignment is preserved.

se metti $r1 = g A$
 $B :- f A B$. allora
 $g e f$ sono fun-
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gare anche l'idea
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3 Semantics intro

We propose two operational semantics for a logic program with cut. The two semantics are based on different syntaxes, the first syntax (called tree) exploits a tree-like structure and is ideal both to have a graphical view of its evolution while the state is being interpreted and to prove lemmas over it. The second syntax, called elpi, is the ELPI's syntax and has the advantage of reducing the computational cost of cutting and backtracking alternatives by using shared pointers. We aim to prove the equivalence of the two semantics together with some interesting lemmas of the cut behavior.

4 Tree semantics

```
Inductive tree :=
| KO | OK | TA of A
| Or  of option tree & Σ & tree
| And of tree & seq A & tree.
```

In the tree we distinguish 5 main cases: *KO*, *OK*, and are special meta-symbols representing, respectively, the failed and a successful terminal. These symbols are considered meta because they are internal intermediate symbols used to give structure to the tree.

The *TA* constructor (acronym for tree-atom) is the constructor of atoms in the tree. TA = Todo/
Goal?

```

Fixpoint get_end s A : Σ * tree :=
  match A with
  | TA _ | KO | OK ⇒ (s, A)
  | Or None s1 B ⇒ get_end s1 B
  | Or (Some A) _ _ ⇒ get_end s A
  | And A _ B ⇒
    let (s', pA) := get_end s A in
    if pA == OK then get_end s' B
    else (s', pA)
  end.

Definition get_subst s A := (get_end s A).1.

Definition path_end A := (get_end ε A).2. (* ~ε~ is the ~ε~ subst*)

Definition success A := path_end A == OK.

Definition failed A := path_end A == KO.

Definition path_atom A := if path_end A is TA _ then true else

```

Figure 3 Definition of *get_end*

104 The two recursive cases of a tree are the *Or* and *And* non-terminals. The *Or* non-terminal
 105 $A \vee B_\sigma$ denotes a disjunction between two trees A and B . The first branch is optional, if
 106 absent it represents a dead tree, i.e. a tree that has been entirely explored. The second
 107 branch is annotated with a suspended substitution σ so that, upon backtracking to B , σ is
 108 used as the initial substitution for the execution of B .

109 The *And* non-terminal $A \wedge_{B_0} B$ represents a conjunction of two trees A and B . We call B_0
 110 the reset point for B ; it is used to restore the state of B to its initial form if a backtracking
 111 operation occurs on A . Intuitively, let $t2l$ be the function flattening a tree in a list of sequents
 112 disjunction, in PROLOG-like syntax the tree $A \wedge_{B_0} B$ becomes $(A_1, t2l B); (A_2, B_0); \dots; (A_n, B_0)$
 t2l nope, mettiti
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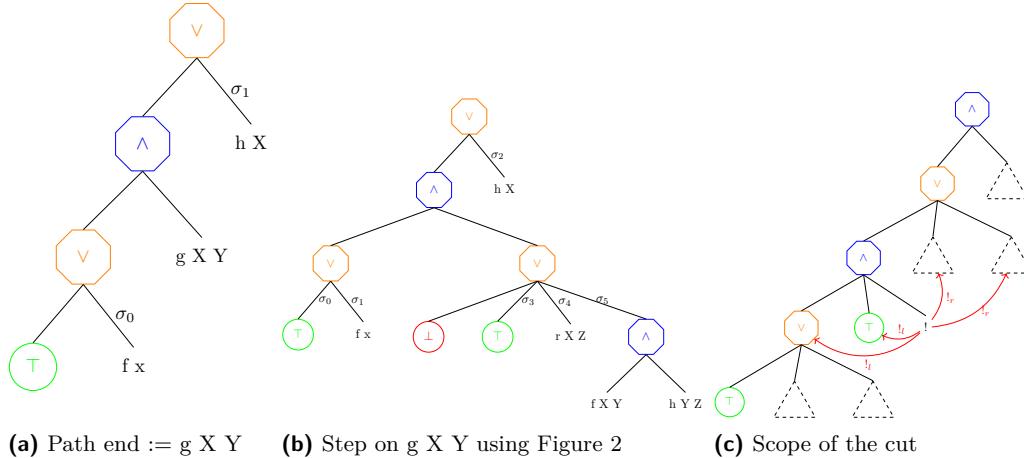


