Translating Nondeterministic Functional Language based on Attribute Grammars into Java

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Abstract. Knowledge-based systems are suitable for realizing advanced functions that require domain-specific expert knowledge, while knowledge representation languages and their supporting environments are essential for realizing such systems. Although Prolog is useful and effective in realizing such a supporting environment, the language interoperability with other implementation languages, such as Java, is often an important issue in practical application development. This paper describes the techniques for translating a knowledge representation language that is a nondeterministic functional language based on attribute grammars into Java. The translation is based on binarization and the techniques proposed for Prolog to Java translation although the semantics are different from those of Prolog. A continuation unit is introduced to handle continuation efficiently, while the variable and register management on backtracking is simplified by using the single and unidirectional assignment features of variables. An experimental translator written in the language itself successfully generates Java code, while experimental results show that the generated code is over 25 times faster than that of Prolog Cafe for nondeterministic programs, and over 2 times faster for deterministic programs. The generated code is also over 2 times faster than B-Prolog for nondeterministic programs.

1 Introduction

There is high demand for advanced information services in various application domains such as medical services and supply-chain management, as information and communication technology penetrates deeply into our society. Clinical decision support [1, 2] to prevent medical errors and order placement support for optimal inventory management [3] are typical examples. It is, however, not prudent to implement such functions as a normal part of the traditional information system using conventional programming languages. This is because expert knowledge is often large scale and complicated, and each application domain typically has its own specific structures and semantics. Therefore, not only the analysis, but also the description, audit, and maintenance of such knowledge are often difficult without expertise in the application domain. It is thus, essential to realize such advanced functions to allow domain experts themselves to describe, audit, and maintain their knowledge. A knowledge-based system approach is suitable for such purposes because a suitable framework for representing and managing expert knowledge is supplied.

Previously, Nagasawa et al. proposed the knowledge representation language DSP [4, 5] and its supporting environment. DSP is a nondeterministic functional language based on attribute grammars [6, 7] and is suitable for representing complex search problems without relying on any side effects. The supporting environment has been developed on top of an integrated development environment called Inside Prolog [8]. Inside Prolog provides standard Prolog functionality, conforming to ISO/IEC 13211-1 [9], and also a large variety of Application Programming Interfaces (APIs) that are essential for practical application development and multi-thread capability for enterprise use [10].

These features allow the consistent development of knowledge-based systems from prototypes to practical systems for both stand-alone and enterprise use [11]. Such systems have been applied to several practical applications, and the effectiveness thereof has been clarified. However, several issues have also been perceived from these experiences. One is the complexity of combining a
Prolog-based system with a system written in a normal procedural language, such as Java. The other is the adaptability to a new computer environment such as mobile devices.

This paper describes the implementation techniques required to translate a nondeterministic functional language based on attribute grammars into a procedural language such as Java. The proposed techniques are based on the techniques for Prolog to Java translation. Section 2 gives an overview of the knowledge representation language DSP, and clarifies how it differs from Prolog. In Section 3, the translation techniques for logic programming languages are briefly reviewed, and basic ideas useful for the translation of DSP identified. Section 4 discusses the program representations of DSP in Java, while Section 5 evaluates the performance using an experimental translator.

## 2 Overview of Knowledge Representation Language DSP

### 2.1 Background

It is essential to formally analyze, systematize, and describe the knowledge of an application domain in the development of a knowledge-based system. The description of knowledge is conceptually possible in any conventional programming language. Nevertheless, it is difficult to describe, audit, and maintain a knowledge base using a procedural language such as Java. This is because the knowledge of an application domain is often large scale and complicated, and each application domain has its own specific structures and semantics. In particular, the audit and maintenance of written knowledge is a major issue in an information system involving expert knowledge, because such a system is very often stiffened and the transfer of expert knowledge to succeeding generations is difficult [12]. Therefore, it is very important to provide a framework to enable domain experts themselves to describe, audit, and maintain their knowledge included in an information system [13]. It is perceived that a description language that is specific to an application domain and is designed so as to be described by domain experts is superior in terms of the minimality, constructibility, comprehensibility, extensibility, and formality of the language [14]. For this reason, Prolog cannot be considered as a candidate for a knowledge representation language.

