Prolog, Mercury and the termination problem

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Abstract

This paper shortly introduces the two logic programming languages Prolog and Mercury. On this background we introduce the problem of analysing termination of programs. Then we present Mercury’s termination analyser, that the authors of the language incorporated into its compiler. We will also discuss the proposition based on the same method analyser for Prolog’s predicates.

1. Prolog

Prolog is a logic programming language with its roots in automated theorem proving. Its terminology and concept are based on the first-order predicate logic. There are a few definitions required to understand the rules of programming in Prolog.

Facts are used to describe some relations between the objects and they are always true. They consist of relation name, predicate and the list of comma-separated arguments enclosed with brackets. Each fact ends with full stop. For example, the fact expressing the relation of admiration and referring to two objects could have a form like(kate, flowers). Names of used object and predicates must start with lower case letters.

The second type of statement in Prolog are rules. Rules comprise two parts, a head and a body connected with ‘:-’ (neck symbol also read as ‘if’) and end with a full stop. Head is a name of the defined rule with the list of its arguments. Body is a set of goals separated with commas which state for logic ‘and’. That conditional form means that to satisfy the rule it is required for all its goals to succeed. While defining a rule it is allowed to use variables both in its head and body. A variable in Prolog is a string of letters, digits, and underscores beginning either with a capital letter or with an underscore. They are used to replace objects that can not be named at the moment. For example, if we want to describe a person who is a brother of somebody, in Prolog we would use the following form: brother(X, Y) :- man(X), parents(O, M, X), parents(O, M, Y).

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Collection of facts and rules creates a **database**. With this database, we can ask Prolog questions. To answer a question about the database, or in other words, to satisfy all the goals that build that query, Prolog has to search the database. Binding variables always go from left to right, backtracking if necessary. When Prolog finishes satisfying the goals, the answer is given.

Extending the previous rule with a few facts the following database is created:

```prolog
man(kriss).
man(mathew).
parents(mathew,anne,kriss).
parents(mathew,anne,maggie).
brother(X,Y) :- man(X), parents(O,M,X), parents(O,M,Y).
```

Now after putting the question

```
?- brother(kriss, melanie).
```

the answer ‘No’ will be obtained as there are no possible variables binding that would satisfy every goal of ‘brother’ relation.

The basic method used in Prolog’s programs and data structures is **recursion**. As the definition says: recursion or recurrency in programming and mathematics is calling function on itself. Each recursive definition requires at least one ending, non-recursive state that would make the recursive calls stop. For example, a predicate that computes factorial in Prolog could have the following form:

```prolog
factorial(1,1):-!.
factorial(X,Y):-X1 is X-1, factorial(X1,S), Y is S*X.
```

First clause is an ending state terminating the recursive calls. Goal written as ‘!’ is called **cut**. It is a goal that always succeeds, but cannot be backtracked. It is used to prevent unwanted backtracking. The second clause is a recursive call with its input arguments properly transformed.

**2. Mercury**

Mercury is a new, pure logic-functional programming language. Such as other existing logic programming languages, it is a high level programming language which allows programmers to concentrate on solving the problem rather than thinking about low-level dependencies like memory management. The project called Mercury was created at Melbourne University in 1995. For the past years there has been done a lot of research and development work. As a result, since December 2002, there has been the version 0.11.0 available that supports most of system platforms.

Main features of Mercury:
1. It is purely declarative which means that predicates and functions do not have non-logical side effects.
2. Strong type system.
3. Strong mode system.
4. Strong determinism system which catches many program errors at compile time.
5. Module system.
6. Support for higher-order programming, with closures, currying and lambda expressions.
7. In comparison with the existing logic programming languages Mercury is very efficient.