Figure 4 Some tree representations

138 In Figure 4a the *path_end* of the tree is `g X Y`.

139 Below we define three special kinds of trees depending on their *path_end*.

140 **Definition** `success A := path_end A == OK.` (3)

141 **Definition** `failed A := path_end A == KO.` (4)

142 **Definition** `path_atom A := if path_end A is TA _ then true else false.` (5)

143 The latter definition identifies path ending in an atom.

144 4.1 The *step* procedure

145 The *step* procedure takes as input a program, a set of free variables (*fv*), a substitution, and
146 a tree, and returns an updated set of free variables, a *step_tag*, and an updated tree.

147 Free variables are those variables that appear in a tree; they are used and updated when
148 a backchaining operation takes place.

149 The *step_tag* (see Type 6) indicates the kind of an internal tree step: `CutBrothers` denotes
150 the interpretation of a superficial cut, i.e., a cut whose parent nodes are all *And*-nodes.
151 `Expanded` denotes the interpretation of non-superficial cuts or predicate calls. `Failure` and
152 `Success` are returned for, respectively, `failed` and `success` trees.

153 The step procedure is intended to interpretate atoms, that is, it transforms the tree iff its
154 *path_end* is an atom, otherwsise, it returns the identity.

155 **Lemma** `succ_step_iff u p fv s A: success A ↔ step u p fv s A = (fv, Success, A).` (1)

156 **Lemma** `fail_step_iff u p fv s A: failed A ↔ step u p fv s A = (fv, Failed, A).` (2)

157 *Call step* The interpretation of a call *c* stars by calling the *bc* function on *c*. The output
158 list *l* is taken to represent build the new subtree. If *l* is empty then *KO* tree is returned,
159 otherwise the subtree is a right-skewed tree made of *n* inner *Or* nodes, where *n* is the length
160 of *l*. The root has *KO* as left child. The lhs of the other nodes is a right-skewed tree of *And*
161 nodes. The *And* nodes are again a right-seked tree containing premises of the selected rule .

162 A step in the tree of Figure 4a makes a backchain operation over the query `g X Y` and, in
163 the program defined in Figure 2, the new tree would be the one in Figure 4b. We have put a
164 red border aroung the new generated subtree. It is a disjunction of four subtrees: the first
165 node is the *KO* node (by default), the second is *OK*, since *r1* has no premises, the third and
166 the fourth contains the premises of respectively *r2* and *r3*.

dire dei reset
point

dire che le sostituzioni del backchain sono importanti

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167 *Cut step* The cut case is delicate, since interpreting a cut in a tree has three main impacts:
 168 at first the cut is replaced by the *OK* node, then some special subtrees, in the scope of the
 169 *Cut*, are cut away: in particular we need to soft-kill the left-siblings of the *Cut* and hard-kill
 170 the right-uncles of the the *Cut*.

171 ► **Definition 1** (Left-siblings (resp. right-sibling)). *Given a node A, the left-siblings (resp.*
 172 *right-sibling) of A are the list of subtrees sharing the same parent of A and that appear on*
 173 *its left (resp. right).*

174 ► **Definition 2** (Right-uncles). *Given a node A, the right-uncles of A are the list of right-sibling*
 175 *of the father of A.*

176 ► **Definition 3** (Hard-kill, $!_r$). *Given a tree t, hard-kill replaces the given subtree with the*
 177 *KO node*

178 ► **Definition 4** (Soft-kill, $!_l$). *Given a successfull tree t, soft-kill replaces with KO all subtrees*
 179 *that are not part of the path in t leading to the OK node.*

180 An example of the impact of the cut is show in Figure 4c, the dashed triangles represent
 181 generic trees. The step routine interprets the cut since it is the node in its path-end: we pass
 182 through a and and all trees on the left of the cut are successful. In the example we have 4
 183 arrow tagged with the $!_l$ or $!_r$ symbols. The $!_l$ arrows go left and soft-kill the pointed subtree,
 184 it keeps *OK* nodes since they are part of the tree leading to the cut, and replaces the other
 185 subtrees with *KO*. The $!_r$ procedure replaces the nodes pointed by the arrows with *KO*.

