Transformation Techniques for Branching-time
Logic Programs

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Abstract

In this paper, we consider program transformation techniques for branching-time
logic programs. We define a set of unfold/fold transformation rules and present suffi-
cient conditions to ensure their correctness. Then, using the proposed transformation
rules we develop an algorithm which transforms a wide class of Cactus programs into a
continuation passing style form.

Keywords: Program Transformation, Logic Programming, Temporal Logic Pro-
gramming, Branching Time, Continuation Passing Style.

1 Introduction

A lot of research effort has been devoted recently in developing logic programming languages
which incorporate, in one or another way, the notion of time [Org91, OM94, Bau93, RGP97b,
GRP97]. Most of the temporal logic programming languages presented in the literature are
based on linear flow of time [OM94, Hry93, OWD93, Bau93, Brz91, Brz93, GRP96]. However,
in [RGP97b, RGP97a, GRP97] a temporal logic programming language called Cactus, which
is based on a tree-like notion of time, was introduced. In Cactus, there is an initial moment
in time and every moment may have more than one next moments.

Temporal logic programming languages are recognized as natural and expressive form-
alisms for describing dynamic systems. In particular, branching-time logic programming
is useful for describing non-deterministic computations as well as computations that involve
the manipulation of trees.

On the other hand, program transformation techniques have been widely used in pro-
gram synthesis [ST84, PP94b], program optimization [PP95, Ger94, AGK96], program spe-
cialization [BCD90] and partial evaluation (partial deduction) [LS91, PP93]. Program transfor-
mation systems, based on unfold/fold rules, have been developed for functional pro-
grams [BD77], as well as for definite and normal (programs permitting negative subgoals)
logic programs [TS84, TS86, KK90, BC93, PP94a, GK94, Sek91, Sek93]. For good surveys
on program transformation of definite and normal logic programs one may refer in [PP97,
PP94a].

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In this paper we define a program transformation system for branching-time (Cactus) logic programs and present sufficient conditions for its correctness. The main rules of the system namely unfolding and folding are extensions of the corresponding rules [TS86, Ger94] for definite clause programs. A transformation rule, called temporal shift which takes into account the properties of time, is also presented.

As an application of the proposed transformation system, we develop an algorithm which compiles a wide class of branching time logic programs into a continuation passing style form.

The rest of the paper is organized as follows: in section 2, we briefly present the branching-time logic programming language Cactus. In section 3, we introduce the transformation rules, and in section 4 we propose sufficient conditions for their correctness. In section 5, based on the transformation system we develop a continuation passing style transformation algorithm for Cactus programs. Finally, section 6 concludes the paper.

2 The Cactus branching-time logic programming language

The syntax of Cactus programs extends the syntax of Definite Clause programs [Llo87]. A Cactus program is a finite set of temporal clauses. A temporal clause is a formula of the form:

\[ H \leftarrow B_1, \ldots, B_m \]

where \( m \geq 0 \) and \( H, B_1, \ldots, B_m \) are temporal atoms. A temporal atom is a classical atom preceded by a (possibly empty) sequence of temporal operators. The sequence of operators of a temporal atom is called the temporal reference of that atom. If \( m = 0 \) then the clause is said to be a unit temporal clause.

A goal clause in Cactus is a formula of the form \( \leftarrow A_1, \ldots, A_n \) where \( A_i, i = 1, \ldots, n \) are temporal atoms.

Cactus supports two temporal operators: the temporal operator \( \text{first} \) which refers to the beginning of time (or alternatively to the root of the time-tree), and the temporal operator \( \text{next}_i \) which refers to the \( i \)-th child of the current moment (or alternatively, the \( i \)-th branch of the current node in the tree). Notice that we actually have a family \( \{ \text{next}_i \mid i \in N \} \) of next operators, each one of them representing a different next moment that immediately follows the present one.

Example 2.1. Consider the following Cactus program

\[
\begin{align*}
p(0). \\
\text{next}_0 \ p(s(X)) & \leftarrow p(X). \\
\text{next}_1 \ p(s(X)) & \leftarrow \text{next}_0 \ p(X).
\end{align*}
\]

which defines the non-deterministic predicate ‘\( p \)’. The sets of values of the argument of ‘\( p \)’ for which the predicate is true at each moment in the time tree are shown in figure 1.