The syntax of Mercury is based on the syntax of Prolog, although the semantics differs a little. Program in Mercury is a set of modules. Each module is a file that contains sequence of elements – declarations and clauses. Element is a term ended with a full stop. Term is a set of tokens and token is a set of characters. Each module starts with a `:-module Module_name` declaration which specifies its name. Next, there should be interface section introduced by `:-interface` declaration. This section specifies the entities that are exported by this module. An `:-implementation` definition indicates the start of next section. This is the place that must contain definitions for all declarations from the interface section. The module may end with `:-end_module Module_name` declaration. To make use of entities exported by other modules it is required to explicitly import those modules using `:-import_module Module_list` or `:-use_module Module_list` declaration. It is important is that one module must export a predicate `main/2` declared as either:

```prolog
:-pred main ( io__state::di, io__state::uo) is det. or
:-pred main (io__state::di, io_state::uo) is cc_multi.
```

Module arranging some list of operations could look like this:

```prolog
:-module list_operations.
:-interface.
    :-type list ( El ).
    :-pred append( El , list( El ), list(El) ).
:-implementation.
    :-type list ( El ) - - - > [] ; [ El | list(El) ].
    append(El , [], [El]).
    append(El , L1 , [El|L1]).
:-end_module list_operations.
```

It is also worth mentioning that there are new kinds of clauses in Mercury, called functions or more precisely: function rules and function facts. If the top-level functor of the head of a rule or a predicate is `=/2`, that clause is suitable
function rule (having the form: head=return_value:-body) or the function fact 
(having form: head=return_value). In both cases head can not be a variable and 
its arguments must be valid terms.

The type system of Mercury, is based on many-sorted, polymorphic logic. 
Next to built-in primitive types there are predicate types - pred, function types – func and universal type univ. Apart from those types new types can be 
introduced with :-type declaration. There are several categories of derived 
types, such as: discriminated unions, equivalence types and abstract types.

Discriminated unions are similar to records or enumeration types known from 
other programming languages. Their declarations have the form: :-type name 
[(T1,...,TN)] - - -> body where body is a comma separated the sequence of 
constructors. For example, the type designed to contain personal data could 
have the following form:

:-type pers_data - - -> pers_data ( firstname :: string, familyname :: string).

Equivalence types are declared with ‘==’ operator. They are considered as 
simplification of the type situated on the right side of the declaration f.e. :-type 
liczba_calkowita == int.

Types with hidden implementation are called abstract types. In the interface 
section there is only type’s name and arguments whereas its definition (list of 
constructors) is situated in the implementation section.

For each predicate or function it is necessary to explicitly determine which 
arguments are input and which are output. These two primary modes are called 
‘in’ and ‘out’ respectively. Mode declaration in the form :- mode term_name( 
mode , ... , mode) [= mode] should be situated in the module interface section, 
usually just after the corresponding predicate or the function declaration.

For each declared mode there should be appropriate determinism declaration. 
Term, which call ends not throwing exception, can have one of the following 
determinism kinds: det, semidet, multi, nondet, failure, erroneous.

In Mercury full declaration and definition of predicate appending two lists 
could look as follows:

:- pred append ( list (T) , list (T) , list (T) ).
:- mode append ( in , out , out ) is det.
:- mode append ( out , out , in ) is multi.
:- mode append ( in , in , in ) is semidet.
append ( L1 , L2 , L3 ) :- ( L1 = [] , L3 = L2; 
L1 = [G|O] , append(O , L2 ,L33 ),L3=[G|L33].

3. Termination problem

Termination problem or halting problem in computability theory there is a 
decision problem that could be expressed as follows: for a program’s description 
and its initial input, determine whether the program, when executed on this
input, ever completes. In 1936 Alan Turing proved that general algorithm to solve the halting problem for all possible inputs cannot exist. It is said that the halting problem is undecidable over Turing machines. There are many methods that are used to analyse termination of programs. I would like to present the Gröger-Plümer approach to the problem.

That method has two stages:
1. Assigning an integer to each clause of analysed predicate that estimates maximum difference between the total size of the output and input arguments.
2. Using the solution from the first stage to check if in each cycle in the predicate’s call graph, input arguments decrease in size.

The subject of this article is only first stage analysis which involves producing and solving a set of linear inequalities in the form:

\[ \sum_{i \in I} p_i + \phi_p \geq \sum_{j \in J} p_j \]

where \( p_i \) stands for the size of argument \( i \) predicate \( p \), \( I \) is a subset of the set of the input arguments and \( J \) is a subset of the set of its output arguments. The aim is to solve for the minimum integer value of \( \phi_p \) satisfying the inequalities inferred for the predicate.