186 4.2 The *next_alt* procedure

187 It is evident that the *step* alone is not sufficient to reproduce entirely the behavior of the full
 188 expected prolog interpreter. In particular, we need to bracktrack on failures. Moreover, in
 189 case of success, we should return a state where the state in cleaned of the success itself, this
 190 is essential to, non deterministically, find all the solution of a given query. By Lemmas 1
 191 and 2, we know that *step* returns the identity on successful and failed states. In order to
 192 continue the computation on these particular trees, we need the *next_alt* procedure aiming
 193 to especially work with failed and successful trees: and its implementation in Figure 5.

194 The *next_alt* procedure takes a boolean and a tree, clean it from failures or success and
 195 returns a new tree if this tree still contains a non explored path. The idea behind *next_alt* is
 196 to clean recursively every subtree in DFS order if its *path_end* is a failure. Moreover, if the
 197 boolean passed to *next_alt* is true, then it erases the first successful path in the tree.

198 The base cases of *next_alt* are immidiate. The *Or* case is rathere intuitive: if the lhs
 199 of the *Or* does not exist we look for the *next_alt* in the rhs. Otherwise, we look for the
 200 *next_alt* in the lhs, if this *next_alt* does not exists, we look for the *next_alt* in the rhs.

201 We want to spend few words about the *And* case, since the reset point *B0* for *B* plays an
 202 important role. The *next_alt* in an *And* tree should consider two cases: if the lhs succeeds,
 203 then the *next_alt* should be retrived in the rhs. If this alternative does not exists it means
 204 that the rhs has entirely been explored. We need to erase the success in the lhs and try to
 205 find if a non-explored alternative exists. If so, we return a new tree with the new lhs and the
 206 rhs is built from the reset point. *big_and* is a trivial function build a right-skewed tree of
 207 and nodes where the leaves are the atoms written in the reset point. We need to reuse the
 208 reset point since, the step procedure in *And* trees evaluates the rhs of a *And* tree if the lhs
 209 succeeds. This evaluation is dependent on the subsitution in the lhs tree. Therefore, if we
 210 need to backtrack in the lhs, we need to reset the rhs.

```

Definition next_alt :  $\mathbb{B} \rightarrow \text{tree} \rightarrow \text{option tree} :=$ 
fix next_alt b A :=
match A with
| KO => None
| OK => if b then None else Some OK
| TA _ => Some A
| And A B0 B =>
let build_B0 A := And A B0 (big_and B0) in
if success A then
  match next_alt b B with
  | None => omap build_B0 (next_alt true A)
  | Some B' => Some (And A B0 B')
  end
else if failed A then omap build_B0 (next_alt false A)
else Some (And A B0 B)
| Or None sB B => omap (fun x => Or None sB x) (next_alt b B)
| Or (Some A) sB B =>
  match next_alt b A with
  | None => omap (fun x => Or None sB x) (next_alt false B)
  | Some A' => Some (Or (Some A') sB B)
end
end.

```

■ **Figure 5** *next_alt* implementation

Some interesting property of *next_alt* are shown below and allow to see how *next_alt* complements *step*.

```

213 Lemma path_atom_next_alt_id b A: path_atom A → next_alt b A = Some A. (3)
214 Lemma next_alt_failedF b A A': next_alt b A = Some A' → failed A' = false. (4)

```

For example, in Figure 4b the step procedure has created a failed state: its path-end ends in *KO*. The expected behavior of *next_alt* is to take this *KO* node and make it a This allows *step* to continue the exploration of the tree. In particular, the path-end of this new state end in *OK*. The step leaves the state unchanged producing the new substitution. This solution however is not unique, we should be able to backtrack on this successful state. To do so we can call *next_alt* and it will deadify the *OK* node allowing *step* to proceed on r X Z.

subst taken form
the or

221 4.3 The *run* inductive

222 The inductive procedure *run* is modeled as a function: it takes as input a program, a set of
 223 free variables, an initial substitution σ_0 , and a tree t_0 , and returns a substitution σ_1 together
 224 with an optional updated tree t_1 . The substitution σ_1 represents the most-general unificator
 225 that makes the execution of the tree t_0 succeed starting from the initial substitution σ_0 , σ_1
 226 is an extension of σ_0 . The tree t_1 is the updated tree containing the alternatives that have
 227 not yet been explored. If the tree contains no solution, then *None* is returned.

