The Prolog debugger and declarative programming

Wlodzimierz Drabent
Institute of Computer Science, Polish Academy of Sciences,
ul. Jana Kazimierza 5, 01-248 Warszawa, Poland
and
Department of Computer and Information Science, Linköping University
S – 581 83 Linköping, Sweden
drabent at ipipan dot waw dot pl
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Abstract
Logic programming is a declarative programming paradigm. Programming language Prolog makes logic programming possible, at least to a substantial extent. However the Prolog debugger works solely in terms of the operational semantics. So it is incompatible with declarative programming. This report discusses this issue and tries to find how the debugger may be used from the declarative point of view.

1 Introduction
The idea of logic programming is that a program is a set of logic formulae, and a computation means producing logical consequences of the program. The logical consequence is that of the standard first order logic. So it is a declarative programming paradigm. The program is not a description of any computation, it may be rather seen as a description of a problem to solve. Answers of a given program (the logic) may be computed under various strategies (the control), the results depend solely on the former. This semantics of programs, based on logic, is called declarative semantics.

Programming language Prolog is a main implementation of logic programming. Its core is an implementation of SLD-resolution under a fixed control: the selection rule is fixed – the first atom of the current query is selected; SLD-trees are searched depth-first, and the children of each node are ordered
For a given program $P$ and query $Q$, Prolog computes those logical consequences of $P$ which are instances of $Q$. If the computation is finite then, roughly speaking, all such consequences are computed. (See e.g. [Apt97] for details.)

This core of the language may be called “pure Prolog”. It is augmented by additional constructs. Most important is a huge collection of built-in predicates. Some of them are “extra logical” – they cannot be expressed by means of SLD-resolution. An example is predicate $\text{var}/1$; query $\text{var}(t)$ succeeds if its argument is a variable. Using $\text{var}/1$ violates a few principles of the standard logic, for instance commutativity of conjunction. The success of $\text{var}(t)$ depends on whether at the moment $\text{var}(t)$ is selected the argument is unbound. Other constructs, most notably the cut ($!$), are added so that programmer may influence the flow of control – prune parts of the search space (i.e. SLD-tree), or modify the selection rule.

Due to all of this, full Prolog can be viewed without any reference to logic, as a programming language with a specific control flow, the terms as the data, and a certain kind of term matching as the main primitive operation. Of course such operational view loses all the advantages of declarative programming.

On the other hand, Prolog makes practical declarative programming possible, by separating logic and control. A program treated as a set of logical clauses is a logic program. The logic determines the answers of the program. At a lower level, the programmer can influence the control. This can be done by setting the order of program clauses and the order of premises within a clause (and by some additional Prolog constructs). Changing the control keeps the logic intact, and thus the program’s answers are unchanged [Kow79]. What is changed is the way they are computed, for instance the computation may be made more efficient. In particular, an infinite computation may be changed into a finite one.

In some cases, programs need to contain some non-logical fragments, for instance for input-output. But the practice shows that Prolog makes possible building programs which are to a substantial extent declarative; in other words, substantial fragments of such programs are logic programs. Numerous examples are given in the textbooks, for instance [SS91]. For a more formal discussion of this issue see [Dra18].

It should be noted that the operational approach to Prolog programming is often overused. In such programs it is not the declarative semantics that matters. A typical example is the red cut [SS94] – a programming technique which is based on pruning the search space; the program has undesired logical

\[1\] An important technical detail is a simplification of the unification algorithm – omitting the occur-check. This makes the implementation unsound in a general case. Some well-known programming hints, and also formal sufficient conditions, show how to construct programs and queries for which the implementation is sound.
consequences, which are however not computed due to the pruning. Under-
standing such program substantially depends on its operational semantics.
And understanding the operational semantics is more difficult than that of
the declarative semantics. In particular, examples are known where a certain
choice of the initial query leads to unexpected results of a program employing
the red cut [SS94, p. 202-203], [CM03, Chapter 4]. It seems that some Prolog
textbooks over-use such style of programming (like [CM03, Bra12], at least
in their earlier editions).

**Debugging tools of Prolog.** We begin with a terminological comment.
Often the term “debugging” is related to locating errors in programs. How-
ever its meaning is wider; it also includes correcting errors. So a better term
for locating errors is *diagnosis.* However this text still does not reject the
first usage, as it is quite common.