For example the query

\[
\leftarrow \text{first} \ \text{next}_0 \ \text{next}_1 \ p(X).
\]

will return the following answers (values of the variable ‘\( X \)’):

\[
\begin{align*}
X &= 0 \\
X &= s(0) \\
X &= s(s(0)) \\
X &= s(s(s(0)))
\end{align*}
\]

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A temporal reference $T$ is said to be canonical if the leftmost operator of $T$ is first.

The semantics of Cactus programs are defined in [RGP97b, GRP97]. It is important to note here that a Cactus program $P$ has a least Herbrand model $M(P)$ which comprises all canonical temporal atoms which are logical consequences of $P$.

In the following sections we will also use the notion of temporal unifiers. Temporal unifiers have been introduced in [GRP97], and extend the notion of unifier in classical logic. Temporal unification requires that temporal references are in normal form. We say that a temporal reference $T$ is in normal form, if either the operator first does not appear in $T$ or there is only one occurrence of first in $T$, which is the leftmost operator in $T$. Every temporal reference $T$ can be transformed into normal form $\text{normal}(T)$ by eliminating all operators appearing before the rightmost occurrence of first. The axioms of branching time logic of Cactus [RGP97b] ensure that for every formula $A$ we have: $T A \leftrightarrow \text{normal}(T) A$. Intuitively, normalization consists in discarding redundant temporal operators. For example, the normal form of the temporal atom $\text{next}_2 \text{first} \text{next}_0 \text{first} \text{next}_1 A$ is $\text{first} \text{next}_1 A$.

Finally, by $T_1 T_2$ we denote the temporal reference obtained by putting the temporal reference $T_1$ before the temporal reference $T_2$. We say that $T_1 T_2$ is the composition of the temporal references $T_1$ and $T_2$.

**Definition 2.1 (Temporal Unifier).** Let $A_1$ and $A_2$ be two temporal atoms, such that $A_1 = R_1 A'_1$ and $A_2 = R_2 A'_2$ where $A'_1$ and $A'_2$ are classical atoms and $R_1$, $R_2$ are (possibly empty) temporal references in normal form. Then $\theta^t = (T, \theta, S)$, where $T$ and $S$ are temporal references in normal form and $\theta$ is a substitution, is said to be a temporal unifier of $A_1$ and $A_2$ iff $T \cdot R_1 A'_1 \theta = S \cdot R_2 A'_2 \theta$ and both $T \cdot R_1$ and $S \cdot R_2$ are also in normal form. Two temporal atoms $A_1$ and $A_2$ are said to be temporally unifiable iff they have a temporal unifier.

**Definition 2.2 (Most general Temporal Unifier).** A temporal unifier $\theta^t = (T, \theta, S)$ of two temporal atoms $A_1$ and $A_2$, is said to be a most general temporal unifier of $A_1$ and $A_2$ (we write $\theta^t = \text{mgu}^t(A_1, A_2)$) iff for every unifier $\sigma^t = (T', \sigma, S')$ of $A_1$ and $A_2$, there is a temporal substitution $\xi^t = (T'', \xi, S'')$ such that $\sigma = \theta \xi$, $T' = T'' T$, and $S' = S'' S$.

---

1. We denote an empty temporal reference by $\varepsilon$. 

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It is easy to see that \((T, \theta, S) = mgu^i(A_1, A_2)\) iff \((S, \theta, T) = mgu^i(A_2, A_1)\). Moreover, if two temporal atoms are temporally unifiable, they have a most general temporal unifier.

3 The transformation Rules

In general, the transformation process starts from a program \(P_0\), called the initial program, and produces a sequence of programs \(P_0, P_1, \ldots, P_l, \ldots\), called a transformation sequence, such that each program in the sequence is obtained by applying a transformation rule to the preceding one.

