

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 `ccsdsc` 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

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



```

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 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(5) R)) :=

```

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 subistution. This substitution is the result of the unification of q with the head of each rule in r .

Below 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 we have chosen in the Elpi language is the hard cut operator used in standard SWI-Prolog. It has two main roles: it eliminates alternatives that are chronologically created both at the same moment as, and after, the creation of the cut operator in the execution state.

As a small example of this high-level definition. Let's take the program in Figure 2 and the query $q = g\ 2\ Z$. All the 3 rules for g can be used on the q . They are executed in order of the definition in the program, i.e., $r1$ is tried first then $r2$ and finally $r3$.

The first rule has no premises returns the assignment $Z = 2$. We however are not finished, there are still two non-explored alternatives consisting in the premises of $r2$ and $r3$.

The premises of $r2$ are " $r\ 2\ Z, !$ ". In this sequent the role of the cut becomes evident: if it is executed, i.e. $r\ 2\ Z$ succeeds, then the premises of $r3$ will be cut away, since they have been created at the same time of the creation of the cut in the alternatives list; moreover, if the call $r\ 2\ Z$ leaves alternatives, only the first is committed and the other are discarded, since these alternatives would have a deeper depth than the cut itself.

Concretely speaking, $r\ 2\ Z$ will provide two alternatives, assigning Z respectively to 4 and 8. The second solution is discarded by the cut.

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.

3.1 Tree semantics

```

Inductive tree :=
| KO | OK | Dead
| TA : A -> tree
| Or  : tree -> Sigma -> tree -> tree
| And : tree -> seq A -> tree -> tree.

```

In the tree we distinguish 6 main cases: *KO*, *OK*, and *Dead* are special meta-symbols representing, respectively, a failed, a successful, and a dead terminal. These symbols are considered meta because they are internal intermediate symbols used to give structure to the tree. While the first two symbols are of immediate understanding, we use *Dead* to represent ghost state, that is, the *Dead* symbol is always ignored by the tree interpreter.

TA (acronym for tree-atom) is the constructor of atoms in the tree.

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Fixpoint is_dead A :=
  match A with
  | Dead => true
  | OK | KO | TA _ => false
  | And A B0 B => is_dead A
  | Or A s B => is_dead A && is_dead B
  end.