Despite Prolog has been designed mainly as an implementation of logic
programming, its debugging tools work solely in terms of the operational
semantics. So all the advantages of declarative programming are lost when
it comes to locating errors in a program. The Prolog debugger is basically
a tracing tool. It communicates with the programmer only in terms of the
operational semantics. She (the programmer) must abandon the convenient
high abstraction level of the declarative semantics and think about her pro-
gram in operational terms.

**Declarative diagnosis.** In principle, it is well known how to locate errors
in logic programs declaratively, i.e. abstracting from the operational seman-
tics (see e.g. [Dra16, Section 7] and the references therein). The approach
is called *declarative diagnosis* (and was introduced under a name *algorithmic debugging* [Sha83]). Two kinds of errors of the declarative semantics
of a program are dealt with: *incorrectness* – producing results which are
wrong according to the specification, and *incompleteness* – not producing re-
sults which are required by the specification. An incorrectness (respectively
incompleteness) diagnosis algorithm locates an error semi-automatically, ask-
ing the user queries about the specification. A starting point for the diagnosis
algorithm is a *symptom* obtained by testing the program.

Unfortunately, declarative diagnosis was not adapted in practice. No
tools for it are included in current Prolog systems.

A possibly main reason for lack of acceptance of declarative diagnosis was
discussed in [Dra16, Section 7]. Namely, declarative diagnosis requires that
the programmer exactly knows the relations to be defined by the program.
Formally this means that the programmer knows the least Herbrand model
of the intended program. (In other words, the least Herbrand model is the
specification.) This requirement turns out to be unrealistic. For instance,
in an insertion sort program we do not know how inserting an element into
an unsorted list should be performed. This can be done in any way, as the algorithm inserts elements only into sorted lists. Usually the programmer knows the intended least Herbrand model of her program only approximately. She knows a certain superset and a certain subset of the intended model. The superset tells what may be computed, and the subset – what must be computed. Let us call the former the specification for correctness and the latter the specification for completeness. Thus the program should be correct with respect to the former specification and complete with respect to the latter. In our example, it is irrelevant how an element is inserted into an unsorted list; thus the specification for correctness would include all such possible insertions.

Now it is obvious that when diagnosing incorrectness the programmer should use the specification of correctness instead of the intended model, and the specification of completeness should be used when diagnosing incompleteness. The author believes that this approach can make declarative diagnosis useful in practice.

This paper. The role of this paper is to find if, how, and to which extent the Prolog debugger can be used as a tool for declarative logic programming. We focus on the debugger of SICStus Prolog. We omit its advanced debugging features, which are sophisticated, but seem not easy to learn and not known by most of programmers.

The paper is organized as follows. The next section deals with the Prolog debugger and the information it can provide. Section 3 discusses applying the debugger for diagnosing incorrectness and incompleteness. The last section contains conclusions.

2 Prolog debugger

In this section we present the Prolog debugger and try to find out how to use it to obtain the information necessary from the point of view of declarative programming. First we relate the computation model used by the debugger to the standard operational semantics (LD-resolution). We also formalize the information needed for incorrectness and incompleteness diagnoses. Roughly speaking, for incorrectness diagnosis we need to know which atomic answers have directly contributed to a given one. For incompleteness diagnosis, the related information is which answers have been computed for each top-level atomic query that has appeared in resolving a given atomic query. In Section 2.2 we describe the messages of the debugger. Section 2.3 investigates how to extract from the debugger’s output the information of interest.
2.1 Byrd box model and LD-resolution

The debugger refers to the operational semantics of Prolog in terms of a “Byrd box model”. Roughly speaking, the model assigns four ports to each atom selected in LD-resolution. From a programmer’s point of view such atom can be called a procedure call. The model is usually easily understood by programmers. However it will be useful to relate it here to LD-resolution, and to introduce some additional notions. In this paper, we often skip “LD-” and by “derivation” we mean “LD-derivation” (unless stated otherwise).

Structuring LD-derivations. Let us consider a (finite or infinite) LD-derivation D with queries Q0, Q1, Q2,..., the input clauses C1, C2,..., and the mgu’s θ1, θ2,..., By a procedure call of D we mean the atom selected in a query of D. Following [DM88, Dra17], we describe a fragment of D which may be viewed as the evaluation of a given procedure call A.

Definition 1 Consider a query Qk−1 = A, B1,..., Bm (m ≥ 0) in a derivation D as above. If D contains a query Ql = (B1,..., Bm)θk···θl, k ≤ l, then the call A (of Qk−1) succeeds in D.

In such case, by the subderivation for A (of Qk−1 in D) we mean the fragment of D consisting of the queries Qi, where k−1 ≤ i ≤ l, and for k−1 ≤ i < l each Qi contains more than m atoms\(^2\). We call such subderivation successful. The (computed) answer for A (of Qk−1 in D) is Aθk···θl.

