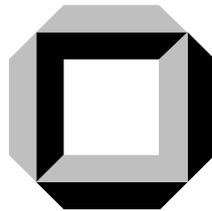


lean*EA*
A Poor Man's
Evolving Algebra Compiler

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Interner Bericht 25/95



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May 15, 1995

Abstract

The Prolog program

```
“term_expansion((define C as A with B), (C=>A:-B,!)).
term_expansion((transition E if C then D),
  ((transition E):-C,!,B,A,(transition _))) :-
  serialize(D,B,A).
serialize((E,F),(C,D),(A,B)) :- serialize(E,C,B), serialize(F,D,A).
serialize(F:=G, ([G]=>*[E],F=..[C|D],D=>*B,A=..[C|B]), asserta(A=>E)).
[G|H]=>*[E|F] :- (G=\E; G=..[C|D],D=>*B,A=..[C|B],A=>E), !,H=>*F.
[]=>*[] .
A=?B :- [A,B]=>*[D,C], D==C.”
```

implements a virtual machine for evolving algebras. It offers an efficient and very flexible framework for their simulation.

Computation models and specification methods seem to be worlds apart. The evolving algebra project started as an attempt to bridge the gap by improving on Turing's thesis.

(Gurevich, 1994)

1 Introduction

Evolving algebras (EAs) (Gurevich, 1991; Gurevich, 1994) are abstract machines used mainly for formal specification of algorithms. The main advantage of EAs over classical formalisms for specifying operational semantics, like Turing machines for instance, is that they have been designed to be usable by human beings: whilst the concrete appearance of a Turing machine has a solely mathematical motivation, EAs try to provide a user friendly and natural—though rigorous—specification tool. The number of specifications using EAs is rapidly growing;¹ examples are specifications of the languages ANSI C (Gurevich & Huggins, 1993) and ISO Prolog (Börger & Rosenzweig, 1994), and of the virtual architecture

¹There is a collection of papers on evolving algebras and their application on the *World Wide Web* at <http://www.engin.umich.edu/~huggins/EA>.

APE (Börger *et al.*, 1994b). EA specifications have also been used to validate language implementations (e.g., Occam (Börger *et al.*, 1994a)) and distributed protocols (Gurevich & Mani, 1994).

When working with EAs, it is very handy to have a simulator at hand for running the specified algebras. This observation is of course not new and implementations of abstract machines for EAs already exist: Angelica Kappel describes a Prolog-based implementation in (Kappel, 1993), and Jim Huggins reports an implementation in C. Both implementations are quite sophisticated and offer a convenient language for specifying EAs.

In this paper, we describe an approach to implementing an abstract machine for EAs which is different, in that it emphasizes on simplicity and elegance of the implementation, rather than on sophistication. We present a simple, Prolog-based approach for executing EAs. The underlying idea is to map EA specifications into Prolog programs. Rather than programming a machine explicitly, we turn the Prolog system itself into a virtual machine for EA specifications: this is achieved by changing the Prolog reader, such that the transformation of EAs into Prolog code takes place whenever the Prolog system reads input. As a result, evolving algebra specifications can be treated like ordinary Prolog programs.

The main advantage of our approach, which we call *leanEA*, is its flexibility: the Prolog program we discuss in the sequel can easily be understood and extended to the needs of concrete specification tasks (non-determinism, special handling of undefined functions, etc.). Furthermore, its flexibility allows to easily embed it into, or interface it with other systems.

The paper is organized as follows: in Section 2, we start with explaining how a deterministic, untyped EA can be programmed in *leanEA*; this section is written pragmatically, in the sense that we do not present a mathematical treatment, but explains what a user has to do in order to use EAs with *leanEA*. The implementation of *leanEA* is explained in parallel. In Section 3 we give some hints for programming in *leanEA*. Rigorous definitions for vigorous readers can be found in Section 4, where the semantics of *leanEA* programs are presented. Extensions of *leanEA* are described in Section 5; these include purely syntactical extensions made just for the sake of programming convenience, as well as more semantical extensions like including typed algebras, or implementing non-deterministic evolving algebras. Section 6 introduces modularized EAs, where Prolog’s concept of modules is used to structure the specified algebras. Finally, we draw conclusions from our research in Section 7. An extended example of using *leanEA* is given in Appendix A.

Through the paper we assume the reader to be familiar with the basic ideas behind evolving algebras, and with the basics of Prolog.

2 Programming Evolving Algebras in *leanEA*

2.1 The Basics of *leanEA*

An algebra can be understood as a formalism for describing static relations between things: there is a universe consisting of the objects we are talking about, and a set of functions mapping members of the universe to other members. *Evolving* algebras offer a formalism for describing changes as well: an evolving algebra “moves” from one state to another, while functions are changed.

leanEA is a programming language that allows to program this behavior. From a declarative point of view, a *leanEA* program is a specification of an EA. Here, however, we will not argue declaratively, but operationally by describing how statements of *leanEA* set up an EA and how it moves from one state to another. A declarative description of *leanEA* can be found in Section 4.

2.2 Overview

leanEA is an extension of standard Prolog, thus a *leanEA* program can be treated like any other Prolog program, i.e., it can be loaded (or compiled) into the underlying Prolog system (provided *leanEA* itself has been loaded before).

leanEA has two syntactical constructs for programming an EA: the first are *function definitions* of the form

```
define Location as Value with Goal.
```

which specify the initial state of an EA.

The second construct are *transition definitions* which define the EA's evolving, i.e., the mapping from one state to the next:

```
transition Name if Condition then Updates.
```

The signature of EAs is in our approach the set of all ground Prolog terms. The (single) universe, that is not sorted, consists of ground Prolog terms, too; it is not specified explicitly.

Furthermore, the final state(s) of the EA are not given explicitly in *leanEA*. Instead, a state S is defined to be final if no transition is applicable in S or if a transition fires that uses undefined functions in its updates.

The computation of the specified evolving algebra is started by calling the Prolog goal

```
transition _
```

which recursively searches for the applicable transitions and executes them until no more transitions are applicable.

2.3 *leanEA*'s Operators

For implementing the syntax for function and transition definitions outlined above, a couple of Prolog operators have to be defined with appropriate preferences; they are shown in Figure 1, Lines 1–6.

Note, that the preferences of operators (those pre-defined by *leanEA* as well as others used in a *leanEA* program) can influence the semantics of Prolog goals included in *leanEA* programs.

2.4 Representation of States in *leanEA*

Before explaining how function definitions set up the initial state of an EA, we take a look at the *leanEA* internals for representing states: A state is given by the mapping of locations to their values, i.e., elements of the universe. A location $f(u_1, \dots, u_n)$, $n \geq 0$, consists of a functor f and arguments u_1, \dots, u_n that are members of the universe.

```

1 :- op(1199,fy,(transition)), op(1180,xfx,(if)),
2   op(1192,fy,(define)),      op(1185,xfy,(with)),
3   op(1190,xfy,(as)),        op(1170,xfx,(then)),
4   op(900,xfx,(=>)),          op(900,xfx,(=>*)),
5   op(900,xfx,(:=)),         op(900,xfx,(=?)),
6   op(100,fx,(\\)).

7 :- multifile (=>)/2.
8 :- dynamic (=>)/2.

9 term_expansion((define Location as Value with Goal),
10               ((Location => Value) :- Goal,!)).

11 term_expansion((transition Name if Condition then Updates),
12               (transition(Name) :-
13                 (Condition,! ,FrontCode,BackCode,transition(_))) :-
14                 serialize(Updates,FrontCode,BackCode)).

15 serialize((A,B),(FrontA,FrontB),(BackB,BackA)) :-
16   serialize(A,FrontA,BackA),
17   serialize(B,FrontB,BackB).

18 serialize((LocTerm := Expr),
19           ([Expr] =>* [Val], LocTerm =.. [Func|Args],
20           Args =>* ArgVals, Loc =.. [Func|ArgVals]),
21           asserta(Loc => Val)).

22 ([H|T] =>* [HVal|TVal]) :-
23   ( H = \\HVal
24   ; H =.. [Func|Args], Args =>* ArgVals,
25     H1 =.. [Func|ArgVals], H1 => HVal
26   ),!,
27   T =>* TVal.

28 [] =>* [].

29 (S =? T) :- ([S,T] =>* [Val1,Val2]), Val1 == Val2.

```

Figure 1: leanEA: the Program

EXAMPLE 1. Assume, for instance, that there is a partial function denoted by \mathbf{f} that maps a pair of members of the universe to a single element, and that 2 and 3 are members of the universe. The application of \mathbf{f} to 2 and 3 is denoted by the Prolog term $\mathbf{f}(2,3)$. This location can either have a value in the current state, or it can be undefined.