DSP is a knowledge representation language based on nondeterministic attribute grammars. It is a functional language with a search capability using the generate and test method. Because the language is capable of representing trial and error without any side-effects or loop constructs, and the knowledge descriptions can be declaratively read and understood, it is suitable for representing domain-specific expert knowledge involving search problems.

### 2.2 Syntax and Semantics of DSP

A program unit to represent knowledge in DSP is called a “module”, and it represents a nondeterministic function involving no side-effects. Inherited attributes, synthesized attributes, and tentative variables for the convenience of program description, all of which are called variables, follow the single assignment rule and the assignment is unidirectional. Therefore, the computation process of a module can be represented as non-cyclic dependencies between variables.

Table 1 shows some typical statements in the language. In this table, the types, generator, calculator, and tester, are functional classifications in the generate and test method. Generators for \( \text{for}(B,E,S) \) and \( \text{select}(L) \) are provided as primitives for the convenience of knowledge representation although they can be defined as modules using the nondeterministic features of the language. Both \( \text{call}(M,I,O) \) and \( \text{dcall}(M,I,O) \) are used for module decomposition, with the latter restricting the first solution of a module call like \( \text{once}/1 \) in Prolog \(^3\), while the former calls a module nondeterministically. Calculator \( \text{find}(M,I,OL) \) collects all outputs of a module and returns a list thereof. Testers \( \text{when}(C) \) and \( \text{test}(C) \) are used to represent decomposition conditions. Both behaves in the same way in normal execution mode \(^4\), although the former is intended to

\(^3\) \( \text{dcall} \) stands for deterministic call.

\(^4\) Failures of \( \text{when}(C) \) and \( \text{test}(C) \) are treated differently in debugging mode because of their semantic differences.
Table 1. Typical statements in the DSP language

| Type      | Statement       | Function                           |
|-----------|-----------------|------------------------------------|
| generator | for(B,E,S)      | Assume a numeric value from B to E with step S |
| generator | select(L)       | Assume one of the elements of a list L |
| generator | call(M,I,O)     | Call a module M nondeterministically with inputs I and outputs O |
| calculator| dcall(M,I,O)    | Call a module M deterministically with inputs I and outputs O |
| calculator| find(M,I,Ol)    | Get a list Ol of all outputs of a module M with inputs I |
| tester    | when(C)         | Specify the domain C of a method |
| tester    | test(C)         | Specify the constraint C of a method |
| tester    | verify(C)       | Specify the verification condition C |

describe a guard of a method, while the latter describes a constraint. Tester verify(C) does not affect the execution of a module although it is classified as the tester. Solutions in which a verification condition is not satisfied are indicated as such, and these verification statuses are used to evaluate the inference results.

```plaintext
pointInQuarterCircle({R : real}, --(a)
  {X : real, Y : real}) --(b)
method
  X : real = for(0.0, R, 1.0); --(c)
  Y : real = for(0.0, R, 1.0); --(d)
  D : real = sqrt(X^2 + Y^2); --(e)
  test(D =< R); --(f)
end method;
end module;
```

Fig. 1. Module pointInQuarterCircle, which enumerates all points in a quarter circle

Figure 1 gives the code for module pointInQuarterCircle, which enumerates all points in a quarter circle with radius R. Statements (a) and (b) in Fig. 1 define the input and output variables of module pointInQuarterCircle, respectively. Statements (c) and (d) assume the values of the variables X and Y from 1 to R with an incremental step 1. Statement (e) calculates the distance D between point (0,0) and point (X,Y). Statement (f) checks if point (X,Y) is within the circle of radius R. Module pointInQuarterCircle runs nondeterministically for a given R, and returns one of all possible \( \{X,Y\} \) values. Therefore, this module also behaves as a generator. Statements (c) to (f) can be listed in any order, and they are executed according to the dependencies between variables. Therefore, the computation process can be described as a non-cyclic data flow. Figure 2 shows the data flow diagram for module pointInQuarterCircle. Because no module includes any side-effects, the set of points returned by the module for the same input is always the same.