If A (of Qk−1) does not succeed in D then the subderivation for A (of Qk−1 in D) is the fragment of D consisting of the queries Qi where k−1 ≤ i.

By a subderivation (respectively an answer) for A of Q in an LD-tree T we mean a subderivation (answer) for A of Q in a branch D of T.

Now we structure a subderivation D for an atom A by distinguishing in it top-level procedure calls. Assume A is resolved with a clause H ← A1,..., An, in the first step of D. If then an instance of A becomes a procedure call, we call it a top-level call. More precisely:

Definition 2 Consider a subderivation D for A. Its first two queries are Qk−1 = A, Q′, Qk = (A1,..., An, Q′)θk, and A1,..., An is the body of the clause used in the first step of the subderivation. Assume n > 0. Let |Qk| be the length of Qk (this means the number of atoms in Qk).

Consider an index j, 1 ≤ j ≤ n. If there exists in D a query of the length |Qk| + 1 − j and Qij = (A1,..., An, Q′)θk···θij is the first such query then we say that Aijθk···θij (of Qij) is a top-level call of D, and the subderivation D′ for Aijθk···θij (of Qij) in D is a top-level subderivation of D.

\(^2\) Thus each such Qij is of the form A1,..., Ami, (B1,..., Bm)θk···θi where mi > 0. This implies that the least l > k is taken such that Qij is of the form (B1,..., Bm)θk···θi.
A top-level call of a subderivation $D$ for $A$ will be also called a top-level call for $A$.

Notice that if $A$ is resolved with a unary clause ($n = 0$, and $D$ consists of two queries) then $D$ has no top-level subderivations. Also, the last query of a top-level subderivation of $D$ is the first query of the next subderivation, or it is the last query of $D$.

We are ready to describe what information to obtain from the debugger in order to facilitate incorrectness and incompleteness diagnosis. First we describe which top-level answers correspond to an answer for $A$; we may say that they have been used to obtain the answer for $A$.

**Definition 3** If subderivation $D$ for $A$ as in Def. 2 is successful then it has $n$ top-level subderivations, for atoms $A_j \theta_k \ldots \theta_{j_1}$ ($j = 1, \ldots, n$). Their answers in $D$ are, respectively, $A'_{j_1} = A_j \theta_k \ldots \theta_{j_1+1}$ (where $i_{n+1}$ is the index of the last query $Q_{i_{n+1}}$ of $D$). In such case, by the top-level success trace for $A$ (in $D$) we mean the sequence $A'_{1}, \ldots, A'_{n}$ of the answers.

Top-level success traces will be employed in incorrectness diagnosis. For diagnosing incompleteness, we need to collect all the answers for each top-level call.

**Definition 4** Consider an LD-tree $T$ with a node $Q$. Let $A$ be the first atom of $Q$. By the top-level search trace (or simply top-level trace) for $A$ (of $Q$ in $T$) we mean the set of pairs

$$\{ (B, \{B_1, \ldots, B_k\}) \mid B \text{ is the first atom of a node } Q' \text{ of } T, \\ Q' \text{ occurs in a subderivation } D' \text{ for } A \text{ of } Q \text{ in } T, \\ B \text{ is a top-level call of } D', \\ B_1, \ldots, B_k \text{ are the answers for } B \text{ of } Q' \text{ in } T \}.$$

2.2 Debugger output.

For the purposes of this paper, this section should provide a sufficient description of the debugger. We focus on the debugger of SICStus. For an introduction and further information about the Prolog debugger see e.g. the textbook [CM03] or the manual [http://sicstus.sics.se/](http://sicstus.sics.se/).

Prolog computation can be seen as traversal of an LD-tree. The Prolog debugger reports the current state of the traversal by displaying one line items, such an item contains a single atom augmented by other information. A procedure call $A$ is reported as an item

```
  n  d Call: A
```

and a corresponding answer $A' = A\theta_k \ldots \theta_i$ as

```
  n  d Exit: A'
```
Here \( n, d \) are, respectively, the unique invocation number and the current depth of the invocation; we skip the details. What is important is that, given an Exit item, the invocation number uniquely determines the corresponding Call item.