A state in *leanEA* is represented by the values of all defined locations. Technically, this is achieved by defining a Prolog predicate $\Rightarrow/2$,² that behaves as follows: The goal “`Loc => Val`” succeeds if `Loc` is bound to a ground Prolog term that is a location in the algebra, and if a value is defined for this location; then `Val` is bound to that value. The goal fails if no value is defined for `Loc` in the current state of the algebra.

To evaluate a function call like, for example, $\mathbf{f}(\mathbf{f}(2,3),3)$, *leanEA* uses $\Rightarrow*/2$ as an evaluation predicate: the relation $t \Rightarrow* v$ holds for ground Prolog terms t and v if the value of t —where t is interpreted as a function call—is v (in the current state of the algebra).

In general, the arguments of a function call are not necessarily elements of the universe (contrary to the arguments of a location), but are expressions that are recursively evaluated. It is possible to use members of the universe in function calls explicitly: these can be denoted by preceding them with a backslash “\”; this disables the evaluation of whatever Prolog term comes after the backslash. We will refer to this as *quoting* in the sequel.

For economical reasons, the predicate $\Rightarrow*/2$ actually maps a *list* of function calls to a list of values. Figure 1, Lines 21–27, shows the Prolog code for $\Rightarrow*$, which is more or less straightforward: if the term to be evaluated (bound to the first argument of the predicate) is preceded with a backslash, the term itself is the result of the evaluation; otherwise, all arguments are recursively evaluated and the value of the term is looked up with the predicate $\Rightarrow/2$. Easing the evaluation of the arguments of terms is the reason for implementing $\Rightarrow*$ over lists. The base step of the recursion is the identity of the empty list (Line 27). $\Rightarrow*$ fails if the value of the function call is undefined in the current state.

EXAMPLE 2. Consider again the binary function \mathbf{f} , and assume it behaves like addition in the current state of the algebra. Then both the goals

$$[\mathbf{f}(\backslash 1, \backslash 2)] \Rightarrow* [X] \quad \text{and} \quad [\mathbf{f}(\mathbf{f}(\backslash 0, \backslash 1), \backslash 2)] \Rightarrow* [X]$$

succeed with binding X to 3. The goal

$$[\mathbf{f}(\backslash \mathbf{f}(0, 1), \backslash 2)] \Rightarrow* [X] \quad ,$$

however, will fail since addition is undefined on the term $\mathbf{f}(0,1)$, which is not an integer but a location. Analogously,

$$[\mathbf{f}(\mathbf{f}(0, 1), \backslash 2)] \Rightarrow* [X]$$

will fail, because 0 and 1 are undefined constants (0-ary functions).

After exploring the *leanEA* internals for evaluating expressions, we come back to programming in *leanEA*. The rest of this section will explain the purpose of function and transition definitions, and how they affect the internal predicates just explained.

²Note, that $\Rightarrow/2$ is defined to be dynamic such that it can be changed by transitions (Fig. 1, Line 7).

2.5 Function Definitions

The initial state of an EA is specified by a sequence of function definitions. They define the initial values of locations by providing Prolog code to compute these values. A construct of the form

```
define Location as Value with Goal.
```

gives a procedure for computing the value of a location that matches the Prolog term *Location*: if *Goal* succeeds, then *Value* is taken as the value of this location. Function definitions set up the predicate => (and thus =>*) in the initial state. One function definition can specify values for more than one functor of the algebra. It is possible in principle, although quite inconvenient, to define all functors within a single function definition. The value computed for a location may depend on the additional Prolog code in a leanEA-program (code besides function and transition definitions), since *Goal* may call any Prolog predicate. If several function definitions define values for a single location, the (textually) first definition is chosen.

2.5.1 Implementation of Function Definitions

A function definition is translated into the Prolog clause

```
(Location => Value) :- Goal,!.
```

Since each definition is mapped into one such clause, *Goal* must not contain a cut “!”; otherwise, the cut might prevent Prolog from considering subsequent => clauses that match a certain location.

The translation of a define statement to a => clause is implemented by modifying the Prolog reader as shown in Figure 1, Lines 8–9.³

2.5.2 Examples for Function Definitions

Constants A definition of the form

```
define register1 as _ with false.
```

introduces the constant (0-ary function) `register1` with an undefined value. Such a definition is actually redundant, since all Prolog terms belong to the signature of the specified EA and will be undefined unless an explicit value has been defined.

A definition of the form

```
define register1 as 1 with true.
```

assigns the value 1 to the constant `register1`.

The definition

```
define register1 as register1 with true.
```

defines that the value of the function call `register1` is `register1`. Thus evaluating `\register1` and `register1` will produce the same result.

³In most Prolog dialects (e.g., SICStus Prolog and Quintus Prolog) the Prolog reader is changed by adding clauses for the `term_expansion/2` predicate. If a term *t* is read, and `term_expansion(t,S)` succeeds and binds the variable *S* to a term *s*, then the Prolog reader replaces *t* by *s*.

Prolog Data Types Prolog Data Types can be easily imported into the algebra. Lists, for instance, are introduced by a definition of the form

```
define X as X with X=[]; X=[H|T].
```

This defines that all lists evaluate to themselves; thus a list in an expression denotes the same list in the universe and it is not necessary to quote it with a backslash. Similarly,

```
define X as X with integer(X).
```

defines that Prolog integers evaluate to themselves in the algebra.

Evaluating Functions by Calling Prolog Predicates The following are example definitions that interface Prolog predicates with an evolving algebra:

```
define X+Y as Z with Z is X+Y.
define append(X,Y) as Result with append(X,Y,Result).
```

Input and Output Useful definitions for input and output are

```
define read as X with read(X).
define output(X) as X with write(X).
```

Whilst the purpose of `read` should be immediate, the returning of the argument of `output` might not be clear: the idea is that the returned value can be used in expressions. That is, an expression of the form `f(\1,output(\2))` will evaluate to the value of the location `f(1,2)` and, as a side effect, write 2 on the screen.

A similar, often more useful version of output is

```
define output(Format,X) as X with format(Format,[X]).
```

which allows to format output and include text.

2.5.3 Necessary Conditions for Function Definitions

The design of *leanEA* constrains function definitions in several ways; the conditions function definitions have to meet are not checked by *leanEA*, but must be guaranteed by the programmer. In particular, the programmer has to ensure that:

1. The computed values are *ground* Prolog terms, and the goals for computing them either fail or succeed (i.e., terminate) for all possible instantiations that might appear. Prolog exceptions that terminate execution have to be avoided as well. It is therefore advisable, for instance, to formulate the definition of `+` as:

```
define X+Y as Z with integer(X), integer(Y), Z is X+Y.
```

2. The goals do not change the Prolog data base or have any other side effects (side effects that do not influence other computations are harmless and often useful; an example are the definitions for input and output in Section 2.5.2).
3. The goals do not (syntactically) contain a cut “!”.
4. The goals do not call the *leanEA* internal predicates `transition/1`, `=>*/2`, and `=>/2`.

Violating these requirements does not necessarily mean that *leanEA* will not function properly anymore; however, unless the programmer is very well aware of what he/she is doing, we strongly recommend against breaking these rules.

2.6 Transition Definitions

Transitions specify the evolving of an evolving algebra. A transition, if applicable, maps one state of an EA to a new state by changing the value of certain locations. Transitions have the following syntax:

```
transition Name if Condition then Updates.
```

where

Name is an arbitrary Prolog term (usually an atom).

Condition is a Prolog goal that determines when the transition is applicable. Conditions usually contain calls to the predicate `=?/2` (see Section 2.6.2 below), and often use the logical Prolog operators “,” (conjunction), “;” (disjunction), “->” (implication), and “\+” (negation).

Updates is a comma-separated sequence of updates of the form

$$\begin{aligned} f_1(r_{11}, \dots, r_{1n_1}) & := v_1, \\ & \vdots \\ f_k(r_{k1}, \dots, r_{kn_k}) & := v_k \end{aligned}$$

An update $f_i(r_{i1}, \dots, r_{in_i}) := v_i$ ($1 \leq i \leq k$) changes the value of the location that consists of (a) the functor f_i and (b) the elements of the universe that are the values of the function calls r_{i1}, \dots, r_{in_i} ; the new value of this location is determined by evaluating the function call v_i . All function calls in the updates are evaluated simultaneously (i.e., in the old state). If one of the function calls is undefined, the assignment fails.