**Definition 3.1 (Initial Program).** An initial program \(P_0\), is a Cactus program satisfying the following conditions:

1. Let \(\mathcal{P}\) be the set of predicates of \(P_0\). Then \(\mathcal{P}\) is divided into two disjoint sets \(\mathcal{P}^p\) and \(\mathcal{P}^t\). The predicates in \(\mathcal{P}^p\) are called primitive predicates while the predicates in \(\mathcal{P}^t\) are called transformable predicates.

2. Transformable predicates do not appear in the bodies of the clauses defining primitive predicates.

Definition 3.1 implies that an initial program \(P_0\) is divided into two disjoint sets of clauses, \(P_0^p\) and \(P_0^t\). \(P_0^p\) comprises the definitions of the primitive predicates while \(P_0^t\) comprises the definitions of the transformable predicates. Will see in the following that the transformation rules are applied only to clauses defining transformable predicates. As a consequence, each program \(P_l\), with \(l \geq 0\), in the transformation sequence consists also of two distinct sets of clauses \(P_l^p\) and \(P_l^t\). Since no transformation rule is applied to the clauses defining primitive predicates, \(P_0^p\) is identical to \(P_0^p\).

Although in practice, new predicate definitions (Eureka definitions) are often introduced during the transformation process, these definitions are considered as part of the initial program.

**Example 3.1.** Let \(P_0 = \{1, 2, 3, 4, 5, 6\}\) be the following Cactus program:

\[
\begin{align*}
(1) & \quad \text{even} \cdot p(x) \leftarrow p(x), \text{even}(x). \\
(2) & \quad p(0). \\
(3) & \quad \text{next}_0 \cdot p(s(x)) \leftarrow p(x). \\
(4) & \quad \text{next}_1 \cdot p(s(x)) \leftarrow \text{next}_0 \cdot p(x). \\
(5) & \quad \text{even}(0). \\
(6) & \quad \text{even}(s(s(x))) \leftarrow \text{even}(x).
\end{align*}
\]

\(P_0\) can be seen as an initial program with \(P_0^p = \{1, 2, 3, 4\}\) and \(P_0^t = \{5, 6\}\). Notice that the clauses \(\{2, 3, 4\}\) define the predicate ‘\(p\)’ as in example 2.1. Clauses \(\{5, 6\}\) define the predicate ‘\(\text{even}\)’ which is true for the even numbers. Finally, ‘\(\text{even} \cdot p\)’ is true at a moment in time, only for the even values of the argument for which ‘\(p\)’ is true at the same moment.

**Definition 3.2 (Unfolding).** Let \(C\) be a clause in \(P_l^t\) of the form

\[
C : \quad A \leftarrow M, B, N
\]
where $A$, $B$ are temporal atoms and $M, N$ are (possibly empty) conjunctions of temporal atoms. Let $D_1, \ldots, D_m$ be all clauses in a program $P_k$, with $0 \leq k \leq l$, whose heads are temporally unifiable with $B$ by the most general temporal unifiers $\theta_1^i, \ldots, \theta_m^i$ respectively. If (at least) one of the following conditions holds:

1. $A, M,$ and $N$ are canonical.
2. $B$ is not canonical.
3. For each clause $D_j$, with $1 \leq j \leq m$, either all body atoms of $D_j$ are canonical, or the head of $D_j$ is not canonical.

Then, the result of unfolding $C$ at $B$ consists in replacing $C$ in $P_j$ by the set of clauses $\{C'_1, \ldots, C'_m\}$ constructed as follows: for each $j$, with $1 \leq j \leq m$, if $D_j : B_j \leftarrow G$

where $G$ is a (possibly empty) conjunction of temporal atoms, then

$C'_j : (T_j A \leftarrow T_j M, S_j G, T_j N)\theta_j$

where $\theta_j = (T_j, \theta_j, S_j) = mgu(B, B_j)$. $C$ is called the unfolded clause and $C_1, \ldots, C_m$ are called the unfolding clauses.

**Example 3.2 (Continued from example 3.1).** Unfolding clause (1) at ‘p(X)’ using clauses \{2, 3, 4\} we get:

1. even.p(0) ← even(0).
2. next_0 even.p(s(X)) ← p(X), next_0 even(s(X)).
3. next_1 even.p(s(X)) ← next_0 p(X), next_1 even(s(X)).