The procedure *run* is based on three main derivation rules, shown in Figure 6. If the *path_end* of the tree *t* is a success, the input substitution is returned and the input tree is cleaned of its successful path. If the *path_end* of the tree is an atom, then *step* is invoked to evaluate this atom, and *run* is recursively called on the new tree. Finally, if the *path_end* of the tree is a failure, *next_alt* is called to clear the failed path; if the resulting cleaned tree exists, *run* is recursively called on it.

$$\begin{array}{c}
 \frac{\text{success } A \rightarrow \text{get_subst } s1 A = s2 \rightarrow (\text{next_alt true } A) = B \rightarrow \text{run fv } s1 A s2 B}{\text{RUN_DONE}} \\
 \\
 \frac{\text{path_atom } A \rightarrow \text{step } u p \text{ fv0 } s1 A = (\text{fv1}, \text{st}, B) \rightarrow \text{run fv1 } s1 B s2 r \rightarrow \text{run fv0 } s1 A s2 r}{\text{RUN_STEP}} \\
 \\
 \frac{\text{failed } A \rightarrow \text{next_alt false } A = \text{Some } B \rightarrow \text{run fv0 } s1 B s2 r \rightarrow \text{run fv0 } s1 A s2 r}{\text{RUN_FAIL}} \\
 \\
 \frac{\text{success } A}{\text{run fv } s1 A (\text{get_subst } s1 A) (\text{next_alt } \top A)} \text{ run_done} \\
 \\
 \frac{\text{path_atom } A \quad \text{step } u p \text{ fv0 } s1 A = (\text{fv1}, \text{st}, B) \quad \text{run fv1 } s1 B s2 r \quad \text{run_step}}{\text{run fv0 } s1 A s2 r} \\
 \\
 \frac{\text{failed } A \quad \text{next_alt } \perp A = \text{Some } B \quad \text{run fv0 } s1 B s2 r \quad \text{run_fail}}{\text{run fv0 } s1 A s2 r}
 \end{array}$$

Figure 6 Rule system for *run*

234 4.4 Valid trees

235 The inductive tree allows one to generate a large number of trees, some of which are not
 236 valid, in the sense that they cannot be produced starting from a given query. The class of
 237 valid trees is characterized by the following function.

```

Fixpoint valid_tree s :=
  match s with
  | TA _ | OK | KO => true
  | Or None _ B => valid_tree B
  | Or (Some A) _ B => valid_tree A && ((B == KO) || B.base_or B)
  | And A B0 B => valid_tree A &&
    if success A then valid_tree B
    else B == big_and B0
  end.
  
```

238 Once again, the most interesting cases to analyze are *Or* and *And*.

239 For the *Or* constructor, we distinguish two cases depending on whether the left-hand
 240 side (lhs) exists. If it does not exist, then the right-hand side (rhs) must be a valid tree.
 241 Otherwise, the lhs must itself be a valid tree, and the rhs is either the *KO* tree, since it may
 242 have been removed by the evaluation of a superficial cut in the lhs, or it has not yet been
 243 explored. In the latter case, it is a *base_or* tree, namely the right-skewed tree formed by a
 244 disjunction of conjunctions.