If the left-hand side of an update is quoted by a preceding backslash, the update will have no effect besides that the right-hand side is evaluated; the meaning of the backslash cannot be changed.

A transition is applicable (fires) in a state, if *Condition* succeeds. For calculating the successor state, the (textually) first applicable transition is selected. Then the *Updates* of the selected transition are executed. If no transition fires or if one of the updates of the first firing transition fails, the new state cannot be computed. In that case, the evolving algebra terminates, i.e., the current state is final. Else the computation continues iteratively with calculating further states of the algebra.

2.6.1 Implementation of Transition Definitions

leanEA maps a transition

```
transition Name if Condition then Updates.
```

into a Prolog clause

```
transition(Name) :-
    Condition, !,
    UpdateCode,
    transition(_).
```

Likewise to function definitions, this is achieved by modifying the Prolog reader as shown in Figure 1, Lines 10–13.

Since the updates in transitions must be executed simultaneously, all function calls have to be evaluated before the first assignment takes place. The auxiliary predicate `serialize/3` (Lines 14–20) serves this purpose: it splits all updates into evaluation code, that uses the predicate `=*/2`, and into code for storing the new values by asserting an appropriate `=>/2` clause.

2.6.2 The Equality Relation

Besides logical operators, `leanEA` allows in the condition of transitions the use of the pre-defined predicate `=?/2` (Fig. 1, Line 28) implementing the equality relation: the goal “ $s =? t$ ” succeeds if the function calls s and t evaluate (in the current state) to the same element of the universe. It fails, if one of the calls is undefined or if they evaluate to different elements.

2.7 An Example Algebra

We conclude this section with considering an example of an evolving algebra:

EXAMPLE 3. The `leanEA` program shown in Figure 2 specifies an EA for computing $n!$. The constant `state` is used for controlling the firing of transitions: in the initial state, only the transition `start` fires and reads an integer; it assigns the input value to `reg1`. The transition `step` iteratively computes the faculty of `reg1`'s value by decrementing `reg1` and storing the intermediate results in `reg2`. If the value of `reg1` is 1, the computation is complete, and the only applicable transition `result` prints `reg2`. After this, the algebra halts since no further transition fires and a final state is reached.

3 Hints for Programmers

This section lists a couple of programming hints that have shown to be useful when specifying EAs with `leanEA`.

Final States. `leanEA` does not have an explicit construct for specifying the final state of an EA. By definition, the algebra reaches a final state if no more transition is applicable, but it is often not very declarative to use this feature. As the algebra can also be halted by trying to evaluate an undefined expression, a construct of the form

```
stop := stop.
```

in an update can increase the readability of specifications a lot. If `stop` is undefined, the EA will halt if this assignment is to be carried out.

Tracing Transitions. It is highly unlikely that a programmer is able to write down a specification of an EA without errors directly. Programming in `leanEA` is just like programming in Prolog and usually requires debugging the code one has written down.

```
define state as initial with true.
define readint as X with read(X), integer(X).
define write(X) as X with write(X).
define X as X with integer(X).
define X-Y as R with integer(X),integer(Y),R is X-Y.
define X*Y as R with integer(X),integer(Y),R is X*Y.

transition step
  if state =? \running, \+(reg1 =? 1)
  then reg1 := reg1-1,
       reg2 := (reg2*reg1).

transition start
  if state =? \initial
  then reg1 := readint,
       reg2 := 1,
       state := \running.

transition result
  if state =? \running, reg1 =? 1
  then reg2 := write(reg2),
       state := \final.
```

Figure 2: An Evolving Algebra for Computing $n!$

For tracing transitions, it is often useful to include calls to `write` or `trace` at the end of conditions: the code will be executed whenever the transition fires and it allows to provide information about the state of the EA.

Another, often useful construct is a definition of the form

```
define break(Format,X) as X with format(Format,[X]),break.
```

Tracing the Evaluation of Terms. A definition of the form

```
define f(X) as _ with write(f(X)), fail.
```

is particularly useful for tracing the evaluation of functions: if the above function definition precedes the “actual” definition of $f(X)$, it will print the expression to be evaluated whenever the evaluation takes place.

Examining States. All defined values of locations in the current state can be listed by calling the Prolog predicate `listing(=>)`. Note, that this does not show any default values.

4 Semantics

This section formalizes the semantics of *leanEA* programs, in the sense that it explains in detail which evolving algebra is specified by a concrete *leanEA*-program.

DEFINITION 4. Let P be a *leanEA*-program; then \mathcal{D}_P denotes the sequence of function definitions in P (in the order in which they occur in P), \mathcal{T}_P denotes the sequence of transition definitions in P (in the order in which they occur in P), and \mathcal{C}_P denotes the additional Prolog-code in P , i.e., P without \mathcal{D}_P and \mathcal{T}_P .

The function definitions \mathcal{D}_P (that may call predicates from \mathcal{C}_P) specify the initial state of an evolving algebra, whereas the transition definitions specify how the algebra evolves from one state to another.

The signature of evolving algebras is in our approach the set *GTerms* of all ground Prolog terms. The (single) universe, that is not sorted, is a subset of *GTerms*.

DEFINITION 5. *GTerms* denotes the set of all ground Prolog terms; it is the *signature* of the evolving algebra specified by a *leanEA* program.

We represent the states S of an algebra (including the initial state S_0) by an evaluation function $\llbracket \cdot \rrbracket_S$, mapping locations to the universe. Section 4.1 explains how $\llbracket \cdot \rrbracket_{S_0}$, i.e., the initial state, is derived from the function definitions \mathcal{D} . In what way the states evolve according to the transition definitions in \mathcal{T} (which is modeled by altering $\llbracket \cdot \rrbracket$) is the subject of Section 4.3.

The final state(s) are not given explicitly in *leanEA*. Instead, a state S is defined to be final if no transition is applicable in S or if a transition fires that uses undefined function calls in its updates (Def. 11).⁴

⁴The user may, however, explicitly terminate the execution of a *leanEA*-program (see Section 3).

4.1 Semantics of Function Definitions

A function definition “**define** F **as** R **with** G .” gives a procedure for calculating the value of a location $f(t_1, \dots, t_n)$ ($n \geq 0$). Procedurally, this works by instantiating F to the location and executing G . If G succeeds, then R is taken as the value of the location. If several definitions provide values for a single location, we use the first one. Note, that the value of a location depends on the additional Prolog code \mathcal{C}_P in a leanEA-program P , since G may call predicates from \mathcal{C}_P .

DEFINITION 6. Let \mathcal{D} be a sequence of function definitions and \mathcal{C} be additional Prolog code. A function definition

$$D = \text{define } F \text{ as } R \text{ with } G.$$

in \mathcal{D} is *succeeding* for $t \in GTerms$ with answer $r = R\tau$, if

1. there is a (most general) substitution σ such that $F\sigma = t$;
2. $G\sigma$ succeeds (possibly using predicates from \mathcal{C});
3. τ is the answer substitution of $G\sigma$ (the first answer substitution if $G\sigma$ is not deterministic).

If no matching substitutions σ exists or if $G\sigma$ fails, D is *failing* for t .

The partial function

$$\llbracket t \rrbracket_{\mathcal{D}, \mathcal{C}} : GTerms \longrightarrow GTerms$$

is defined by

$$\llbracket t \rrbracket_{\mathcal{D}, \mathcal{C}} = r \text{ ,}$$

where r is the answer (for t) of the first function definition $D \in \mathcal{D}$ succeeding for t . If no function definition $D \in \mathcal{D}$ is succeeding for t , then $\llbracket t \rrbracket_{\mathcal{D}, \mathcal{C}}$ is undefined.

The following definition formalizes the conditions function definitions have to meet (see Section 2.5.3):

DEFINITION 7. A sequence \mathcal{D} of function definitions and additional Prolog code \mathcal{C} are *well defining* if

1. no function definition $D_i \in \mathcal{D}$ is for some term $t \in GTerms$ neither succeeding nor failing (i.e., not terminating), unless there is a definition $D_j \in \mathcal{D}$, $j < i$, in front of D_i that is succeeding for t ;
2. if $D \in \mathcal{D}$ is succeeding for $t \in GTerms$ with answer r , then $r \in GTerms$;
3. \mathcal{D} does not (syntactically) contain a cut “!”;⁵
4. the goals in \mathcal{D} and the code \mathcal{C}
 - (a) do not change the Prolog data base or have any other side effects;
 - (b) do not call the leanEA internal predicates `transition/1`, `=>*/2`, and `=>/2`.

⁵Prolog-negation and the Prolog-implication “ \rightarrow ” are allowed.