Fixpoint path_end A :=
  match A with
  | Dead | OK | KO | TA _ => A
  | Or A _ B =>
    if is_dead A then path_end B
    else path_end A
  | And A B0 B =>
    match path_end A with
    | OK => path_end B
    | A => A
    end
  end.

```

(a) Defintion of *is_dead*(b) Defintion of *path_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 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 in prolog-like syntax, in a tree $A \wedge_{B_0} B$, if $t2l$ is the function flattening the tree in a list of sequents disjunction and $t2l(A) = A_1, \dots, A_n$, then we would have $(A_1, t2l B); (A_2, B_0); \dots; (A_n, B_0)$.

A graphical representation of the 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* and *Dead* terminals 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 *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 *fv* 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)

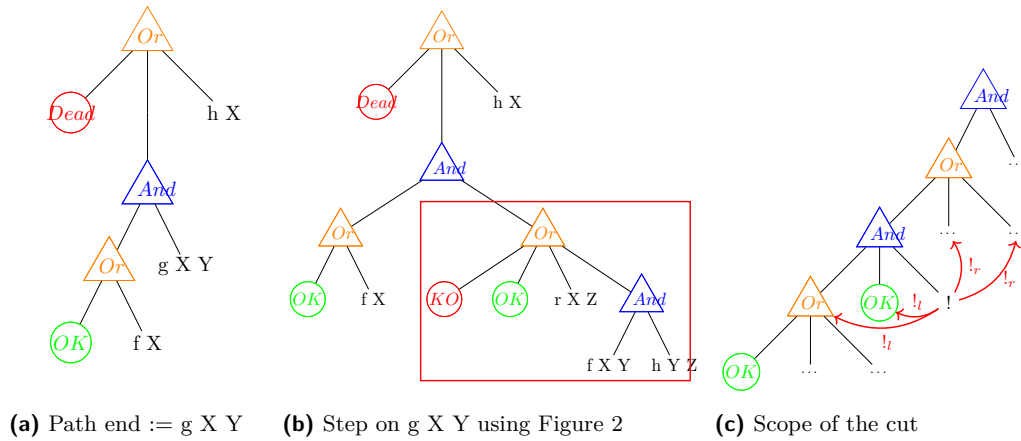
Definition *next_alt* : bool -> tree -> option tree := (8)

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

A particular tree we want to identify is a *is_dead* tree (defined in Figure 3a). This tree has the property to never produce a solution: it is either the *Dead* tree or both branches of *Or* are dead, or the lhs of *And* is dead. In the latter case, we note that B can be non-dead, but this is not a problem since the interpreter can run B only if A is non-dead.

The prolog interpreter explores the state in DFS strategy, it finds the “first-to-be-explored” (ftbe) atom of the tree and then interpretes it. In a non-*is_dead* tree, we get the ftbe node via *path_end*, shown in Figure 3b. The *path_end* is either the tree itself if the tree is a leaf. Otherwise, if the tree is a disjunction, the path continues on the left- or the right-subtree depending of if the the lhs is a *is_dead* tree. In the *Or* case we are clearing ignoring the dead (ghost) state.

In the case of a conjunction, it is more interesting to see what happens. If the *path_end* p of the lhs is a success then we look for the *path_end* in the rhs, otherwise we return p . In



■ **Figure 4** Some tree representations

137 Figure 4a the *path_end* of the tree is g X.

138 Below we define two special kind of trees depending on their pathend.

139 **Definition** $\text{success } A := \text{path_end } A == \text{OK}.$ (1)

140 **Definition** $\text{failed } A := (\text{path_end } A == \text{KO}) \mid (\text{path_end } A == \text{Dead}).$ (2)

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

142 Free variables are those variables that appear in a tree; they are used in the backchaining operation to refresh the variables in the program.

143 The *step_tag* indicates the type of internal tree step that has been performed. **CutBrothers** denotes the interpretation of a superficial cut, i.e., a cut whose parent nodes are all *And*-nodes. **Expanded** denotes the interpretation of non-superficial cuts or predicate calls. **Failure** and **Success** are returned for, respectively, *failed* and *success* trees.

144 The step procedure is intended to interpretate atoms, that is, it returns the identity for *success* and *failed* tree.

151 **Lemma** $\text{success_step } u \text{ p fv s } A: \text{success } A \rightarrow \text{step } u \text{ p fv s } A = (\text{fv}, \text{Success}, A).$ (1)

152 **Lemma** $\text{failed_step } u \text{ p fv s1 } A: \text{failed } A \rightarrow \text{step } u \text{ p fv s1 } A = (\text{fv}, \text{Failed}, A).$ (2)

153 Therefore, the two interesting cases of a tree the interpretation of trees with path-end equal to a call or a cut atom.

154 *Call step* The interpretation of a call *c* is performed by replacing the call wrt the result of the $\mathcal{B} c$, then if *l* is empty then *KO* tree is returned, otherwise the call is replaced by right-skewed tree made of *n* inner *Or* nodes, where *n* is the length of *l*. The root has *KO* as left child. The lhs of the other nodes is a right-skewed tree of *And* nodes. The *And* nodes are again a right-skewed tree containing then atoms (either cut or call) taken from the list *l*.

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

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

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

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

174 ► **Definition 3** (Soft-kill). *Given a tree t , soft-kill replaces all the leaves of the tree with the node KO except for the leaves that are part of the path p of t .*

176 ► **Definition 4** (Hard-kill). *Given a tree t , hard-kill replaces all the leaves of the tree with the node KO*

178 An example of the impact of the cut is show in Figure 4c. The step routine interprets
 179 the cut if it is at the end of the current path. In the example we have tagged in red the
 180 arrow $!_l$ indicating which sub-trees is soft-killed and $!_r$ indicated which is sub-trees are to be
 181 hard-killed.

182 3.1.1 Execution example

183 3.1.2 Valid tree

184 3.2 Elpi semantics

185 TODO: dire che la semantica ad albero è più facile per le prove

186 The Elpi interpreter is based on an operational semantics close to the one picked by
 187 Pusch in [16], in turn closely related to the one given by Debray and Mishra in [6, Section
 188 4.3]. Push mechanized the semantics in Isabelle/HOL together with some optimizations that
 189 are present in the Warren Abstract Machine [20, 1].

190 In these operational semantics we need to decorate the cut atom with a list of alternative,
 191 morally a pointer to a sub-list of the overall alternatives. An atom in the elpi semantics is
 192 defined as follows:

```

Inductive alts :=
  | no_alt
  | more_alt : (Sigma * goals) -> alts -> alts
with goals :=
  | no_goals
  | more_goals : (A * alts) -> goals -> goals .

```

193 We are completely loosing the tree structure. There are no clean reset points. The
 194 backtracking operation is simpler: it is the tail function. The cutr and cutl operations
 195 disappears: the alternatives are stored directly in the cutE terminal.

196 The elpi interpreter is as follows:

```

(*TODO: add system of rules*)
Inductive nur : Sigma -> goals -> alts -> Sigma -> alts -> Type :=
  | StopE s a : nur s nilC a s a
  | CutE s s1 a ca r gl : nur s gl ca s1 r -> nur s ((cutE ca) :: gl) a s1 r
  | CallE p s s1 a b bs gl r t :
    F u p t s = [:: b & bs ] ->
      nur b.1 (save_goals a gl (a2gs1 p b)) (save_alts a gl ((aa2gs p) bs) ++ a) s1 r ->
      nur s ((callE p t) :: gl) a s1 r
  | FailE p s s1 s2 t gl a al r :
    F u p t s = [::] -> nur s1 a al s2 r -> nur s ((callE p t) :: gl) ((s1, a) :: al) s2 r.

```

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

```

198 Fixpoint t2l (A: tree) s (bt : alts) : alts :=
199 match A with
200 | OK          => [:: (s, [::])] ]
201 | (KO | Dead) => [::]
202 | TA a        => [:: (s, [:: (a, [::])] ) ]
203 | Or A s1 B   =>
204   let lB := t2l B s1 [::] in
205   let lA := t2l A s lB in
206   add_ca_deep bt (lA ++ lB)
207 | And A B0 B  =>
208   let lB0 : goals := r2l B0 in
209   let lA  := t2l A s bt in
210   if lA is [:: (slA, x) & xs] then
211     let xz := add_deepG bt lB0 x in
212     let xs := add_deep bt lB0 xs in
213     let xs := make_lB0 xs lB0 in
214     let lB := t2l B slA (xs ++ bt) in
215     (make_lB01 lB xz) ++ xs
216   else [::]
217 end.

```

► **Theorem 5** (tree_to_elpi).

198 $\forall A \sigma_1 B \sigma_2 b \sigma_0, vt A \rightarrow$
 199 $run_u \sigma_1 A (Some \sigma_2) B b \rightarrow$
 200 $\exists x xs, t2l A \sigma_1 \emptyset = x :: xs \wedge nur_u x.1 x.2 xs \sigma_2 (t2l B \sigma_0 \emptyset).$

► **Theorem 6** (elpi_to_tree).

201 $\forall \sigma_1 \sigma_2 a na g,$
 202 $nur_u \sigma_1 g a \sigma_2 na \rightarrow$
 203 $\forall \sigma_0 t, vt t \rightarrow (t2l t \sigma_0 \emptyset) = ((\sigma_1, g) :: a) \rightarrow$
 204 $\exists t' n, run_u \sigma_0 t (Some \sigma_2) t' n \wedge t2l t' \sigma_0 \emptyset = na.$

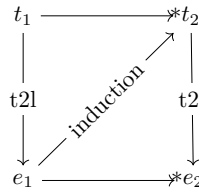
205 The proof of Theorem 6 is based on the idea explained in [2, Section 3.3]. An ideal
 206 statement for this lemma would be: given a function `l2t` transforming an elpi state to a tree,
 207 we would have that the the execution of an elpi state e is the same as executing `run` on
 208 the tree resulting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

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

216 We have 4 cases to analyse:

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■ **Figure 5** Induction scheme for Theorem 6

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