245 For the *And* constructor, the lhs is required to be a valid tree. The shape of the rhs
 246 depends on whether the lhs represents a success. If the lhs is not successful, then the rhs
 247 has never been explored: the procedures *step* and *next_alt* modify the rhs only when the
 248 lhs succeeds. In this case, the lhs must be the right-skewed tree containing the conjunctions
 249 of the atoms present in the reset point *B*₀. In other words, the rhs coincides with the reset
 250 point. If the lhs is a success tree, then the rhs must be a valid tree.

```

Definition stepE fv t s a gl :=
  let (fv', rs) := bc u p fv t s in
  let rs_ca := save_alts a gl (r2a rs) in
  (fv', rs_ca).

Inductive nur :  $\mathcal{F}_v \rightarrow \Sigma \rightarrow \text{goals} \rightarrow \text{alts} \rightarrow \Sigma \rightarrow \text{alts} \rightarrow \text{Prop} :=$  (10)

  
$$\frac{}{\text{nur } fv \ s \ [::] \ a \ s \ a} \text{STOPE}$$

  
$$\frac{}{\text{nur } fv \ s \ gl \ ca \ s1 \ r \rightarrow \text{nur } fv \ s \ [:: \ (\text{cut}, \ ca) \ \& \ gl] \ a \ s1 \ r} \text{CUTE}$$


```

CA

$$\text{stepE } fv \ t \ s \ al \ gl = (fv', [:: b \ \& \ bs]) \rightarrow \text{nur } fv' \ b.1 \ b.2 \ (bs++al) \ s1 \ r \rightarrow \text{nur } fv \ s \ [:: \ (\text{call } t, \ ca) \ \& \ gl] \ al \ s1 \ r$$

$$\text{stepE } fv \ t \ s \ al \ gl = (fv', [::]) \rightarrow \text{nur } fv' \ s1 \ a \ al \ s2 \ r \rightarrow \text{nur } fv \ s \ [:: \ (\text{call } t, \ ca) \ \& \ gl] \ [:: \ (s1, \ a) \ \& \ al] \ s2 \ r. \text{FAILE}$$

Figure 7 Rule system for *nur*

251

5 Elpi semantics

252 We now want to introduce the elpi semantics. The interpreter we show reflects the interpreter
 253 of the ELPI language and is an operational semantics close to the one picked by Pusch in
 254 [16], in turn closely related to the one given by Debray and Mishra in [6, Section 4.3]. Pusch
 255 mechanized the semantics in Isabelle/HOL together with some optimizations that are present
 256 in the Warren Abstract Machine [20, 1].

257 The inductive representing a state of the ELPI language is shown below.

```

Inductive alts := no_alt | more_alt of ( $\Sigma * \text{goals}$ ) & alts
with goals := no_goals | more_goals of ( $A * \text{alts}$ ) & goals .

```

258 An elpi state is an enhanced two-dimension list. The outermost list represents the list
 259 of alternatives in disjunction accompagne with the substitution that should be used to
 260 for their interpretation. The innermost list is a list of atom, representing a list of goals in
 261 cunjunctions. These goals are decorated with a pointer to an elpi state, and are used to keep
 262 trace of the alternatives that should be kept when a cut is interpreted. We call these, special,
 263 alternatives the cut-to alternatives.

264 The idea of the ELPI interpreter is to receive a list of alternatives. The first alternative
 265 consists of a list of goals. Four cases must be taken into account; they are shown in Figure 7.
 266 In order to simplify goal retrieval, we split the head of the alternatives from the tail, so
 267 that it can be immediately matched in the inductive definition. Note that an empty list of
 268 alternatives represents, by definition, a failing state. If the goal list is empty (STOPE), then
 269 we have, by definition, a success, and the input solution together with the list of alternatives
 270 is returned. If the goal list starts with a cut (CUTE), then the current alternatives are erased
 271 in favour of the cut alternatives, and a recursive call is made on the remaining goal list.

272 Finally, we must consider the case in which the goal list starts with a call. The call
 273 can either fail (FAILE) or succeed (CALLE). We distinguish the two cases by looking if the
 274 backchaining operation returns zero or more rules. We have wrapped this task in the *stepE*

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275 procedure, which also updates the goal and cut-alternative list. The fail case, is relatively
 276 easy: the first goal does not succeed, we need to take the head of the alternatives, and make
 277 it the new list of goals to be explored.