PROPOSITION 8. If a sequence \mathcal{D} of function definitions and additional Prolog code \mathcal{C} are well defining, then $\llbracket \cdot \rrbracket_{\mathcal{D}, \mathcal{C}}$ is a well defined partial function on $GTerms$ (a term mapping).

A well-defined term mapping $\llbracket \cdot \rrbracket$ is the basis for defining the evaluation function of an evolving algebra, that is the extension of $\llbracket \cdot \rrbracket$ to function calls that are not a location:

DEFINITION 9. Let $\llbracket \cdot \rrbracket$ be a well defined term mapping. The partial function

$$\llbracket \cdot \rrbracket^* : GTerms \longrightarrow GTerms$$

is defined for $t = f(r_1, \dots, r_n) \in GTerms$ ($n \geq 0$) as follows:

$$\llbracket t \rrbracket^* = \begin{cases} s & \text{if } t = \backslash s \\ \llbracket f(\llbracket r_1 \rrbracket^*, \dots, \llbracket r_n \rrbracket^*) \rrbracket & \text{otherwise} \end{cases}$$

4.2 The Universe

A well-defined term mapping $\llbracket \cdot \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}$ enumerates the universe \mathcal{U}_P of the evolving algebra specified by P ; in addition, \mathcal{U}_P contains all quoted terms (without the quote) occurring in P :

DEFINITION 10. If P is a `leanEA` program, and $\llbracket \cdot \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}$ is a well defined term mapping, then the universe \mathcal{U}_P is the union of the co-domain of $\llbracket \cdot \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}$, i.e.,

$$\llbracket GTerms \rrbracket_{\mathcal{D}_P, \mathcal{C}_P} = \{ \llbracket t \rrbracket_{\mathcal{D}_P, \mathcal{C}_P} : t \in GTerms, \llbracket t \rrbracket_{\mathcal{D}_P, \mathcal{C}_P} \downarrow \} ,$$

and the set

$$\{ t : t \in GTerms, \backslash t \text{ occurs in } P \} .$$

Note, that (obviously) the co-domain of $\llbracket \cdot \rrbracket^*$ is a subset of the universe, i.e.,

$$\llbracket GTerms \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}^* \subset \mathcal{U}_P .$$

The universe \mathcal{U}_P as defined above is not necessarily decidable. In practice, however, one usually uses a decidable universe, i.e., a decidable subset of $GTerms$ that is a superset of \mathcal{U}_P (e.g. $GTerms$ itself). This can be achieved by adding function definitions and thus expanding the universe.⁶

4.3 Semantics of Transition Definitions

After having set up the semantics of the function definitions, which constitute the initial evaluation function and thus the initial state of an evolving algebra, we proceed with the dynamic part.

The transition definitions \mathcal{T}_P of a `leanEA`-program P specify how a state S of the evolving algebra represented by P maps to a new state S' .

⁶It is also possible to change Definition 10; that, in its current form, defines the minimal version of the universe.

DEFINITION 11. Let S be a state of an evolving algebra corresponding to a well defined term mapping $\llbracket \cdot \rrbracket_S$, and let \mathcal{T} be a sequence of transition definitions.

A transition

transition *Name* **if** *Condition* **then** *Updates*

is said to *fire*, if the Prolog goal *Condition* succeeds in state S (possibly using the predicate `=?/2`, Def. 13).

Let

$$\begin{aligned} f_1(r_{11}, \dots, r_{1n_1}) &:= v_1 \\ &\vdots \\ f_k(r_{k1}, \dots, r_{kn_k}) &:= v_k \end{aligned}$$

($k \geq 1, n_i \geq 0$) be the sequence *Updates* of the first transition in \mathcal{T} that fires. Then the term mapping $\llbracket \cdot \rrbracket_{S'}$ and thus the state S' are defined by

$$\llbracket t \rrbracket_{S'} = \begin{cases} \llbracket v_i \rrbracket_S^* & \text{if there is a smallest } i, 1 \leq i \leq k, \\ & \text{such that } t = f_i(\llbracket r_{i1} \rrbracket_S^*, \dots, \llbracket r_{in_i} \rrbracket_S^*) \\ \llbracket t \rrbracket_S & \text{otherwise} \end{cases}$$

If $\llbracket \cdot \rrbracket_S^*$ is undefined for one of the terms r_{ij} or v_i , $1 \leq i \leq k$, $1 \leq j \leq n_i$ of the first transition in \mathcal{T} that fires, or if no transition fires, then the state S is *final* and $\llbracket \cdot \rrbracket_{S'}$ is undefined.

PROPOSITION 12. If $\llbracket \cdot \rrbracket_{S'}$ is a well defined term mapping, then $\llbracket \cdot \rrbracket_{S'}$ (as defined in Def. 11) is well defined.

4.4 The Equality Relation

Besides “,” (and), “;” (or), “\+” (negation), and “->” (implication) leanEA allows in conditions of transitions the pre-defined predicate `=?/2`, that implements the equality relation for examining the current state:

DEFINITION 13. In a state S of an evolving algebra (that corresponds to the well defined term mapping $\llbracket \cdot \rrbracket_S$), for all $t_1, t_2 \in GTerms$, the relation $t_1 =? t_2$ holds iff

1. $\llbracket t_1 \rrbracket_S^* \downarrow$ and $\llbracket t_2 \rrbracket_S^* \downarrow$,
2. $\llbracket t_1 \rrbracket_S^* = \llbracket t_2 \rrbracket_S^*$.

4.5 Runs of leanEA-programs

A run of a leanEA-program P is a sequence of states S_0, S_1, S_2, \dots of the specified evolving algebra. Its initial state S_0 is given by

$$\llbracket \cdot \rrbracket_{S_0} = \llbracket \cdot \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}$$

(Def. 9). The following states are determined according to Definition 11 and using

$$S_{n+1} = (S_n)' \quad (n \geq 0) .$$

This process continues iteratively until a final state is reached.

PROPOSITION 14. *leanEA* implements the semantics as described in this section; i.e., provided $\llbracket \cdot \rrbracket_{\mathcal{D}_P, \mathcal{C}_P}$ is well defined,

1. in each state S of the run of a *leanEA*-program P the Prolog goal “[t] =>* [X]” succeeds and binds the Prolog variable X to u iff $\llbracket t \rrbracket_S^* = u$;
2. the execution of P terminates in a state S iff S is a final state;
3. the predicate `=?` implements the equality relation.

4.6 Some Remarks Regarding Semantics

4.6.1 Relations

There are no special pre-defined elements denoting true and false in the universe. The value of the relation `=?` (and similar pre-defined relations, see Section 5.2) is represented by succeeding (resp. failing) of the corresponding predicate.

4.6.2 Undefined Function Calls

Similarly, there is no pre-defined element `undef` in the universe, but evaluation *fails* if no value is defined. This, however, can be changed by adding

```
define _ as undef with true.
```

as the last function definition.

4.6.3 Internal and External Functions

In *leanEA* there is no formal distinction between internal and external functions. Function definitions can be seen as giving default values to functions; if the default values of a function remain unchanged, then it can be regarded external (pre-defined). If no default value is defined for a certain function, it is classically internal. If the default value of a location is changed, this is what is called an external location in (Gurevich, 1994). The relation `=?` (and similar predicates) are static.

Since there is no real distinction, it is possible to mix internal and external functions in function calls.

4.6.4 Importing and Discarding Elements

leanEA does not have constructs for importing or discarding elements. The latter is not needed anyway. If the former is useful for an application, the user can simulate “import v ” by “ $v := \text{import}$ ”, where `import` is defined by the function definition

```
define import as X with gensym(f,X).7
```

4.6.5 Local Nondeterminism

If the updates of a firing transition are inconsistent, i.e., several updates define a new value for the same location, the first value is chosen (this is called local nondeterminism in (Gurevich, 1994)).

⁷The Prolog predicate `gensym` generates a new atom every time it is called.

5 Extensions

5.1 The let Instruction

It is often useful to use local abbreviations in a transition. The possibility to do so can be implemented by adding a clause

```
serialize((let Var = Term),([Term] =>* [Val], Var = \Val),true).
```

to leanEA.⁸ Then, in addition to updates, instructions of the form

```
let x = t
```

can be used in the update part of transitions, where x is a Prolog variable and t a Prolog term. This allows to use x instead of t in subsequent updates (and `let` instructions) of the same transition. A variable x must be defined only once in a transition using `let`. Note, that x is bound to the quoted term $\llbracket t \rrbracket^*$; thus, using an x inside another quoted term may lead to undesired results (see the first part of Example 15).