Note that a node in an LD-tree may be visited many times, and usually more than one item correspond to a single visit. For instance, to the last node \( Q_l \) of a successful subderivation (from Definition 1), there correspond, at least, an Exit item with atom \( A\theta_k \cdots \theta_l \) and a Call item with atom \( B_1\theta_k \cdots \theta_l \) (provided \( m > 0 \)). Note that such a node is often the last query of more than one successful subderivations (cf. Def. 2). In such case other Exit items correspond to \( Q_l \). They are displayed in the order which may be described as leaving nested procedure calls. More formally, the order of displaying the Exit items is that of the increasing lengths of the corresponding successful subderivations. (The displayed invocation depths of these items are decreasing consecutive natural numbers.)

An Exit item is preceded by \(?\) when backtrack-points exist between the corresponding Call and the given Exit. Thus more answers are possible for (the atom of) this Call.

At backtracking the debugger displays Redo items of the form

\[
\begin{align*}
n & \quad d \quad \text{Redo:} \quad A'
\end{align*}
\]

Such item corresponds to an Exit item with the same numbers \( n, d \) and atom \( A' \). Both items correspond to the same node of the LD-tree. The Redo item appears, speaking informally, when the answer \( A' \) is abandoned, and the computation of a new answer for the same query begins. SICStus produces a Redo item only when the corresponding Exit item was preceded by \(?\).

A Fail item

\[
\begin{align*}
n & \quad d \quad \text{Fail:} \quad A
\end{align*}
\]

is displayed at backtracking. It means that a node with \( A \) selected is being left (and will not be visited anymore). The numbers and the atom in a Fail item are the same as those in the corresponding Call item. Both the Call and Fail items correspond to the same node of the LD-tree.

We described the output of the debugger of SICStus. The debuggers of most Prolog systems are similar. However important differences happen. For instance the debugger of SWI-Prolog (http://swi-prolog.org/) does not display the invocation number, and the approach presented below is inapplicable to it. On the other hand, the debuggers or Ciao (http://ciao-lang.org/) and Yap (https://www.dcc.fc.up.pt/vsc/yap/) seem to display such numbers.
2.3 Obtaining top-level traces

We are ready to describe how to obtain top-level traces using the Prolog debugger. We first deal with the search trace.

Algorithm 5 (Top-level trace) Assume that we are at a Call port; the debugger displays

\[ n \ d \ Call: \ A \]

We show a way of obtaining the top-level search trace for \( A \).

1. Type \[ \text{enter} \] to make one step of computation.
   
   (There are three possibilities. If the result is an item \( n_1 \ d+1 \ Call: \ B_1 \) then \( B_1 \) is an instance of the first atom of the body of the clause used in the resolution step. Obtaining \( n \ d \ Exit: \ A' \) means that a unary clause was used and \( A \) succeeded immediately. Obtaining \( n \ d \ Fail: \ A \) means that \( A \) failed immediately, as it was not unifiable with any clause head.)

2. Now repetitively do the following.
   
   (a) If item

   \[ n \ d \ Fail: \ A \]

   is displayed then the search is completed. The trace is to be extracted from the output that the debugger has produced.

   (b) If item

   \[ n_i \ d+1 \ Call: \ B_i \quad \text{or} \quad n_i \ d+1 \ Redo: \ B_i \]

   is displayed then type \[ \text{s} \], to go to the corresponding Exit or Fail port.

   (c) If

   \[ n_i \ d+1 \ Exit: \ B_i \quad \text{or} \quad n_i \ d+1 \ Fail: \ B_i \]

   is displayed then type \[ \text{enter} \] to make a single step.

   (d) Obtaining an item

   \[ n \ d \ Exit: \ A' \]

   means that an answer \( A' \) for \( A \) has been produced. In other words, a successful subderivation for \( A \) has been constructed. Unfortunately, the Prolog debugger does not directly support continuing the search for further answers for \( A \). We can do this as follows.

   - If the item \( n \ d \ Exit: \ A' \) is obtained by applying a unary clause to \( A \) (i.e. obtained immediately by typing \[ \text{enter} \] at \( n \ d \ Call: \ A \) or at \( n \ d \ Redo: \ A \) then
i. If the item \( n \ d \ \text{Exit}: A' \) is not preceded by \( ? \) then the search is completed (similarly as in case 2a).

ii. Otherwise the item is a backtrack point, perform the backtracking by issuing the command \( \text{jr} n \). Item \( n \ d \ \text{Redo}: A' \) is displayed. Type \( \text{enter} \) as in step 1.

- Otherwise (a non-unary clause has been used) identify in the printed items the top-level success trace for \( A \), as described below.