Figure 3 shows an example of module for, which implements the generator primitive for. If multiple methods are defined in a module with some overlap in their domains specified by when, the module works nondeterministically, and thus a module can also be a generator. In this example, there is overlap between the domains specified by statements (a) and (c).

2.3 Execution Model for DSP

Since the variables follow the single assignment rule and the assignment is unidirectional, the statements are partially ordered according to the dependencies between variables. In the execution,
Fig. 2. Data flow diagram of module pointInQuarterCircle

\[
\text{pointInQuarterCircle}
\]

\[
\text{(c) for}(0.0,R,1.0) \rightarrow \text{(d) for}(0.0,R,1.0)
\]

\[
\text{(c) sqrt}(X^2+Y^2) \rightarrow D
\]

\[
\text{(d) } D \sim R
\]

\[
\text{X} \rightarrow \text{generator} \rightarrow \text{Y} \rightarrow \text{calculator} \rightarrow \text{tester}
\]

**Fig. 2. Data flow diagram of module pointInQuarterCircle**

\[
\text{for}((B : \text{real}, E : \text{real}, S : \text{real}), (N : \text{real}))
\]

\[
\text{method} \quad -- \text{The fist method}
\]

\[
\text{when}(B \leq E); \quad --(a)
\]

\[
N : \text{real} = B; \quad --(b)
\]

\[
\text{end method;}
\]

\[
\text{method} \quad -- \text{The second method}
\]

\[
\text{when}(B+S \leq E); \quad --(c)
\]

\[
B1 : \text{real} = B+S; \quad --(d)
\]

\[
call(\text{for}, \{B1, E, S\}, \{N\}); \quad --(e)
\]

\[
\text{end method;}
\]

\[
\text{end;}
\]

**Fig. 3. Module for, which implements the generator primitive for**

the statements must be totally reordered and evaluated in this order. Although the method used to order the partially ordered statements totally does not affect the set of solutions, the order of the generators affects the order of the solutions returned from a nondeterministic module.

The execution model for DSP can be represented in Prolog. Figure 4 illustrates an example of a simplified DSP interpreter in Prolog. In this interpreter, statements are represented as terms concatenated by “;” and it is assumed that the statements are totally ordered. Variables are represented using logical variables in Prolog. Actually, the development environment for DSP provides a compiler that translates into Prolog code, with the generated Prolog code translated into bytecode by the Prolog compiler in the runtime environment.

3 Translation Techniques for Logic Programming Languages

Prolog is a logic programming language that offers both declarative features and practical applicability to various application domains. Many implementation techniques for Prolog and its family have been proposed, while abstract machines represented by the WAM (Warren’s Abstract
solve((A ; B)) :-
    solve(A),
    solve(B).
solve(call(M, In, Out)) :-
    reduce(call(M, In, Out), Body),
    solve(Body).
solve(dcall(M, In, Out)) :-
    reduce(call(M, In, Out), Body),
    solve(Body), !.
solve(find(M, In, OutList)) :-
    findall(Out, solve(M, In, Out), OutList).
solve(when(Exp)) :- !,
    call(Exp), !.
solve(test(Exp)) :- !,
    call(Exp), !.
solve(V := for(B, E, S)) :- !,
    for(B, E, S, V).
solve(V := select(L)) :- !,
    member(V, L).
solve(V := Exp) :-
    V is Exp.

Fig. 4. Simplified DSP interpreter in Prolog

Machine) [15] have proven effective practical implementation techniques. On the other hand, few Prolog implementations provide practical functionality applicable to both stand-alone systems and enterprise-mission-critical information systems without using other languages. Practically, Prolog is often combined with a conventional procedural language, such as Java, C, and C#, for use in practical applications. In such cases, language interoperability is an important issue.