EXAMPLE 15. “`let X = \a, reg := \f(X)`” is equivalent to “`reg := \f(\a).`” (which is different from “`reg := \f(a).`”).

```
let X = \b,
let Y = f(X,X),
reg1 := g(Y,Y),
reg2(X) := X.
```

is equivalent to

```
reg1 := g(f(\b,\b),f(\b,\b)),
reg2(\b) := \b.
```

Using `let` not only shortens updates syntactically, but also enhances efficiency, because function calls that occur multiply in an update do not have to be re-evaluated.

5.2 Additional Relations

The Prolog predicate `=?`, that implements the equality relation (Def. 13), is the only one that can be used in the condition of a transition (besides the logical operators). It is possible to implement similar relations using the leanEA internal predicate `=>*` to evaluate the arguments of the relation:

A predicate $p(t_1, \dots, t_n)$, $n \geq 0$, is implemented by adding the code

```
p(t1, ..., tn) :-
    [t1, ..., tn] =>* [x1, ..., xn],
Code.
```

to leanEA.⁹ Then the goal “ $p(t_1, \dots, t_n)$ ” can be used in conditions of transitions instead of $p'(t_1, \dots, t_n) =? \text{true}$ ”, where p' is defined by the function definition

⁸And defining the operator `let` by adding “`:- op(910,fx,(let)).`”.

⁹ x_1, \dots, x_n must be n distinct Prolog variables and must not be instantiated when `=>*` is called. Thus, “`(S =? T) :- ([S,T] =>* [V,V])`” must not be used to implement `=?`, but “`(S =? T) :- ([S,T] =>* [V1,V2]), V1 == V2.`”.

define $p'(x_1, \dots, x_n)$ as true with *Code*.

(which is the standard way of implementing relations using function definitions). Note, that p fails, if one of $\llbracket t_1 \rrbracket_S^*, \dots, \llbracket t_n \rrbracket_S^*$ is undefined in the current state S .

EXAMPLE 16. The predicate $\langle \rangle$ implements the is-not-equal relation: $t_1 \langle \rangle t_2$ succeeds iff $\llbracket t_1 \rrbracket^* \downarrow$, $\llbracket t_2 \rrbracket^* \downarrow$, and $\llbracket t_1 \rrbracket^* \neq \llbracket t_2 \rrbracket^*$. $\langle \rangle$ is implemented by adding the clause

$$(A \langle \rangle B) :- ([A,B] =>* [Val1,Val2], Val1 \neq Val2).$$

to *leanEA*.

5.3 Non-determinism

It is not possible to define non-deterministic EAs in the basic version of *leanEA*. If more than one transition fire in a state, the first is chosen.

This behavior can be changed — such that non-deterministic EAs can be executed — in the following way:

- The cut from Line 12 has to be removed. Then, further firing transitions are executed if backtracking occurs.
- A “retract on backtrack” has to be added to the transitions to remove the effect of their updates and restore the previous state if backtracking occurs. Line 20 has to be changed to

$$(\text{asserta}(\text{Loc} \Rightarrow \text{Val}) ; (\text{retract}(\text{Loc} \Rightarrow \text{Val}), \text{fail})).$$

Now, *leanEA* will enumerate all possible sequences of transitions. Backtracking is initiated, if a final state is reached, i.e., if the further execution of a *leanEA* program fails.

The user has to make sure that there is no infinite sequence of transitions (e.g., by imposing a limit on the length of sequences).

Note, that usually the number of possible transition sequences grows exponentially in their length, which leads to an enormous search space if one tries to find a sequence that ends in a “successful” state by enumerating all possible sequences.

6 Modularized Evolving Algebras

One of the main advantages of EAs is that they allow a problem-oriented formalization. This means, that the level of abstraction of an evolving algebra can be chosen as needed. In the example algebra in Section 2.7 (p. 9) for instance, we simply used Prolog’s arithmetics over integers and did not bother to specify what multiplication or subtraction actually means. In this section, we demonstrate how such levels of abstraction can be integrated into *leanEA*; the basic idea behind it is to exploit the module-mechanism of the underlying Prolog implementation.

```

algebra fak([N],[reg2])
  using [mult]
  start reg1 := N,
        reg2 := 1
  stop  reg1 =? 1.

define readint as X with read(X), integer(X).
define write(X) as X with write(X).
define X as X with integer(X).
define X-Y as R with integer(X),integer(Y),R is X-Y.
define X*Y as R with mult([X,Y],[R]).

transition step
  if  \+(reg1 =? 1)
  then reg1 := (reg1-1),
       reg2 := (reg2*reg1).

```

Figure 3: A Modularized EA for Computing $n!$

6.1 The Algebra Declaration Statement

In the modularized version of *leanEA*, each specification of an algebra will become a Prolog module; therefore, each algebra must be specified in a separate file. For this, we add an *algebra declaration statement* that looks as follows:

```

algebra Name(In,Out)
  using [Include-List]
  start Updates
  stop Guard.

```

Name is an arbitrary Prolog atom that is used as the name of the predicate for running the specified algebra, and as the name of the module. It is required that *Name.pl* is also the file name of the specification and that the algebra-statement is the first statement in this file.

In, *Out* are two lists containing the input and output parameters of the algebra. The elements of *Out* will be evaluated if the algebra reaches a final state (see below).

Include-List is a list of names of sub-algebras used by this algebra.

Updates is a list of updates; it specifies that part of the initial state of the algebra (see Section 2.6, p. 8), that depends on the input *In*.

Guard is a condition that specifies the final state of the evolving algebra. If *Guard* is satisfied in some state, the computation is stopped and the algebra is halted (see Section 2.6, p. 8).

```

algebra mult([X,Y],[result])
  using []
  start  reg1 := X,
         reg2 := Y,
         result := 0
  stop   reg1 =? 0.

define write(X) as X with write(X).
define X as X with integer(X).
define X+Y as R with integer(X),integer(Y),R is X+Y.
define X-Y as R with integer(X),integer(Y),R is X-Y.

transition step
  if    \+(reg1 =? 0)
  then  reg1 := (reg1-1),
        result := (result+reg2).

```

Figure 4: A Modularized EA for Multiplication

EXAMPLE 17. As an example consider the algebra statement in Figure 3: an algebra `fak` is defined that computes $n!$. This is a modularized version of the algebra shown in Section 2.7 on page 9. The transitions `start` and `result` are now integrated into the algebra statement.

The last function definition in the algebra is of particular interest: it shows how the sub-algebra `mult`, included by the algebra statement, is called. Where the earlier algebra for computing $n!$ on page 9 used Prolog’s built-in multiplication, a sub-algebra for carrying out multiplication is called. Its definition can be found in Figure 4.

6.2 Implementation of Modularized EAs

The basic difference between the basic version of `leanEA` and the modularized version is that the `algebra`-statement at the beginning of a file containing an EA specification is mapped into appropriate `module` and `use_module` statements in Prolog. Since the algebra will be loaded within the named module, we also need an evaluation function that is defined internally in this module. This allows to use functions with the same name in different algebras without interference.

Figure 5 (p. 20) lists the modularized program. It defines four additional operators (`algebra`, `start`, `stop`, and `using`) that are needed for the algebra statement. The first `term_expansion` clause (Lines 6–21) translates such a statement into a Prolog module header, declares `=>/2` to be dynamic in the module, and defines the evaluation predicate `=>*` for this module.¹⁰ The effect of the `term_expansion`-statement is probably best seen at an example: the module declaration in Figure 3, for instance, is mapped into