Let us consider the predicate \( \text{append}(H1,H2,H3) \), which attaches a list to the back of another, and its arguments modes are in, in, out respectively. Starting with the recursive clause, the first stage analysis would have the following course:

\[
\text{append}(H1, H2, H3) : - \\
H1 = [ X | Xs ], \\
\text{append}(Xs, H2, Zs), \\
H3 = [ X | Zs ]. \quad \text{%h3}
\]

Starting from the right side of the inequality for this clause is output variable \( H3 \). On the strength of the last goal it can be replaced by the sum of variables \( X \) and \( Zs \) and 1 representing the size of cons cell.

\[
\text{append}(H1, H2, H3) : - \\
H1 = [ X | Xs ], \quad \text{%x + zs + 1} \\
\text{append}(Xs, H2, Zs), \quad \%h3 \\
H3 = [ X | Zs ]. \quad \%h3
\]

The second goal is a recursive call that also defines one of the active variables \( Zs \). We cannot estimate the exact size of \( Zs \) precisely but we know that its upper bound is: \( xs+h2+\phi_a \)

\[
\text{append}(H1, H2, H3) : - \\
H1 = [ X | Xs ], \quad \%x + xs + h2 + \phi_a + 1 \\
\text{append}(Xs, H2, Zs), \quad \%x + zs + 1
\]
H3 = [ X | Zs ].  

First goal states that h1=x+x_{s}+1 so x+x_{s} on the right side can be replaced by h1-1

\begin{align*}
\text{append} \ (H1, H2, H3) &::= \ h1 \ + \ h2 \ + \ \varphi_a \ + \ 1 \ - \ 1 \\
H1 &= [ X | Xs ], \ h2 + \varphi_a + 1 \\
\text{append} \ (Xs, H2, Zs) &::= \ x + zs + h2 + \varphi_a + 1 \\
H3 &= [ X | Zs ]. \ h3
\end{align*}

As a result inequality of the form \( h1 + h2 + \varphi_a \geq h1 + h2 + \varphi_a + 1 - 1 \) is gained which is always true.

The annotation for the other, nonrecursive clause would be:

\begin{align*}
\text{append} \ (H1, H2, H3) &::= \ h2 \\
H1 &= [], \ h2 \\
H3 &= H2. \ h3
\end{align*}

which gives the inequality of the form \( h1 + h2 + \varphi_a \geq h2 \) also always true which finally allows us to estimate \( \varphi_a \) equals 0.

### 4. Algorithms

A few of Mercury’s creators: Chris Speirs, Zoltan Somogyi and Harald Søndergaard have implemented a termination analyzer and incorporated it into the Mercury compiler. Their algorithm is mainly based on the previously described method, however with small modifications. The first stage analysis is based around the inequalities

\[
\sum \text{output\_supplier\_variables} + \varphi \geq \sum \text{output\_variables},
\]

where output\_supplier\_variables represent the set of these input variables whose value contribute to the size of the output variables. The set of output variables from the right side of inequality is calculated by using the fixed point analysis. At first it is assumed that none of the procedures use none of its input arguments to produce output. Then in each of the following steps the output\_suppliers set is being completed by M set which is subset of input arguments of p_j procedure. This process is repeated until reaching a fixed point. The code of Stage 1 algorithm is as follows:

For each procedure \( p \in S \) set new\_output\_suppliers(p) to []

Do

\[
\text{old\_output\_suppliers} := \text{new\_output\_suppliers}
\]

Step1(old\_output\_suppliers, new\_output\_suppliers)

while new\_output\_suppliers \neq old\_output\_suppliers

output\_suppliers := new\_output\_suppliers

If I is unsatisfiable then for each p \in S set \varphi_p to \infty
else set \((\phi_1, \ldots, \phi_n)\) to \((d_1, \ldots, d_n)\)
where \((d_1, \ldots, d_n)\) is the least solution satisfying \(I\)