Language translation is one possible solution for improving the interoperability between Prolog and other combined languages. jProlog [16] and Prolog Cafe [17] are Prolog to Java translators based on binarization [18], while P# [19] is a Prolog to C# translator based on Prolog Cafe with concurrent extensions. The binarization with continuation passing is a useful idea for handling nondeterminism simply in procedural languages. For example, the following clauses

\[
p(X) :- q(X, Y), r(Y).
q(X, X).
r(X).
\]

can be represented by semantically equivalent clauses that take a continuation goal \texttt{Cont} as the last parameter:

\[
p(X, \text{Cont}) :- q(X, Y, r(Y, \text{Cont})).
q(X, X, \text{Cont}) :- \text{call(Cont)}.
r(X, \text{Cont}) :- \text{call(Cont)}.
\]

Once clauses have been transformed into this form, clauses composing a predicate can be translated into Java classes. Figure 5 gives an example of code generated by Prolog Cafe. Predicate \texttt{p/2} after binarization is represented as a Java class called \texttt{PRED\_p1}, which is a subclass of class \texttt{Predicate}. The parameters of a predicate call are passed as the arguments of the constructor of a class, while the right hand side of a clause is expanded as method \texttt{exec}.

If a predicate consists of multiple clauses as in the following predicate \texttt{p/1}, it may have choice points.

\[
p(X) :- q(X, Y), r(Y).
p(X) :- r(X).
\]
public class PRED_p_1 extends Predicate {
    public Term arg1;

    public PRED_p_1(Term a1, Predicate cont) {
        arg1 = a1;
        this.cont = cont; /* this.cont is inherited. */
    }
    ...
    public Predicate exec(Prolog engine) {
        engine.setB0();
        Term a1, a2;
        Predicate p1;
        a1 = arg1;
        a2 = new VariableTerm(engine);
        p1 = new PRED_r_1(a2, cont);
        return new PRED_q_2(a1, a2, p1);
    }
}

Fig. 5. Java code generated by Prolog Cafe

In such a case, the generated code becomes more complex than before because the choice points of p/1 must be handled for backtracking. Figure 6 gives an example of the generated code for predicate p/1 in the previous example. Each clause of a predicate is mapped to a subclass of a class representing the predicate. In this example, classes PRED_p_1_1 and PRED_p_1_2 correspond to the two clauses of predicate p/1. Methods jtry and trust of the Prolog engine correspond to WAM instructions that manipulate stacks and choice points for backtracking. The key ideas in Prolog Cafe are that continuation is represented as an instance of a Java class representing a predicate, and the execution control including backtracking follows the WAM. The translation is straightforward through the WAM, while the interoperability with Java-based systems is somewhat improved. On the other hand, the disadvantage is the performance of the generated code.

4 Program Representation in Java and Inference Engine

This section describes the translation techniques for the nondeterministic functional language DSP into Java based on the translation techniques for Prolog. Current implementations of the compiler and inference engine for DSP have been developed on top of Inside Prolog with the compiler generating Prolog code. Therefore, it is possible to translate this generated Prolog code into Java using Prolog Cafe. However, there are several differences between DSP and Prolog in terms of the semantics of variables and the determinism of statements. These differences allow several optimizations in performance, and the generated code can run faster than the code generated by Prolog Cafe for compatible Prolog programs. Fundamental ideas of our translation techniques utilize the single and unidirectional assignment features of variables and the deterministic features of some statements.

The overall structure of the Java code translated from DSP provides for one module being mapped to a single Java class, and each method in a module mapped to a single inner class of the class. Figure 7 shows an example of Java code for module pointInQuarterCircle given in Fig. 1. Inner classes are used to represent an execution context of a predicate as an internal state of a class instance. Therefore, the instances of an inner class are not declared as static unlike classes in Fig. 6.