278 The case in which backchaining produces a non empty list, the *save_alts* routine is in
 279 charge of: taking the list of premises and add to each atom the the list of alternatives *a* as
 280 their new cut-alternatives, then it append the list of goals *gl* to each of these new lists.

281 6 Semantic equivalence

282 The equivalence between the two semantics is possible under two conditions: we need to
 283 work with "valid states", i.e. state that can be generated from a query of type call.

284 6.1 From trees to lists

285 The translation of a tree to a list is as follows:

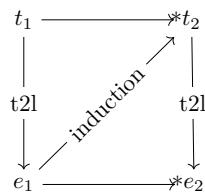
```
Fixpoint t2l (A: tree) s (bt : alts) : alts :=
  match A with
  | OK          => [:: (s, [::]) ]
  | KO          => [::]
  | TA a        => [:: (s, [:: (a,[::]) ]) ]
  | Or None s1 B => add_ca_deep bt (t2l B s1 [::])
  | Or (Some A) s1 B =>
    let 1B := t2l B s1 [::] in
    let 1A := t2l A s 1B in
    add_ca_deep bt (1A ++ 1B)
  | And A B0 B   =>
    let 1A := t2l A s bt in
    if 1A is [:: (s1A, x) & xs] then
      let 1B0 := a2g B0 in
      let xz := add_deepG bt 1B0 x in
      let xs := add_deep bt 1B0 xs in
      let xs := map (catr 1B0) xs in
      let 1B := t2l B s1A (xs ++ bt) in
      (map (catl xz) 1B) ++ xs
    else [::]
  end.
```

► **Theorem 5 (tree_to_elpi).**

286 $\forall A \sigma_1 B \sigma_2 b \sigma_0, \text{vt } A \rightarrow$
 287 $\text{run}_u \sigma_1 A (\text{Some } \sigma_2) B b \rightarrow$
 288 $\exists x xs, \text{t2l } A \sigma_1 \emptyset = x ::: xs \wedge \text{nur}_u x.1 x.2 xs \sigma_2 (\text{t2l } B \sigma_0 \emptyset).$

► **Theorem 6 (elpi_to_tree).**

289 $\forall \sigma_1 \sigma_2 a na g,$
 290 $\text{nur}_u \sigma_1 g a \sigma_2 na \rightarrow$
 291 $\forall \sigma_0 t, \text{vt } t \rightarrow (\text{t2l } t \sigma_0 \emptyset) = ((\sigma_1, g) :: a) \rightarrow$
 292 $\exists t' n, \text{run}_u \sigma_0 t (\text{Some } \sigma_2) t' n \wedge \text{t2l } t' \sigma_0 \emptyset = na.$



■ **Figure 8** Induction scheme for Theorem 6

293 The proof of Theorem 6 is based on the idea explained in [2, Section 3.3]. An ideal
 294 statement for this lemma would be: given a function $12t$ transforming an elpi state to a tree,
 295 we would have have that the the execution of an elpi state e is the same as executing run on
 296 the tree resulting from $12t(e)$. However, it is difficult to retrive the strucutre of an elpi state
 297 and create a tree from it. This is because, in an elpi state, we have no clear information
 298 about the scope of an atom inside the list and, therefore, no evident clue about where this
 299 atom should be place in the tree.

300 Our theorem states that, starting from a valid state t which translates to a list of
 301 alternatives $(\sigma_1, g) :: a$. If we run in elpi the list of alternatives, then the execution of the
 302 tree t returns the same result as the execution in elpi. The proof is performed by induction
 303 on the derivations of the elpi execution. We have 4 derivations.

304 We have 4 case to analyse:

305 **7 Case study: determinacy alanyisis**

306 we mechanize the first order part of xxx.

307 snippet det, main thm, invariant det tree (valid tree prev section?)

308 proof induciton on exec, step/next alt preserving invariant proved by induction on the
 309 tree.

310 with list semantics cut and next alt requires to express a link btween the ca or next alts
 311 and the current goal, which is non trivial without an intermediate data strature like the tree

312 **8 Related work**

313 prolog semantics, King lost

314 yves for the proof technique

315 **9 Conclusion**

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