Find the last item of the trace that is preceded by \( ? \), assume it is

\[
? \quad n_j \ d+1 \ \text{Exit}: B_j
\]

This is the backtrack-point to which backtracking from \( n \ d \ \text{Exit}: A' \) should go.

iii. If there is no such item then the search is completed (similarly as in case 2a).

iv. Otherwise perform the backtracking by issuing the command \( \text{jr} n_j \). Item \( n_j \ d+1 \ \text{Redo}: B_j \) is displayed. Type \( \text{enter} \) as in step 1.

3. Now the top-level trace has to be extracted from the information printed by the debugger in stage 2 above. A call and its corresponding answers have the same unique invocation number \( n_j \). Thus the calls may be paired with their answers by means of sorting the debugger output.

In a particular case of using SICStus under Emacs, the sorting can be done by running a shell command `cut -b 2- | sort -nk 1 | egrep 'Call:|Exit:'` on the debugger output in buffer *prolog*, using Emacs command `shell-command-on-region`. This removes from each line the first character (space or \( ? \)), sorts the items according to the first number (which is the invocation number) and selects Call and Exit items.

The result of sorting provides the top-level trace for \( A \) in a readable form.

An alternative version of step 3 of the algorithm is running Prolog for each query from the Call items of the debugger output.

**Algorithm 6 (Top-level success trace)** Assume that we obtained an Exit item containing an answer \( A' \). The item corresponds to the last query of a successful subderivation \( D \) for an atom \( A \). In order to extract from the debugger output the top-level trace for \( D \), we need that the debugger has displayed the Call and Exit items containing the top-level calls of \( D \) and the corresponding answers. If this is not the case then, at the \( n \ d \ \text{Exit}: A' \)
item, type r to arrive to the corresponding Call item. Then start constructing
top-level search trace, until arriving again to the Exit item.

This may be made more efficient, by re-starting the computation with
\( A' \) the initial query. Then the search space to obtain a success of \( A' \) (and
the corresponding top-level trace) may be substantially smaller than that for
original atomic query from the Call item. Additionally, case 2d of Algorithm
5 never needs to be performed.

To select a top-level success trace from the printed debugger items, do
repetitively the following. The trace will be constructed backwards. Initially
the current item is \( n \ d \ \text{Exit:} \ A' \).

The current item is
\[
n \ d \ \text{Exit:} \ A' \quad \text{or} \quad n_j \ d+1 \ \text{Call:} \ B_j
\]

Consider the preceding item.

If the immediately preceding item is
\[
n_{j'} \ d+1 \ \text{Exit:} \ B'_{j'}
\]
then \( B'_{j'} \) is obtained as an element of the success trace. Find the cor-
responding
\[
n_{j'} \ d+1 \ \text{Call:} \ B'_{j'}
\]
item, and make it the current item

Otherwise, the preceding item is
\[
n \ d \ \text{Call:} \ A
\]
and all the elements of of the success trace have been found.

3 Diagnosis

This section discusses first diagnosis of incorrectness, and then that of incom-
pleteness. In each case we first present the diagnosis itself, and then discuss
how it may be performed employing the Prolog debugger.

3.1 Diagnosing incorrectness.

A *symptom* of incorrectness is an incorrect answer of the program. More
formally, consider a program \( P \) and a Herbrand interpretation \( S_{corr} \), which
is our specification for correctness. A symptom is an answer \( Q \) such that

\[3\] An answer in the sense used here is called a “correct instance of a query” in [Apt97].
In other words, it is the result of applying a correct answer substitution to a query.
$S_{corr} \not\models Q$, where $S_{corr}$ is the specification for correctness. (In other words, $Q$ has a ground instance $Q\theta$ such that $Q \notin S_{corr}$.) When testing finds such a symptom, the role of diagnosis is to find the error, this means the reason of incorrectness. An error is a clause of the program which out of correct (w.r.t. $S_{corr}$) premises produces and incorrect conclusion. More precisely:

**Definition 7** Given a definite program $P$ and a specification $S_{corr}$ (for correctness), an **incorrectness error** is an instance

$$H \leftarrow B_1, \ldots, B_n \quad (n \geq 0)$$

of a clause of $P$ such that $S_{corr} \models B_i$ for all $i = 1, \ldots, n$, but $S_{corr} \not\models H$.

An **incorrect clause** is a clause $C$ having an instance $C\theta$ which is an incorrectness error.

In other words, $C$ is an incorrect clause iff $S_{corr} \not\models C$. In what follows, by a **correct atom** we consider an atom $A$ such that $S_{corr} \models A$ (where $S_{corr}$ is the considered specification for correctness).