An overview of the translation process follows. First, the data flow of a module is analyzed for each method based on the dependencies between variables, and the statements are reordered according to the analysis results. Next, the statements are grouped into translation units called
public class PRED_p_1 extends Predicate {
    static Predicate _p_1_sub_1 = new PRED_p_1_sub_1();
    static Predicate _p_1_1 = new PRED_p_1_1();
    static Predicate _p_1_2 = new PRED_p_1_2();
    public Term arg1;

    public Predicate exec(Prolog engine) {
        engine.aregs[1] = arg1;
        engine.cont = cont;
        engine.setB0();
        return engine.jtry(_p_1_1, _p_1_sub_1);
    }
}

class PRED_p_1_sub_1 extends PRED_p_1 {
    public Predicate exec(Prolog engine) {
        return engine.trust(_p_1_2);
    }
}

class PRED_p_1_1 extends PRED_p_1 {
    public Predicate exec(Prolog engine) {
        Term a1, a2;
        Predicate p1;
        Predicate cont;
        a1 = engine.aregs[1];
        cont = engine.cont;
        a2 = new VariableTerm(engine);
        p1 = new PRED_r_1(a2, cont);
        return new PRED_q_2(a1, a2, p1);
    }
}

class PRED_p_1_2 extends PRED_p_1 {
    public Predicate exec(Prolog engine) {
        Term a1;
        Predicate cont;
        a1 = engine.aregs[1];
        cont = engine.cont;
        return new PRED_r_1(a1, cont);
    }
}

Fig. 6. Java code with choice points generated by Prolog Cafe
continuation units, and Java code is generated for each method according to the continuation units.

4.1 Data Flow Analysis

As described in Sect. 2, it is necessary to reorder and evaluate statements so as to fulfill variable dependencies since statements can be listed in any order. Therefore, partially ordered statements must first be totally reordered. In the reordering process, the order of the generators should be kept as long as the variable dependencies are satisfied, because the order of generators affects the order of the solutions as described in Sec. 2. On the other hand, calculators or testers can be moved forward for the least commitment as long as partial orders are kept.

4.2 Continuation Unit

If statements of a method are totally ordered, they can be divided into several groups of statements. Each group is called a continuation unit and consists of a series of deterministic statements, such as calculators and testers, followed by a single generator. It should be noted that a continuation unit may not contain a generator if it is the last one in a method. In the translation, a continuation unit is treated as a unit to translate, and is mapped to a Java class representing a continuation.

In the example in Fig. 7, module `pointInQuarterCircle` has one method, and there are three continuation units in the method. Inner class `Method_1` corresponds to this method of the module, and class `Method_1_cu1` corresponds to the continuation unit for statement (c), class `Method_1_cu2` to one for statement (d), and class `Method_1_cu3` to one for statements (e) and (f), respectively.

4.3 Variable and Parameter Passing

Although variables follow the single assignment rule like Prolog, the binding of a variable is unidirectional unlike Prolog. Therefore, it is not necessary to introduce logical variables and unification, unlike in Prolog Cafe. This also implies that the trail stack and variable unbinding using the stack are unnecessary on backtracking. Therefore, a class representing the variables is only necessary as a place holder for the output values of a module. Class `Variable` is introduced to represent such variables.

Prolog Cafe uses the registers of the Prolog VM to manage the arguments of a goal. This approach is consistent with the WAM, but is sometimes inefficient since it requires arguments to be copied from/to registers to/from the stack on calls and backtracking. On the other hand, because the direction of variable binding is clearly defined in DSP, it is unnecessary to restore variable bindings on backtracking as described before. Instead, variables can always be overwritten when a goal is re-executed after backtracking. Therefore, input and output parameters can be passed as arguments of a class constructor. This simplifies the management of variables and arguments. In addition, as shown in Fig. 7, basic Java types, such as `int` and `double`, can be passed directly as inputs in some cases. This contributes to the performance improvement.