¹⁰This implementation is probably specific for SICStus Prolog and needs to be changed to run on other Prolog systems. The “`Name:`”-prefix is required in SICStus, because a “`:- module(...)`”-declaration becomes effective *after* the current term was processed.

```

1 :- op(1199,fy,(transition)), op(1180,xfx,(if)),
2   op(1192,fy,(define)),      op(1185,xfy,(with)),
3   op(1190,xfy,(as)),         op(1170,xfx,(then)),
4   op(900,xfx,(=>)),          op(900,xfx,(=>*)),
5   op(900,xfx,(:=)),         op(900,xfx,(=?)),
6   op(100,fx,(\\)),          op(1199,fx,(algebra)),
7   op(1190,xfy,(start)),     op(1170,xfx,(stop)),
8   op(1180,xfy,(using)).

9 term_expansion((algebra Head using Include_list
10                start Updates stop Guard),
11                [(:- module(Name, [Name/2])),
12                Name:(:- use_module(Include_list)),
13                (:- dynamic(Name:(=>)/2)),
14                Name:(( [H|T] =>* [HVal|TVal] ) :-
15                    (   H = \\HVal
16                      ;   H =.. [Func|Args], Args =>* ArgVals,
17                        H1 =.. [Func|ArgVals], H1 => HVal),!,
18                        T =>* TVal),
19                Name:([ ] =>* [ ]),
20                Name:((A =? B) :- ([A,B] =>* [Val1,Val2]),
21                            Val1 == Val2),
22                Name:(NewHead :- FrontCode,BackCode,!,
23                        (transition _),Out =>* Value),
24                Name:(transition(result) :- (Guard,!)))]:-
25   Head =.. [Name,In,Out], NewHead =.. [Name,In,Value],
26   serialize(Updates,FrontCode,BackCode).

27 term_expansion((define Location as Value with Goal),
28                ((Location => Value) :- Goal,!)).

29 term_expansion((transition Name if Condition then Updates),
30                (transition(Name) :-
31                    (Condition,!,FrontCode,BackCode,transition(_))) :-
32                serialize(Updates,FrontCode,BackCode).

33 serialize((A,B),(FrontA,FrontB),(BackB,BackA)) :-
34   serialize(A,FrontA,BackA),
35   serialize(B,FrontB,BackB).

36 serialize((LocTerm := Expr),
37            ([Expr] =>* [Val], LocTerm =.. [Func|Args],
38            Args =>* ArgVals, Loc =.. [Func|ArgVals]),
39            asserta(Loc => Val)).

```

Figure 5: Modularized EAs: the Program

```

:- module(fak, [fak/2]).
fak:(:-use_module([mult])).
:- dynamic fak:(=>)/2.

```

plus the usual definition of `=>*/2`.

6.3 Running Modularized EAs

In contrast to the basic version of the EA interpreter, a modularized EA has a defined interface to the outside world: The algebra-statement defines a Prolog predicate that can be used to run the specified EA. Thus, the user does not need to start the transitions manually. Furthermore, the run of a modularized EA does not end with failure of the starting predicate, but with success. This is the case since a modularized EA has a defined final state. If the predicate succeeds, the final state has been reached.

For the example algebra above (Figure 3), the run proceeds as follows:

```

| ?- [ea].
{consulting ea.pl...}
{ea.pl consulted, 50 msec 3424 bytes}

yes
| ?- [fak].
{consulting fak.pl...}
{consulting mult.pl...}
{consulted mult.pl in module mult, 20 msec 10112 bytes}
{consulted fak.pl in module fak, 50 msec 19888 bytes}

yes
| ?- fak(4,Result).

Result = [24] ?

yes
| ?-

```

After loading¹¹ the EA interpreter, the EA of Figure 3 is loaded from the file `fak.pl`. Thus loads in turn the algebra for multiplication in `mult.pl`. The algebra is then started and the result of `4!` is returned.

7 Conclusion

We presented *leanEA*, an approach to implementing an abstract machine for evolving algebras. The underlying idea is to modifying the Prolog reader, such that loading a specification of an evolving algebra means compiling it into Prolog clauses. Thus, the Prolog system itself is turned into an abstract machine for running EAs. The contribution of our work is twofold:

¹¹For more complex computations it is of course advisable to compile, rather than to load the Prolog code.

Firstly, *leanEA* offers an efficient and very flexible framework for simulating EAs. *leanEA* is open, in the sense that it is easily interfaced with other applications, embedded into other systems, or adapted to concrete needs. We believe that this is a very important feature that is often underestimated: if a specification system is supposed to be used in practice, then it must be embedded in an appropriate system for program development. *leanEA*, as presented in this paper, is surely more a starting point than a solution for this, but it demonstrates clearly one way for proceeding.

Second, *leanEA* demonstrates that little effort is needed to implement a simulator for EAs. This supports the claim that EAs are a practically relevant tool, and it shows a clear advantage of EAs over other specification formalisms: these are often hard to understand, and difficult to deal with when implementing them. EAs, on the other hand, are easily understood and easily used. Thus, *leanEA* shows that one of the major goals of EAs, namely to “bridge the gap between computation models and specification methods” (following Gurevich (1994)), was achieved.

A An Extended Example: First Order Semantic Tableaux

A.1 An Evolving Algebra Description of Semantic Tableaux

The following is a *leanEA* specification of semantic tableaux for first order logic. It is a deterministic version of the algebra described in (Börger & Schmitt, 1995). We assume the reader to be familiar with free variable semantic tableau (Fitting, 1990).

We use Prolog syntax for first-order formulae: atoms are Prolog terms, “-” is negation, “;” disjunction, and “,” conjunction. Universal quantification is expressed as `all(X,F)`, where `X` is a Prolog variable and `F` is the scope; similarly, existential quantification is expressed as `ex(X,F)`.

EXAMPLE 18. `(p(0),all(N,(-p(N);p(s(N)))))` stands for $p(0) \wedge (\forall n(\neg p(n) \vee p(s(n))))$.

Since formulae have to be represented by *ground* terms, the variables are instantiated with `'$VAR'(1)`, `'$VAR'(2)`, etc. using `numbervars`¹².

A branch is represented as a (Prolog) list of the formulae it contains; a tableau is represented as a list of the branches it consists of.

The external functions `nxt_fm1`, `nxt_branch`, `update_branch`, and `update_tableau` are only described declaratively in (Börger & Schmitt, 1995); they determine in which order formulae and branches are used for expansion of a tableau. A simple version of these functions has been implemented (see below), that nevertheless is quite efficient. It implements the same tableau procedure that is used in the tableau based theorem prover *leanTAP* (Beckert & Posegga, 1994).

A.2 Preliminaries

First, library modules are included that are used in the function definitions.¹³ The usage of the included predicates is described below.

¹²`numbervars(?Term,+N,?M)` unifies each of the variables in term `Term` with a special term `'$VAR'(i)`, where `i` ranges from `N` to `M-1`. `N` must be instantiated to an integer. `write`, `format`, and `listing` print the special terms as variable names `A`, `B`, ..., `Z`, `A1`, `B1`, etc.

¹³These are modules from the SICStus Prolog library. They might be named differently and/or behave differently in other Prolog systems.

```

1 :- use_module(library(charsio), [format_to_chars/3,
2                               open_chars_stream/3]).
3 :- use_module(library(lists), [append/3]).
4 :- use_module(unify, [unify/2]).

```

The formula Fml to be proven to be inconsistent is given as a Prolog fact `formula(Fml)` (which is additional Prolog code): Fml has to be a closed formula, and the same variable must not be bound by more than one quantifier. In Fml the Prolog variables are not yet replaced by ground terms.

```

5 formula((all(X, (-p(X); p(f(X))))), p(a), -p(f(f(a)))).

```

A.3 Function Definitions

A.3.1 Initial Values of Internal Constants

The constant `tmode` (called `mode` in (Börger & Schmitt, 1995)) defines the mode of the tableau prover which is either `close` (the next transition will check for closure of the current tableau), `expand` (the next transition tries to expand the tableau), `failure` (the tableau is not closed and cannot be expanded), or `success` (the tableau is closed, i.e., a proof has been found). The initial value of `tmode` is `close`:

```

6 define tmode as close.

```

The current branch `cbranch` initially contains only the formula to be proven to be inconsistent. The variables in this formula are instantiated with ' $\$VAR$ ' (1), ' $\$VAR$ ' (2), etc. using `numbervars`, such that `[Formula]` becomes a ground term.

```

7 define cbranch as [Formula] with formula(Formula),
8                               numbervars(Formula, 1, _).

```

The current tableau `ctab` is initially a list containing the initial current branch (described above) as its single element.

```

9 define ctab as [[Formula]] with formula(Formula),
10                               numbervars(Formula, 1, _).

```

The current formula `cfml` is initially set to `[[nxtfml(cbranch)]]*`, where the external function `nxtfml` (see Sec. A.3.2) chooses the next formula from a branch to be expanded. Since the function `nxtfml` cannot be called immediately,¹⁴ the predicate `nxtfml_impl`, that implements `nxtfml`, is used instead.

```

11 define cfml as Cfml with formula(Formula),
12                               numbervars(Formula, 1, _),
13                               nxtfml_impl([Formula], Cfml).

```

`varcount` is the number of variables already used in the proof (plus one). Its initial value is the number of (different) variables in the initial current formula (plus one).

```

14 define varcount as Count with formula(Formula),
15                               numbervars(Formula, 1, Count).

```

¹⁴It is not possible in `leanEA` to use a function of the specified algebra in the Prolog code of function definitions.