Note that we cannot formally establish which part of the clause is erroneous. Easy examples can be constructed showing that an incorrect clause $C$ can be corrected in various ways; and each atom of $C$ remains unchanged in some corrected version of $C$ [Dra16, Section 7.1].

The incorrectness diagnosis algorithm is based on the notion of a proof tree, called also implication tree.

**Definition 8** Let $P$ be a definite program and $Q$ an atomic query. A **proof tree** for $P$ and $Q$ is a finite tree in which the nodes are atoms, the root is $Q$ and

if $B_1, \ldots, B_n$ are the children of a node $B$ then $B \leftarrow B_1, \ldots, B_n$ is an instance of a clause of $P$ \ $(n \geq 0)$.

Note that the leaves of a proof tree are instances of unary clauses of $P$.

Now diagnosing incorrectness is rather obvious. If an atom $Q$ is (an instance of) an answer of $P$ then there exists a proof tree for $P, Q$. The tree must contain an incorrectness error (otherwise the root of the tree is correct, i.e. $S_{corr} \models Q$). A natural way of searching for the error is to begin from the root and, recursively, check the children $B_1, \ldots, B_n$ of the current node whether they are correct (formally, whether $S_{corr} \models B_i$). If all of them are correct, the error is found. Otherwise take an incorrect child $B_i$, and continue the search taking $B_i$ as the current node.

Obviously, such search locates a single error. So correcting the error does not guarantee correctness of the program.\footnote{This does not even guarantee that the symptom we began with would disappear – there may be some other errors involved.}
3.2 Prolog debugger and incorrectness

Now we try to find out to which extent the algorithm described above can be mimicked by the standard Prolog debugger. Unfortunately, the debugger does not provide a way to construct a proof tree for a given answer. We can however employ top-level success traces to perform a search similar to that done by the incorrectness diagnosing algorithm.

3.2.1 A strategy for incorrectness errors

Here we describe how to locate incorrectness errors using the Prolog debugger.

Algorithm 9 Assume that while tracing the program we found out an incorrect answer $A'$ (for a query $A$). So we are at an Exit item containing $A'$. Type r to arrive to the corresponding Call item $n \text{ call: } A$. Do repetitively the following:

1. Construct the top-level success trace $B'_1, \ldots, B'_m$ for the subderivation $D$ (for an atom $A$, where $A'$ is the answer for $A$ in $D$), as described in Algorithm 6.

2. Check whether the atoms of the trace are correct (formally, whether $\mathcal{S}_{\text{corr}} \models B'_i$). If all of them are, then the search ends. Otherwise take an item $n_i \text{ d+1 Exit: } B'_i$ containing an incorrect $B'_i$. Type jc $n_i$ to arrive to the corresponding Call item $n_i \text{ d+1 call: } B$. Now repeat the search (with $A, A'$ replaced by, respectively, $B, B'_i$).

The last obtained top-level success trace $B'_1, \ldots, B'_m$ points out the erroneous clause of the program. The clause is $C = H \leftarrow B_1, \ldots, B_m$ such that the obtained answers are instances of the body atoms of $C$: each $B'_j$ is an instance of $B_j$, for $j = 1, \ldots, m$. The head $H$ of $C$ is unifiable with the last call $B$ for which the top-level success trace was built. Formally, $C$ has an instance which is an incorrectness error (cf. Def. 7).

Obviously, the algorithm can be improved by checking the correctness of each element $B'_i$ of the trace as soon as it is located. (So the trace needs to be constructed only until an incorrect element is found.)

The approach of Algorithm 9 is rather tedious. A more natural way to locate incorrectness errors is as follows.

Algorithm 10

1. Assume, as above, that an incorrect answer $A'$ was found. Begin as above, by arriving to the call $A$ that resulted in the incorrect answer, and starting constructing a top-level search trace.
2. For each obtained item $n_i \ d+1\ \text{Exit: } B'$ check if $B'$ is correct.

3. If $B'$ is an incorrect answer, then restart the search from $B'$.

4. If no incorrect answer has appeared until arriving to the incorrect answer $A'$ then the error is found. It is the last clause $C$ whose had was unified with $A$ in the computation. (Formally, an instance of $C$ is an incorrectness error.)

The clause may be identified, as previously, by extracting the top-level success trace (for the subderivation that produced $A'$).