4.4 Inference Engine

An inference engine for the translated code is very simple because management of variables and registers on backtracking is unnecessary. Figure 8 shows an example of the inference engine called `VM`, which uses a stack represented as an array of interface `Executable` to store choice points. Method `call()` is an entry point to call the module to find an initial solution, while method `redo()` is used to find the next solution. A typical call procedure of a client program in Java is given below.

```java
VM vm = new VM();
Double r = new Double(10.0);
Variable x = new Variable();
```
public class PointInQuarterCircle implements Executable {
    private Double r;
    private Variable x;
    private Variable y;
    private Executable cont;
    public PointInQuarterCircle(Double r,
            Variable x, Variable y, Executable cont)
    {
        this.r = r;
        this.x = x;
        this.y = y;
        this.cont = cont;
    }
    public Executable exec(VM vm) {
        return (new Method_1()).exec(vm);
    }
}

class Method_1 implements Executable {
    private Variable d = new Variable();
    private Executable method_1_cu1 = new Method_1_cu1();
    private Executable method_1_cu2 = new Method_1_cu2();
    private Executable method_1_cu3 = new Method_1_cu3();
    public Executable exec(VM vm) {
        return method_1_cu1.exec(vm);
    }
}

class Method_1_cu1 implements Executable {
    public Executable exec(VM vm) {
        return new ForDouble(0.0, r.doubleValue(), 1.0, x, method_1_cu2);
    }
}

class Method_1_cu2 implements Executable {
    public Executable exec(VM vm) {
        return new ForDouble(0.0, r.doubleValue(), 1.0, y, method_1_cu3);
    }
}

class Method_1_cu3 implements Executable {
    public Executable exec(VM vm) {
        d.setValue(Math.sqrt(x.doubleValue()*x.doubleValue() +
                           y.doubleValue()*y.doubleValue()));
        if(!(d.doubleValue() <= r.doubleValue())){
            return Executable.failure;
        }
        return cont;
    }
}

Fig. 7. Java code generated for module pointInQuarterCircle
Variable y = new Variable();
Executable m = new PointInQuarterCircle(r, x, y,
    Executable.success);
for (boolean s = vm.call(m); s == true; s = vm.redo()) {
    System.out.println("X=" + x.doubleValue() +
        ", Y=" + y.doubleValue());
}

This client program creates an inference engine, prepares output variables to receive the values of a solution, creates an instance of class PointInQuarterCircle with inputs and outputs, and calls call() to find an initial solution. It then calls redo() to find the next one until there are no more solutions.

Because the implementation of the inference engine is simple and multi-thread safe, and the generated classes of a module are also multi-thread safe, it is easy to deploy instances of the engine in a multi-thread environment.

```java
public class VM {
    private Executable[] choicepoint;
    private int ccp = -1; // Current choice point.
    ...

    public VM(int initSize) {
        choicepoint = new Executable[initSize];
    }
    ...

    public boolean call(Executable goal) {
        while (goal != null) {
            goal = goal.exec(this);
            if (goal == Executable.success) {
                return true;
            } else if (goal == Executable.failure) {
                goal = getChoicePoint();
            }
        }
        return false;
    }

    public boolean redo() {
        return call(getChoicePoint());
    }
}
```

Fig. 8. Inference engine for DSP

5 Implementation and Performance Evaluation

We have implemented the translator for DSP into Java based on the techniques proposed in Sec. 4. The translator is written in DSP itself and generates Java code.

Table 2 shows the performance results of 6 sample programs executed under Windows Vista on an Intel Core2Duo 2.53 GHz processor with 3.0 GB memory. Java 1.6, Prolog Cafe 1.2.5, and B-Prolog 7.4 [20] were used in the experiments. Because the Java garbage collector affects the performance, 512 MB memory was statically allocated for the heap in all cases except for one.

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6 About 1000 MB was allocated for the generated code for tarai w/o cuts.
Program plan is a simple architecture design program for a parking structure. It can enumerate all possible column layouts for the given design conditions, such as free land space and the number of stories. Programs nqueens, ack, and tarai are well-known benchmarks, with ack and tarai using green cuts for guards in Prolog, while ack w/o cuts and tarai w/o cuts do not use cuts for guards. In the case of DSP, ack and tarai use dcall for self-recursive calls not to leave choice points, while ack w/o cuts and tarai w/o cuts use call. The programs written in DSP are compiled into Prolog and then compiled into bytecode. The programs are forced to backtrack in each iteration to enumerate all solutions, and the execution times in milliseconds are averages over 10 trials.