The constant `fcount` contains the number of Skolem function symbols already used (plus one). Its initial value is 1:

```
16 define fcount as 1.
```

A.3.2 Definitions of External Functions

The function `rename(Fml, Count)` replaces the atom `'$VAR'(0)` — which is a place holder for the special variable that is called v in (Börger & Schmitt, 1995) — in `Fml` by `'$VAR'(n)`, where n is the integer `Count` is bound to. `'$VAR'(n)` is the place holder for the n th variable. `rename` is implemented using the predicate `replace` (see Section A.4).

```
17 define rename(Fml, Count) as Newfml with
18     replace(Fml, '$VAR'(0), '$VAR'(Count), Newfml).
```

The function `inst` is similar to `rename`; but instead of inserting a new variable for the atom `'$VAR'(0)`, it is replaced by a Skolem term. The Skolem term is composed of the functor `f`, the number that is bound to `Fcount` (which makes the Skolem terms different for different values of `Fcount`), and (the place holders of) the first `Varcount` variables (the predicate `freevars` is described in Section A.4).

```
19 define inst(Fml, Fcount, Varcount) as Newfml with
20     freevars(Varcount, Free),
21     Skolem =.. [f, Fcount | Free],
22     replace(Fml, '$VAR'(0), Skolem, Newfml).
```

The value of the function `exhausted` is 1 if the tableau T bound to `Tab` is exhausted, else it is 0. A tableau is exhausted, if no next branch can be chosen, i.e., if `[[nxtbranch(T)] = bottom`.

```
23 define exhausted(Tab) as 1 with nxtbranch_impl(Tab, bottom).
24 define exhausted(_) as 0.
```

`succ` is the successor function on integers:

```
25 define succ(X) as X1 with integer(X), X1 is X+1.
```

`update_branch` removes the old formula `Old_fml` from the branch `Old_branch`; if `Old_fml` is a γ -formula, it is then appended at the end of the branch. New formulae are added to the beginning of the branch. There are two versions of this function: for one new formula (25–30) and one for two new formulae (32–39). Note, that `Old_fml` is never a literal.

In combination with the implementation of `nxtfml` that always chooses the *first* non-literal formula, `update_branch` implements branches as queues, which leads to a complete tableau proof procedure.

```
26 define update_branch(Old_branch, Old_fml, New_fml) as New_branch with
27     remove(Old_branch, Old_fml, Tmp_branch),
28     ( fmltype_impl(Old_fml, gamma) ->
29         append([New_fml | Tmp_branch], [Old_fml], New_branch)
30     ;   New_branch = [New_fml | Tmp_branch]
31     ).
```

```

32 define update_branch(Old_branch,Old_fml,New_fml_1,New_fml_2) as
33   New_branch with
34   remove(Old_branch,Old_fml,Tmp_branch),
35   ( fmltype_impl(Old_fml,gamma) ->
36     append([New_fml_1,New_fml_2|Tmp_branch],
37           [Old_fml],New_branch)
38   ;   New_branch = [New_fml_1,New_fml_2|Tmp_branch]
39   ).

```

The function `update_tabl` removes the old branch from the tableau and appends the new branch(es) to the end of the tableau. There are two version of this function, for one new branch and for two new branches.

```

40 define update_tabl(Old_tabl,Old_branch,New_branch) as New_tabl with
41   remove(Old_tabl,Old_branch,Tmp_tabl),
42   append(Tmp_tabl,[New_branch],New_tabl).

43 define update_tabl(Old_tabl,Old_branch,
44                   New_branch_1,New_branch_2) as
45   New_tabl with
46   remove(Old_tabl,Old_branch,Tmp_tabl),
47   append(Tmp_tabl,[New_branch_1,New_branch_2],New_tabl).

```

In (Börger & Schmitt, 1995) the value of the function `clsubst` is a list of the closing substitutions of a tableau. But, since we only need to know whether there is a closing substitution or not, the value of `clsubst` is in our version just `empty` or `nonempty`. The predicate `is_closed`, that checks whether a tableau is closed, is described in Section A.4.

```

48 define clsubst(T) as nonempty with is_closed(T).
49 define clsubst(_) as empty.

```

The function `nxtfml` chooses the first formula on the branch that is not a literal; if no such formula exists, its value is `bottom`. The predicate `nxtfml_impl` is described in Section A.4.

```

50 define nxtfml(B) as Next with nxtfml_impl(B,Next).

```

`nxtbranch` chooses the first branch of a tableau that is expandable, i.e., the first branch B such that $\llbracket \text{nxtfml}(B) \rrbracket$ is not `bottom`. The predicate `nxtbranch_impl` is described in Section A.4.

```

51 define nxtbranch(T) as Next with nxtbranch_impl(T,Next).

```

The function `fmltype` determines the type of a formula, which is one of `alpha`, `beta`, `gamma`, `delta`, and `lit` (for literals). The predicate `fmltype_impl` is described in Section A.4.

```

52 define fmltype(Fml) as Type with fmltype_impl(Fml,Type).

```

The function `fst_comp(Fml)` (53–63) computes the first formula that is the result of applying the appropriate tableau rule to Fml ; if the rule application results in two new formulae, `snd_comp(Fml)` returns the second formula. In (Börger & Schmitt, 1995) the γ -

and δ -rules are defined in such a way that the atom ' $\$VAR$ '(0), which is the place holder for the special variable v , is substituted for the bound variable. The substitution is done using the predicate `replace` (see below). v is replaced by the appropriate term (a new variable or a Skolem term) in the transitions `gamma` and `delta`, respectively.

```

53 define fst_comp(Fml) as First with
54   (   Fml = (F,_)      -> First = F
55     ;   Fml = -(F;_)   -> First = -F
56     ;   Fml = -(-(F))  -> First = F
57     ;   Fml = -(F,_)   -> First = -F
58     ;   Fml = (F;_)    -> First = F
59     ;   Fml = all(X,F)  -> replace(F,X,'$VAR'(0),First)
60     ;   Fml = -(ex(X,F)) -> replace(-(F),X,'$VAR'(0),First)
61     ;   Fml = -(all(X,F)) -> replace(-(F),X,'$VAR'(0),First)
62     ;   Fml = ex(X,F)   -> replace(F,X,'$VAR'(0),First)
63   ).

64 define snd_comp(Fml) as Second with
65   (   Fml = (_,F)      -> Second = F
66     ;   Fml = -((_;F)) -> Second = -F
67     ;   Fml = -(-(F))  -> Second = F
68     ;   Fml = -((_,F)) -> Second = -F
69     ;   Fml = (_,F)    -> Second = F
70   ).

```

A.4 Additional Code Used in the Function Definitions

The predicate `nxtfml_impl` implements the function `nxtfml`; it chooses the first formula on a tableau branch that is not a literal. If no such formula exists, the value of `nxtfml` is `bottom`; the value of `nxtfml(bottom)` is `bottom` as well.

```

71 nxtfml_impl(bottom,bottom).
72 nxtfml_impl([],bottom).
73 nxtfml_impl([First|_],Fml) :-
74   \+(fmltype_impl(First,lit)),!,Fml=First.
75 nxtfml_impl([_|Rest],Next) :- nxtfml_impl(Rest,Next).

```

The predicate `nxtbranch_impl` implements the function `nxtbranch`; it chooses the first branch of a tableau that is expandable, i.e., the first branch that contains a formula that is not a literal. If no such branch exists, the value of `nxtbranch` is `bottom`.

```

76 nxtbranch_impl([],bottom).
77 nxtbranch_impl([First|_],Branch) :-
78   \+(nxtfml_impl(First,bottom)),!,Branch=First.
79 nxtbranch_impl([_|Rest],Next) :- nxtbranch_impl(Rest,Next).

```

The predicate `fmltype_impl` implements the function `fmltype` (in the obvious way).

```

80 fmltype_impl(Fml,Type) :-
81   (   Fml = (_,_)      -> Type = alpha

```

```

82 ; Fml = -((_;_)) -> Type = alpha
83 ; Fml = -(-(_)) -> Type = alpha
84 ; Fml = -((_,_)) -> Type = beta
85 ; Fml = (_;_) -> Type = beta
86 ; Fml = all(,_)_ -> Type = gamma
87 ; Fml = -(ex(,_)_ -> Type = gamma
88 ; Fml = -(all(,_)_ -> Type = delta
89 ; Fml = ex(,_)_ -> Type = delta
90 ; Type = lit
91 ).