**Comments**

In Algorithm 10 it is often not necessary to know the (whole) top-level success trace to identify the erroneous clause in the program. In many cases, knowing the last one or two answers of the trace is sufficient. For instance, let $n' \ d' \ \text{Call: } B$ be the last call for which top-level trace was inspected. The last item displayed by the debugger is $n' \ d' \ \text{Exit: } B'$ (where $B'$ is incorrect). Assume that the previous item is $n_j \ d'+1\ \text{Exit: } B'_j$. Then the top-level trace of interest is not empty, $B'_j$ is its last atom and is an instance of the last body atom of an erroneous clause. If the program has only one such clause, then finding the rest of the top-level success trace is unnecessary.

The error located by the second approach (Algorithm 10) may be not the one that caused the initial incorrect answer $A'$. This is because the search may go into a branch of the LD-tree distinct from the branch in which $A'$ is produced. Anyway, an actual error has been discovered in the program. This outcome is useful, as each error in the program should be corrected.

Note that the approach is complete, in the sense that the error(s) responsible for $A'$ can be found. This is due to the nondeterministic search performed by the algorithm. The error(s) will be located under some choice of incorrect answers in the top-level search traces.

The search may be made more efficient if, instead of tracing the original computation, we re-start it with an incorrect answer as a query. The corresponding modification (of both algorithms) is as follows. Whenever an incorrect answer $B'$ is identified, instead of continuing the search for the corresponding call $B$, one interrupts the debugger session and begins a new one by starting Prolog with query $B'$. The query will succeed with $B'$ (i.e. itself) as an answer, but the size of the trace may be substantially smaller (and is never greater).

The Prolog debugger does not facilitate searching for the reason of incorrectness. Finding a top-level success trace is tedious and far from obvious. In particular, there seems to be no way of skipping the backtracking that precedes obtaining the wrong answer. The abilities of the debugger make
Algorithm 10 preferable; this approach in a more straightforward way uses what is offered by the debugger.

Looking for the reason of an incorrect answer is a basic task. It is strange that such a task is not conveniently facilitated by the available debugging tools.

### 3.3 Diagnosing incompleteness

A specification for completeness is, as already stated, a Herbrand interpretation which is the set of all required ground answers of the program. A symptom of incompleteness is lack of some answers of the program. More formally, given a program $P$ and a specification $S_{\text{compl}}$, by an incompleteness symptom we may consider an atom $A$ such that $S_{\text{compl}} \models A$ but $P \not\models A$. As a symptom is to be obtained out of an actual computation, we additionally require that the LD-tree for $A$ is finite. We will consider a more general version:

**Definition 11** Consider a definite program $P$ and a specification $S_{\text{compl}}$ (for completeness). Let $A$ be an atomic query for which an LD-tree is finite and let $A\theta_1, \ldots, A\theta_n$ be the computed answers for $A$ from the tree. If there exists an instance $A\sigma \in S_{\text{compl}}$ such that $A\sigma$ is not an instance of any $A\theta_i$ ($i = 1, \ldots, n$) then $A, A\theta_1, \ldots, A\theta_n$ is an **incompleteness symptom** (for $P$ w.r.t. $S_{\text{compl}}$).

We will often skip the sequence of answers, and say that $A$ alone is the symptom. The definition can be generalized to non-atomic queries in an obvious way.

**Definition 12** Let $P$ be a definite program, and $S_{\text{compl}}$ a specification. A ground atom $A$ is **covered** by a clause $C$ w.r.t. $S_{\text{compl}}$ if there exists a ground instance $A \leftarrow B_1, \ldots, B_n$ of $C$ ($n \geq 0$) such that all the atoms $B_1, \ldots, B_n$ are in $S_{\text{compl}}$.

$A$ is covered by the program $P$ (w.r.t. $S_{\text{compl}}$) if $A$ is covered by some clause $C \in P$.

Informally, $A$ is covered by $P$ if it can be produced by a rule from $P$ out of some atoms from the specification.

For any program $P$ incomplete w.r.t. $S_{\text{compl}}$ there exists an atom $A \in S_{\text{compl}}$ uncovered by $P$ w.r.t. $S_{\text{compl}}$ [Dra16]. Such an uncovered atom $p(\vec{t})$ locates the error in $P$. This is because no rule of $P$ can produce $p(\vec{t})$ out of atoms required to be produced. This shows that the procedure $p$ (the set of clauses beginning with $p$) is the reason of the incompleteness and has to be modified, to make the program complete. Note that similarly to the incorrectness case, we cannot locate the error more precisely. Various clauses
may be modified to make $p(\vec{t})$ covered, or a new clause may be added. An extreme case is adding to $P$ a fact $p(\vec{t})$.