These results show that the proposed translator generates over 25 times faster code than Prolog Cafe, over 2 times faster code than B-Prolog, and over 5 times faster code than DSP on top of Inside Prolog for plan and nqueens. On the other hand, for ack and tarai the translator generates about 2 to 3 times faster code than Prolog Cafe, but about 5 to 15 times slower code than B-Prolog. The translator also generates about 8 to 13 times faster code than Prolog Cafe, but about 4 to 10 times slower code than B-Prolog for ack w/o cuts and tarai w/o cuts. Here, plan and nqueens are nondeterministic, while ack and tarai are deterministic. ack w/o cuts and tarai w/o cuts are also deterministic, but they involve backtracking because of the lack of green cuts.

These experiments indicate that the proposed translation techniques can generate faster code than Prolog Cafe and DSP on top of Inside Prolog for all 6 programs, and faster code than B-Prolog for nondeterministic programs. In the case of deterministic programs, the advantage of the proposed translation techniques is obvious against Prolog Cafe if green cuts are not used in Prolog. The reason why these distinctive differences are observed seems to be that the simplification of the variable and register management for backtracking contributes to the performance improvement of nondeterministic programs, but it is not effective for deterministic programs with green cuts.

In the case of B-Prolog, the execution time of tarai is almost the same as that of tarai w/o cuts. This is because B-Prolog compiler reduces choice points using matching trees for both tarai and tarai w/o cuts [21]. Although the DSP language has no explicit cut operator of Prolog, improving the performance by inserting cut instructions automatically in the case of exclusive when conditions is a future issue.

The number of instances created during an execution has a negative impact on performance because of the garbage collection. Obviously, the number of instances created by the generated code for the proposed translation techniques is greater than that for Prolog Cafe. In the case of tarai w/o cuts, the generated code requires more memory than others to prevent the garbage collection. In the example in Fig. 7, it is clear that the number of instances can be reduced by merging class Method_1_cui with class Method_1. Improving the performance by the reduction of instance creation is an important future issue.

| Program | DSP on Prolog | B-Prolog | Prolog Cafe | Translator |
|---------|---------------|----------|-------------|------------|
| plan    | 685.0         | 295.1    | 2519.4      | 90.5       |
| nqueens | 594.9         | 296.2    | 3279.2      | 120.3      |
| ack     | 1568.2        | 52.9     | 990.7       | 265.0      |
| tarai   | 1302.7        | 49.4     | 1680.1      | 740.8      |
| ack w/o cuts | 2035.1 | 104.7    | 3421.3      | 403.9      |
| tarai w/o cuts | 1307.8 | 49.2     | 6282.2      | 489.5      |

### 6 Conclusions

This paper described the techniques for translating the nondeterministic functional language DSP based on attribute grammars into Java. The DSP is designed for knowledge representation of
large scale and complicated expert knowledge in application domains. It is capable of representing trial and error without any side-effects or loop constructs using nondeterministic features. Current development and runtime environments are built on top of Inside Prolog, while the runtime environment can be embedded in a Java-based application server. However, issues regarding language interoperability and adaptability to new computer environments are envisaged when applied to practical application development. The language translation is intended to improve the interoperability and adaptability of DSP.

The proposed translation techniques are based on binarization and the techniques proposed for the translation of Prolog. The performance, however, is improved by introducing the continuation unit and simplifying the management of variables and registers using the semantic differences of variables and explicit determinism of some statements. An experimental translator written in DSP itself generates Java code from DSP descriptions, and the experimental results indicate that the generated code is over 25 times faster than that of Prolog Cafe for nondeterministic programs, and over 2 times faster for deterministic programs. The generated code is also over 2 times faster than B-Prolog for nondeterministic programs. However, the generated code is about 3 to 15 times slower than B-Prolog for deterministic programs. Improving the performance of deterministic programs is an important future issue.

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