```

`replace(+Term,+Old,+New,New_term)` replaces all occurrences of `Old` in `Term` by `New`. The result is bound to `New_term`. `replace_list(+List,+Old,+New,New_list)` does the same for a list `List` of terms.

```

92 replace(Term,Old,New,New) :-
93     Term == Old,
94     !.
95 replace(Term,Old,New,NTerm) :-
96     Term =.. [F|Args],
97     replace_list(Args,Old,New,NArgs),
98     NTerm =.. [F|NArgs].

99 replace_list([],_ ,_ , []).
100 replace_list([H|T],Old,New,[NH|NT]) :-
101     replace(H,Old,New,NH),
102     replace_list(T,Old,New,NT).

```

The predicate `freevars(+N,-List)`, generates a list of the place holders for the first n variables, where n is the integer `N` is bound to.

```

103 freevars(1,[]) :- !.
104 freevars(N,['$VAR'(N1)|Free]) :-
105     integer(N),
106     N1 is N-1,
107     freevars(N1,Free).

```

`remove(+Old_list,+Elem,-New_list)` removes all occurrences of the term `Elem` from the list `Old_list`; the result is bound to `New_list`.

```

108 remove([],_ , []).
109 remove([H|T],Elem,New) :-
110     remove(T,Elem,NT),
111     ( H == Elem ->
112         New = NT
113     ; New = [H|NT]
114     ),
115     !.

```

The predicate `is_closed(+T)` (Lines 116–119) checks whether the tableau bound to `T` is closed. First, the predicate `denumbervars` is called (described below), that replaces

the variable place holders by Prolog variables; then the predicate `is_closed_2` (120–123) is called, which closes the branches of a tableau (containing Prolog variables as object variables) one after the other using `close_branch`.

`close_branch` (124–127) negates the first formula on the branch (and further formulae if backtracking occurs) and tries to unify this negation with another formula on the branch.

`is_closed` and the predicates it calls heavily depend on backtracking for finding a single substitution that closes all branches of the tableau simultaneously.

```

116 is_closed(T) :-
117     denumbervars(T,T1),
118     is_closed_2(T1),
119     !.

120 is_closed_2([]).
121 is_closed_2([First|Rest]) :-
122     close_branch(First),
123     is_closed_2(Rest).

124 close_branch([H|T]) :-
125     (H = -Neg; -H = Neg) ->
126     member_unify(Neg,T).
127 close_branch(_|T) :- close_branch(T).

```

`member_unify` is the same as `member`, except that it uses sound unification (with occur check).

```

128 member_unify(X,[H|T]) :-
129     (    unify(X,H)
130     ;    member_unify(X,T)
131     ).

```

The predicate `denumbervars` replaces the place holders of the form '`$VAR`' (n) by (new) Prolog variables. It is the most system dependent predicate in the definition of this evolving algebra. It works by writing the tableau to a “character stream” using `format_to_chars/3`¹⁵, which replaces the place holders by Prolog variables¹⁶, and then re-reading the tableau from the “character stream”¹⁷. `append(Chars,[46],CharsPoint)` adds a period “.” to the term such that it becomes a Prolog fact.

```

132 denumbervars(T,T1) :-
133     format_to_chars("~p",[T],Chars),
134     append(Chars,[46],CharsPoint),
135     open_chars_stream(CharsPoint,read,Stream),
136     read(Stream,T1),
137     close(Stream).

```

¹⁵`format_to_chars(+Format,+Arguments,-Chars)` prints `Arguments` into a list of character codes using `format/3` (which in this case just prints the term). `Chars` is unified with the list.

¹⁶See Footnote 12 on Page 22.

¹⁷`open_chars_stream(+Chars,read,-Stream)` opens `Stream` as an input stream to an existing list of character codes. The stream may be read with the Stream IO predicates and must be closed using `close/1`.

A.5 Transition Definitions

The main difference to the original version of the EA as described in (Börger & Schmitt, 1995) is that instead of using an additional transition

```
transition enter_closure
  if tmode =? \expand,
  then tmode := \close.
```

the closure mode is entered explicitly at the end of each of the expanding transitions **alpha**, **beta**, **gamma** and **delta**. Using the transition **enter_closure** would make the EA non-deterministic, because it fires whenever one of the expanding transitions fires.

If the EA is in closure mode, there are three transitions that might apply:

1. If the current tableau is closed, transition **success** (138–141) fires and **tmode** is set to **success**. Then, the EA is in a final state, because no further transition fires.
2. If the tableau is not closed but expandable, transition **closure** (142–146) fires, **tmode** is set to **expand**, and the tableau will be expanded in the next step.
3. If the current tableau is neither closed nor expandable, transition **failure** (147–151) fires. It sets **tmode** to **fail**, and the EA reaches a final state.

```
138 transition success
139   if tmode =? \close,
140     clsubst(ctab) <> \empty
141   then tmode := \success.

142 transition closure
143   if tmode =? \close,
144     clsubst(ctab) =? \empty,
145     exhausted(ctab) =? \0
146   then tmode := \expand.

147 transition failure
148   if tmode =? \close,
149     clsubst(ctab) =? \empty,
150     exhausted(ctab) <> \0
151   then tmode := \fail.
```

There are four transitions for expanding the current tableau, one for each possible type of the current formula (which is never a literal). The definitions of these transitions make use of the **let** construct (Sec. 5.1).

The transition **alpha** first stores the two formulae that are the result of the rule application to the current formula in **F1** and **F2**, respectively. These two formulae are added to the current branch (and the old current formula is removed); the new branch, that is stored in **B** is added to the current tableau (and the old branch is removed). The resulting tableau **T** becomes the next current tableau, and the next current branch and current formula are chosen from **T**.

```
152 transition alpha
```

```

153   if   tmode =? \expand,
154       fmltype(cfml) =? \alpha
155   then let F1 = fst_comp(cfml),
156         let F2 = snd_comp(cfml),
157         let B  = update_branch(cbranch,cfml,F1,F2),
158         let T  = update_tabl(ctab,cbranch,B),
159         ctab := T,
160         cbranch := nxtbranch(T),
161         cfml := nextfml(nxtbranch(T)),
162         tmode := \close.

```

The transition `beta`, too, stores the two formulae that are the result of the rule application to the current formula in `F1` and `F2`, respectively. But contrary to the transition `alpha`, it generates *two* new branches `B1` and `B2` by adding the new formulae separately to the current branch. Both new branches are added to the current tableau (the old branch is removed). The resulting tableau `T` becomes the next current tableau, and the next current branch and current formula are chosen from `T`.

```

163 transition beta
164   if   tmode =? \expand,
165       fmltype(cfml) =? \beta
166   then let F1 = fst_comp(cfml),
167         let F2 = snd_comp(cfml),
168         let B1 = update_branch(cbranch,cfml,F1),
169         let B2 = update_branch(cbranch,cfml,F2),
170         let T  = update_tabl(ctab,cbranch,B1,B2),
171         ctab := T,
172         cbranch := nxtbranch(T),
173         cfml := nextfml(nxtbranch(T)),
174         tmode := \close.

```

The transition `gamma` first stores the result of applying `fst_cmp` to the current formula in `F`, which is the scope of the quantification with the bound variable replaced by the special variable `v` (resp. its place holder '`$VAR`' (0)). `v` is then replaced by a new free variable using `rename`. The resulting formula `F1` is added to the current branch and the new branch is added to the current tableau (replacing the old branch). The next current branch and current formula are chosen, and `varcount` is increased by one.

```

175 transition gamma
176   if   tmode =? \expand,
177       fmltype(cfml) =? \gamma
178   then let F  = fst_comp(cfml),
179         let F1 = rename(F,varcount),
180         let B  = update_branch(cbranch,cfml,F1),
181         let T  = update_tabl(ctab,cbranch,B),
182         ctab := T,
183         cbranch := nxtbranch(T),
184         cfml := nextfml(nxtbranch(T)),
185         varcount := succ(varcount),

```

```
186         tmode := \close.
```

The transition `delta` is very similar to the transition `gamma`. The only differences are that the variable `v` is replaced by a Skolem term (instead of a free variable) using `inst`, and that `fcount` is increased instead of `varcount`.

```
187 transition delta
188   if   tmode =? \expand,
189       fmltype(cfml) =? \delta
190   then let F = fst_comp(cfml),
191         let F1 = inst(F,fcount,varcount),
192         let B = update_branch(cbranch,cfml,F1),
193         let T = update_tabl(ctab,cbranch,B),
194         ctab := T,
195         cbranch := nxtbranch(T),
196         cfml := nxfml(nxtbranch(T)),
197         fcount := succ(fcount),
198         tmode := \close.
```

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