Incompleteness diagnosis means looking for an uncovered atom, or – more generally – for an atom with an instance which is uncovered: Such atom localizes the procedure of the program which is responsible for incompleteness.

**Definition 13** Let $P$ be a definite program, and $S_{\text{compl}}$ a specification. An **incompleteness error** (for $P$ w.r.t. $S_{\text{compl}}$) is an atom that has an instance which is not covered (by $P$ w.r.t. $S_{\text{compl}}$).

Name “incompleteness error” may seem unnatural, but we find it convenient.

A class of incompleteness diagnosis algorithms employs the following idea. Start with an atomic query $A$ (which is a symptom) and construct a top level trace for it. Inspect the trace, whether it contains a symptom $B$. If so then invoke the search recursively with $B$. Otherwise the error is located; it is some instance of $A$, and we located the procedure of the program which is the reason of the error. Such approach (see e.g. [Per86, DNTM89]) is sometimes called **Pereira-style** incompleteness diagnosis [Nai92].

### 3.4 Prolog debugger and incompleteness

We show how Pereira-style diagnosis may be performed with help of the Prolog debugger.

**Algorithm 14 (Incompleteness diagnosis)** Begin with a symptom $A$. Obtain the top-level search trace for $A$. In the trace, check if the atom $B$ from a Call item together with the answers $B_1, \ldots, B_n$ from the corresponding Exit items is an incompleteness symptom. If yes, invoke the same search starting from $B$. If the answer is no for all Call items of the trace, the search is ended as we located $A$ as an incompleteness error.

**Comments**

Standard comments about incompleteness diagnosis apply here. To decrease the search space, it is useful to start the diagnosis from a ground instance $A\theta \notin S_{\text{compl}}$ of the symptom $A$ (instead of $A$ itself). The same for each symptom $B$ found during the search – re-start the computation and the diagnosis from an appropriate instance of $B$.

Often an incorrectness error coincides with an incompleteness error – a wrong answer is produced instead of a correct one. The programmer learns about this when facing an incorrect answer $B_i$ (appearing in a top-level trace). A standard advice in such case [DNTM89, Nai92] is to switch to incorrectness diagnosis. This is because incorrectness diagnosis is simpler, and it locates an error down to a program clause (not to a whole procedure, as incompleteness
diagnosis does). The gain of such switch is less obvious in our case, since the effort needed for incorrectness diagnosis (Algorithm 10) seems not smaller than that for incompleteness (Algorithm 14).

4 Conclusions

Prolog makes declarative logic programming possible – programs may be written and reasoned about in terms of their declarative semantics, to a substantial extent abstracting from the operational semantics. This advantage is lost when it comes to locating errors in programs, as the Prolog debugger works solely in terms of the operational semantics. This paper is an attempt to study if and how the Prolog debugger can be used for declarative programming. It presents how the debugger can be used to perform incorrectness and incompleteness diagnosis. The debugger used is that of SICStus; the presented approach is inapplicable to the debugger of SWI-Prolog, as the latter does not display unique invocation numbers.

We may informally present the underlying idea of this paper in a different way: To understand what program execution can tell us about the declarative semantics of the program, we need to be able to obtain the following information. 1. For a given atomic answer $A$, what are the top-level answers that have lead to $A$? 2. For a given atomic query $Q$, and for each top-level atomic query $B$ in the computation for $Q$, what are all the answers for $B$?

It turns out that the information needed to declaratively locate errors in logic programs is difficult and tedious to obtain by means of a standard Prolog debugger. In the author’s opinion, this is a substantial drawback for employing declarative logic programming in practice.

This drawback particularly concerns incorrectness diagnosis. Additionally, debugging of incorrectness seems more important than that of incompleteness. This is because incompleteness is often caused by producing incorrect answers instead of correct ones. Also, incorrectness diagnosis is more precise, as it locates the erroneous fragment of the program more precisely than incompleteness diagnosis. Hence the first thing to do in order to facilitate more declarative debugging is to implement a tool supporting incorrectness diagnosis. The author supposes that it does not need to be a full implementation of an incorrectness diagnosis algorithm. It may be sufficient to provide a tool for convenient browsing of a proof tree (which abstracts the part of computation responsible for the considered incorrect answer).

The author will be thankful for any comments.

5 The top-level answers are instances of the body atoms $B_1, \ldots, B_n$, of the clause $H \leftarrow B_1, \ldots, B_n$ that was used at the first LD-resolution step in computing the answer $A$. This is formalized in Section 2.1 as top-level success trace.
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