Proc step1(in old_output_suppliers, out new_output_suppliers) is
Set \(I\) to true
For \(j:=1\) to \(n\):
  Let \(B_0:-B_1, \ldots B_m\) be the clause defining \(p_j\) (\(m \geq 0\))
  \(M:=\text{outvars}(p_j)\)
  \(\delta:=0\)
  For \(i:=m\) to 1:
    If \(M \cap \text{outvars}(B_i) \neq \emptyset\) then
      \(M:=(M \setminus \text{outvars}(B_i)) \cup \text{old_output_suppliers}(B_i)\)
      \(\delta:=\delta + \text{change}(B_{\{i\}})\)
  If \(M \not\subseteq \text{invars}(p_j)\) then for each \(p \in S\) set \(\phi_p\) to \(\infty\) and exit
  \(\text{new_output_suppliers}(p_j):=M\)
  If \(\delta\) contains \(\infty\) then \(I:=\text{false}\)
else \(I:=I \wedge \phi_{p_j} \geq \delta\)

Proposition of algorithm realising Stage 1 analysis in Prolog could have the following form:

\[
\begin{align*}
\text{compare}(\text{InVar}, \text{OutVar}) & : - \ldots \\
\text{replace}(\text{VarSet}, \text{OutVar}, \text{InVar}, \text{VarSetNew}) & : - \ldots \\
\text{step}([], \text{Var}, \text{Var}) & : - !. \\
\text{step}(\text{Body}, \text{Var}, \text{VarX}) & : - \text{last}(\text{Body}, \text{Clause}), \\
& \quad \text{not recursiveCall}(\text{Clause}), \\
& \quad \text{replace}(\text{Var}, \text{outvar}(\text{Clause}), \text{invar}(\text{Clause}), \text{Var1}), \\
& \quad \text{remove}(\text{Body}, \text{Clause}, \text{Body1}), \\
& \quad \text{step}(\text{Body1}, \text{Var1}, \text{VarX}). \\
\text{step}(\text{Body}, \text{Var}, \text{VarX}) & : - \text{last}(\text{Body}, \text{Clause}), \\
& \quad \text{recursiveCall}(\text{Clause}), \\
& \quad \text{add}(\text{Var}, \text{Gamma}, \text{Var1}), \\
& \quad \text{replace}(\text{Var}, \text{outvar}(\text{Clause}), \text{invar}(\text{Clause}), \text{Var1}), \\
& \quad \text{remove}(\text{Body}, \text{Clause}, \text{Body1}), \\
& \quad \text{step}(\text{Body1}, \text{Var1}, \text{VarX}). \\
\text{step1_check}(X:-\text{Body}) & : - \text{Var} = \text{outvar}(H), \\
& \quad \text{step}(\text{Body}, \text{Var}, \text{VarNew}), \\
& \quad \text{In} = \text{invar}(H)+\text{Gamma}, \\
& \quad \text{compare}(\text{In}, \text{VarNew}).
\end{align*}
\]
The presented algorithm’s framework has been partially written with some informal language to improve clarity. It assumes that there is information about predicate’s modes available and also that predicates are allowed to make recursive calls only to itself. Predicate `step1_check` for each predicate orders to perform stage 1 analysis. Predicate `step` for each goal of analyzed predicate’s body converts set of input variables including new active variables. Predicate `compare` for variables sets it gains, builds up proper inequality and returns its solution. Predicate `replace` does some required list operations.

Conclusions

Unfortunately stage 1 analysis is not enough to get a reliable answer whether that predicate terminates or not. To prove it, let us again consider the predicate calculating factorial.

```prolog
factorial ( 1 , 1 ).
factorial (X, Y ) :- X>1 ,
    X1 is X – 1,
    factorial ( X1 , Y1 ),
    Y is Y1 * X.
```

The inequality that is obtained is of the form \( x + \varphi \geq x + \varphi \) and it is always true. Yet it is enough to change only one sign

```prolog
factorial ( 1 , 1 ).
factorial (X, Y ) :- X>1 ,
    X1 is X + 1,
    factorial ( X1 , Y1 ),
    Y is Y1 * X.
```

to see that:
1. It changes nothing in the obtained inequality and its solution.
2. Causes that this predicate’s call will never terminate.

To draw some further conclusions about termination of a given predicate it is necessary to make stage two analysis.

References