Unfolding clause (7) using (5) we get:

4. even.p(0).

Unfolding clause (8) at ‘next_0 even(s(X))’ using (6), and clause (9) at ‘next_1 even(s(X))’ using (6) we get:

5. next_0 even.p(s(s(X))) ← p(s(X)), next_0 even(s(X)).
6. next_1 even.p(s(s(X))) ← next_0 p(s(X)), next_1 even(s(X)).

Unfolding clause (11) at ‘p(s(X))’ using \{3, 4\} we get:

7. next_0 next_0 even.p(s(s(X))) ← p(X), next_0 next_0 even(X).
8. next_1 next_0 even.p(s(s(X))) ← next_0 p(X), next_1 next_0 even(X).

Unfolding clause (12) at ‘next_0 p(s(X))’ using (3) we get:

9. next_1 even.p(s(s(X))) ← p(X), next_1 even(X).

The violation of the conditions 1-3 in definition 3.2, destroys the equivalence of programs, as shown in the following example:

**Example 3.3.** Let $P$ be the following program:

1. first p ← first q, r.
2. first q ← s.
3. first r.
4. first next_0 s.
Unfolding (1) at first q using clause (2), we get the program $P_1 = \{2, 3, 4, 5\}$, where:

\[(5) \quad \text{first } p \leftarrow s, r.\]

It is easy to see that $M(P) = \{ \text{first } r, \text{first next}_0 s, \text{first } q, \text{first } p \}$, while $M(P_1) = \{ \text{first } r, \text{first next}_0 s, \text{first } q \}$. Hence $M(P) \neq M(P_1)$.

**Definition 3.3 (Rigid predicate).** A predicate $p$ is said to be rigid if it does not depends on time i.e. every ground instance of $p$ is either true in all moments in time or false in all moments in time. A predicate $p$ is said to be *syntactically rigid* (or s-rigid for short) if all predicates on which $p$ depends on, are defined by operator-free clauses\(^2\).

**Definition 3.4 (Temporal Shift).** Let $C$ be a clause in $P^t_i$ of the form

\[ C : \quad A \leftarrow M, B, N \]

where $A, B$ are temporal atoms, and $M, N$ are (possibly empty) conjunctions of temporal atoms. Let $B$ be of the form $Tref B'$, where the temporal reference $Tref$ may be empty. Let $C'$ be a clause obtained by replacing $Tref B'$ in the body of $C$ by $Tref'B'$. We say that $C'$ is obtained by applying the *temporal shift* transformation rule to $C$, if

1. The predicate of $B'$ is rigid, and
2. Either
   a. $B'$ is primitive, or
   b. $B'$ is also s-rigid in $P_0$.

**Example 3.4 (Continued from example 3.2).** Since the predicate ‘even’ is s-rigid, we can eliminate the temporal reference ‘next\(_0\) next\(_0\)’ of the atom ‘next\(_0\) next\(_0\) even(X)’ by applying the temporal shift transformation rule in the body of (13). We obtain

\[(16) \quad \text{next}_0 \text{ next}_0 \text{ even}.p(\text{s}(\text{s}(X))) \leftarrow p(X), \text{even}(X).\]

In the same way, we can replace the temporal reference ‘next\(_1\) next\(_0\)’ of the temporal atom ‘next\(_1\) next\(_0\) even(X)’ in the body of (14), by the temporal reference ‘next\(_0\)’. We get

\[(17) \quad \text{next}_1 \text{ next}_0 \text{ even}.p(\text{s}(\text{s}(X))) \leftarrow \text{next}_0 p(X), \text{next}_0 \text{ even}(X).\]

Finally, by applying the temporal shift rule to the clause (15) we get

\[(18) \quad \text{next}_1 \text{ even}.p(\text{s}(\text{s}(X))) \leftarrow p(X), \text{even}(X).\]

