

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

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Abstract

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2012 ACM Subject Classification Replace ccsdesc macro with valid one

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1 Introduction

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

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

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

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

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```

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

```

■ **Figure 1** Tm and Callable types

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

2 Common code: the language

Before going to the two semantics, we show the piece of data structure that are shared by the them. The smallest unit of code that we can use in the language 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.

Inductive A := cut | call : Callable -> A. (1)

Record R := mkR { head : Callable; premises : list A }. (2)

Record program := { rules : seq R; sig : sigT }. (3)

Definition Sigma := {fmap V -> Tm}. (4)

Definition bc : Unif -> program -> fvS -> Callable -> Sigma -> fvS * seq (Sigma * R) := (5)

A rule (see Type 2) is made a head of type term and a list of premises, the premises are 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. it is either a base type or an arrow. We decorate arrows to know the mode of the lhs type.

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

```

Record Unif := {
  unify : Tm -> Tm -> Sigma -> option Sigma;
  matching : Tm -> Tm -> Sigma -> option Sigma;
}.

```

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

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

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 & Sigma & 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.

se metti $r1 = g \ A$
 $B :- f \ A \ B$. allora
 $g \ e \ f$ sono fun-
 zioni, e puoi spie-
 gare anche l'idea
 del detcheck qui

$TA = \text{Todo/-}$
 Goal?

```

Fixpoint get_end s A : Sigma * 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.

```

(a) Definition of *get_end*

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

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

A graphical representation of a tree is shown in Figure 4a. To make the graph more compact, the *And* and *Or* non-terminals are n-ary rather than binary, with right-binding priority. The *KO* terminal act as the neutral elements in the *Or* list, while *OK* is the neutral element of the *And* list.

The interpretation of a tree is performed by two main routines: *step* and *next_alt* that traverse the tree depth-first, left-to-right. Then, then *run* inductive makes the transitive closure of *step* and *next_alt*: it iterates the calls to its auxiliary functions. In Types 7–9 we give the types contrats of these symbols where *fvS* is a set of variable names.

Inductive step_tag := Expanded | CutBrothers | Failed | Success. (6)

Definition step : program -> fvS -> Sigma -> tree -> (fvS * step_tag * tree) := (7)

Definition next_alt : bool -> tree -> option tree := (8)

Inductive run (u:Unif) (p : program): fvS -> Sigma -> tree -> Sigma -> option tree -> Prop := (9)

The tree interpreter, as in prolog, explores the state in DFS strategy, to discover the substitution and the leaf of the tree that should be interpreted. The *get_end* routine, shown in Figure 3a, accomplishes to this task. The *get_end* returns its inputs if the tree is a leaf. Otherwise, if the tree is a disjunction, the path continues on the left subtree, if it exists, otherwise it recursively retrieves the wanted piece of information in the rhs using the substitution stored in the *Or* branch: the current substitution when we cross the rhs of a *Or* is the one store in the *Or* node itself. In the case of a conjunction, if the to-be-explored leaf in the lhs is *OK*, then we look for the *get_end* in the rhs, otherwise we return the result of the lhs.

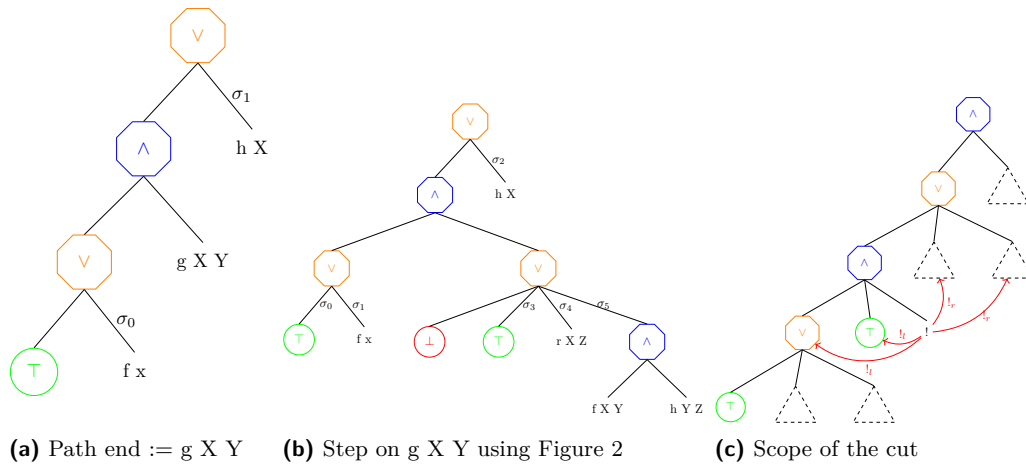
We derive the following two functions from *get_end*:

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

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

non-terminal è
roba di gram-
matiche, usa
nodes/con-
structors

t2l nope, mett
un r3 = 18
X Z :- r .., 116
.., !, e rifatti
all'esempio della
sezione prima
(fai in modo che
f funzioni solo
con la seconda
regola per r)
associate to
the...
as much as
needed, indee
prolog programs
do not necessar
ily terminate



■ **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, otherwise, 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* starts 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 around 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 e

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 successful 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 is 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 expecially 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 immediate. The *Or* case is rather 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 substitution in the lhs tree. Therefore, if we
 210 need to backtrack in the lhs, we need to reset the rhs.