**Definition 3.5 (Folding).** Let $C$ be a clause in $P^t_i$ of the form

\[ C : \quad A \leftarrow M, F, N \]

and $D$ be a clause in $P^t_0$ of the form:

\[ D : \quad B \leftarrow G \]

where $A$ and $B$ are temporal atoms and $M, F, N, G$ are (possibly empty) conjunctions of atoms. Then folding $C$ using $D$ consists in replacing $C$ in $P_i$ by the clause $C'$, where:

\[ C' : \quad A \leftarrow M, T B \theta, N \]

iff the following conditions hold:

\(^2\)I.e. clauses with no temporal operator applied to their atoms.
1. There exists a temporal reference $T$ and a substitution $\theta$ such that:

(a) $T G\theta = F$, and
(b) $\theta$ maps the variables which occur in the body of $D$ but not in the head of $D$, into distinct variables which do not occur in $C'$.

2. (At least) one of the following holds:

(a) $A$, $M$ and $N$ are canonical.
(b) $G$ is canonical.
(c) $B$ is not canonical.

3. $D$ is the only clause in $P_0$ whose head is temporally unifiable with $T B\theta$.

$C$ is called a folded clause, $D$ is called the folding clause and $T B_0\theta$ the atom introduced by folding.

**Example 3.5 (Continued from example 3.4).** Folding (16) using (1) we get

\begin{equation}
\text{next}_0 \text{ next}_0 \text{ even.p(s(s(X)))} \leftarrow \text{even.p(X)}.
\end{equation}

Folding (17) using (1) we get

\begin{equation}
\text{next}_1 \text{ next}_0 \text{ even.p(s(s(X)))} \leftarrow \text{next}_0 \text{ even.p(X)}.
\end{equation}

Finally, folding (18) using (1) we obtain

\begin{equation}
\text{next}_1 \text{ even.p(s(s(X)))} \leftarrow \text{even.p(X)}.
\end{equation}

Violation of condition 2 in definition 3.5, destroys the equivalence of programs:

**Example 3.6.** Let $P$ be the following program:

\begin{enumerate}
\item $p \leftarrow q,r.$
\item first $s \leftarrow r.$
\item first $q$.
\item first next$_0$ $r$.
\end{enumerate}

Then $M(P) = \{\text{first } q, \text{first next}_0 r, \text{first } s\}$. Let us fold (violating condition 2) clause (1) using clause (2). We get the program $P_1 = \{2,3,4,5\}$, where:

\begin{enumerate}
\item $p \leftarrow q, \text{first } s$.
\end{enumerate}

Then $M(P_1) = \{\text{first } q, \text{first next}_0 r, \text{first } s, \text{first } p\}$. Thus $M(P_1) \neq M(P)$.

**Definition 3.6 (Transformation Sequence).** A sequence of programs $P_0, P_1, \ldots, P_i$ is called a transformation sequence starting from the initial program $P_0$ iff each program $P_i$, with $i > 0$, is obtained by applying one of the rules: unfolding, temporal shift and folding, to $P_{i-1}$.

**Example 3.7 (Continued from example 3.5).** The final program in the transformation sequence is $P_{\text{final}} = \{2,3,4,5,6,10,19,20,21\}$, where:
\begin{align*}
(10) \quad & \text{even.p}(0). \\
(19) \quad & \text{next}_0 \text{ next}_0 \text{ even.p}(s(s(X))) \leftarrow \text{even.p}(X). \\
(20) \quad & \text{next}_1 \text{ next}_0 \text{ even.p}(s(s(X))) \leftarrow \text{next}_0 \text{ even.p}(X). \\
(21) \quad & \text{next}_1 \text{ even.p}(s(s(X))) \leftarrow \text{even.p}(X). \\
(2) \quad & \text{p}(0). \\
(3) \quad & \text{next}_0 \text{ p}(s(X)) \leftarrow \text{p}(X). \\
(4) \quad & \text{next}_1 \text{ p}(s(X)) \leftarrow \text{next}_0 \text{ p}(X). \\
(5) \quad & \text{even}(0). \\
(6) \quad & \text{even}(s(s(X))) \leftarrow \text{even}(X). 
\end{align*}

It is easy to see that the set of clauses \{10, 19, 20, 21\} in \(P_{final}\), form a recursive definition for the predicate \text{even.p}.