```

Definition next_alt : bool -> tree -> 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*.

Lemma *path_atom_next_alt_id* b A: *path_atom* A -> *next_alt* b A = Some A. (3)

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 from
the or

4.3 The *run* inductive

The inductive procedure *run* is modeled as a function: it takes as input a program, a set of free variables, an initial substitution σ_0 , and a tree t_0 , and returns a substitution σ_1 together with an optional updated tree t_1 . The substitution σ_1 represents the most-general unificator that makes the execution of the tree t_0 succeed starting from the initial substitution σ_0 , σ_1 is an extension of σ_0 . The tree t_1 is the updated tree containing the alternatives that have 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.

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

■ **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.

```

238 Fixpoint valid_tree s :=
239   match s with
240     | TA _ | OK | KO => true
241     | Or None _ B => valid_tree B
242     | Or (Some A) _ B => valid_tree A && ((B == KO) || B.base_or B)
243     | And A B0 B => valid_tree A &&
244       if success A then valid_tree B
245       else B == big_and B0
246   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.

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 * goals) & alts
with goals := no_goals | more_goals of (A * alts) & goals .

```



```

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

```

Inductive nur : fvS -> Sigma -> goals -> alts -> Sigma -> alts -> Prop := (10)

$$\begin{array}{c}
 \frac{}{\text{nur fv s } [::] \text{ a s a}} \text{STOPE} \\
 \\
 \frac{\text{nur fv s gl ca s1 r}}{\text{nur fv s } [::] (\text{cut, ca}) \& \text{gl} \text{ a s1 r}} \text{CUTE} \\
 \\
 \frac{\text{stepE fv t s al gl} = (\text{fv}', [::] \text{ b \& bs }]) \quad \text{nur fv' b.1 b.2 (bs++al) s1 r}}{\text{nur fv s } [::] (\text{call t, ca}) \& \text{gl} \text{ al s1 r}} \text{CALLE} \\
 \\
 \frac{\text{stepE fv t s al gl} = (\text{fv}', [::]) \quad \text{nur fv' s1 a al s2 r}}{\text{nur fv s } [::] (\text{call t, ca}) \& \text{gl} [::] (\text{s1, a}) \& \text{al} \text{ s2 r.}} \text{FAILE}
 \end{array}$$

■ **Figure 7** Rule system for *nur*

258 An elpi state is an enhanced two-dimension list. The outermost list represents the list
 259 of alternatives in disjunction accompagnate 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 conjunctions. 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 succeed (CALLE) or fail (FAILE). In the latter case, a backchaining operation is
 274 mandatory: the first goal does not succeed, we need to take the head of the alternatives, and
 275 make it the new list of goals to be explored. In the former case, we need to build a new state
 276 and this ask some attention. When we are calling a rules,

277 5.1 From trees to lists

278 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 lB := t2l B s1 [::] in
  let lA := t2l A s lB in
  add_ca_deep bt (lA ++ lB)
| And A B0 B =>
  let lA := t2l A s bt in
  if lA is [:: (s1A, x) & xs] then
    let lB0 := a2g B0 in
    let xz := add_deepG bt lB0 x in
    let xs := add_deep bt lB0 xs in
    let xs := map (catr lB0) xs in
    let lB := t2l B s1A (xs ++ bt) in
    (map (catl xz) lB) ++ xs
  else [::]
end.

```

6 Semantic equivalence

► **Theorem 5** (`tree_to_elpi`).

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

► **Theorem 6** (`elpi_to_tree`).

$$\begin{aligned}
& \forall \sigma_1 \sigma_2 a \text{ na } g, \\
& \text{nur}_u \sigma_1 g a \sigma_2 \text{ na} \rightarrow \\
& \forall \sigma_0 t, \text{vt } t \rightarrow (t2l t \sigma_0 \emptyset) = ((\sigma_1, g) :: a) \rightarrow \\
& \exists t' n, \text{run}_u \sigma_0 t (\text{Some } \sigma_2) t' n \wedge t2l t' \sigma_0 \emptyset = \text{na}.
\end{aligned}$$

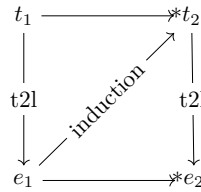
The proof of Theorem 6 is based on the idea explained in [2, Section 3.3]. An ideal statement for this lemma would be: given a function `l2t` transforming an elpi state to a tree, we would have that the execution of an elpi state e is the same as executing `run` on the tree resulting from `l2t(e)`. However, it is difficult to retrieve the structure of an elpi state and create a tree from it. This is because, in an elpi state, we have no clear information about the scope of an atom inside the list and, therefore, no evident clue about where this atom should be placed in the tree.

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

We have 4 cases to analyse:

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

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