## 4 Correctness of the transformations

In this section, we present some correctness results concerning the transformation rules of section 3. For this, we define the notions of partial and total correctness.

**Definition 4.1 (Partially Correct Transformation).** Let \(P_0, \ldots, P_i\) be a transformation sequence. We say that the transformation is partially correct iff \(M(P_i) \subseteq M(P_0)\).

**Definition 4.2 (Totally Correct Transformation).** Let \(P_0, \ldots, P_i\) be a transformation sequence. We say that the transformation is totally correct iff \(M(P_i) = M(P_0)\).

The transformation rules presented in the previous section are partially correct:

**Lemma 4.1 (Partial Correctness).** Let \(P_0, P_1, \ldots, P_s\) be a transformation sequence. If \(M(P_0) = M(P_1) = \ldots = M(P_i)\), with \(1 \leq l \leq s - 1\), then \(M(P_i) \supseteq M(P_{i+1})\).

Lemma 4.1 shows that a transformation step is partially correct if all the preceding transformation steps are totally correct.

The transformation rules presented above are not totally correct unless we impose some additional restrictions on the application of the transformation rules. In order to introduce some sufficient conditions we need some more definitions.

**Definition 4.3 (Level of predicate/atom/clause).** Let \(P_0\) be an initial program in a transformation sequence. To each predicate \(p\) in \(P_0\), we assign a non-negative integer \(I_p\) called the level of \(p\). The level of an atom is the level of its predicate. The level of a clause is the level of its head.

**Assumption 4.1 (On the assignment of levels in the initial program).**

1. All primitive predicates are assigned the level 0.

2. Each transformable predicate is assigned a level \(i \geq 1\) such that for each clause \(C\) in \(P_0\), the level of the head atom of \(C\) is greater than or equal to the level of each atom in the body of \(C\).
Definition 4.4 (Unfolding state). Let $P_1$ with $l \geq 0$, be a program in a transformation sequence, starting from $P_0$. To each clause $C$ in $P^l_1$ we assign a pair $[d_C, b_C]$ of natural numbers called the unfolding state of $C$, where $d_C$ is called the descent level of $C$ while $b_C$ is called the boundary unfolding number (or $BU$-number for short) of $C$. The unfolding state of a clause is defined as follows:

1. If $C$ is a clause in $P^l_1$ and $l_C$ is the level of $C$, then $[d_C, b_C] = [l_C, 1]$.
2. Let $C$ be the result of unfolding a clause $C'$ at a non primitive atom $A$, using a clause $D$. Let $[d_{C'}, b_{C'}]$ and $[d_D, b_D]$ be the unfolding states of $C'$ and $D$ respectively. Then the unfolding state of $C$ is $[d_C, b_C]$, where $d_C = \min\{d_{C'}, d_D\}$ and

   $$b_C = \begin{cases} 
   b_{C'} & \text{if } d_{C'} < d_D \\
   b_D & \text{if } d_{C'} > d_D \\
   b_{C'} + b_D & \text{if } d_{C'} = d_D
   \end{cases}$$

3. Let $C$ be the result of applying the temporal shift rule to a clause $C'$ or the result of unfolding $C'$ at a primitive atom. Let $U$ be the unfolding state of $C'$. Then the unfolding state of $C$ is also $U$.

4. Let $C$ be the result of folding a clause $C'$ in $P^l_{l-1}$ using a clause $D$ in $P^l_1$. Let $[d_{C'}, b_{C'}]$ be the unfolding state of $C$ and $l_D$ be the level of $D$. Then the unfolding state of $C$ is $[d_C, b_C]$, where $d_C = d_{C'}$ and

   $$b_C = \begin{cases} 
   b_{C'} & \text{if } d_C < l_D \\
   b_{C'} - 1 & \text{if } d_C = l_D
   \end{cases}$$

Using the above definition, we introduce the following sufficient condition which ensure the correctness of the folding transformation rule.

Assumption 4.2 (On the application of Folding). Let $P_1$, with $l \geq 0$, be a program in a transformation sequence starting from $P_0$ and $P_{l+1}$ a program obtained by applying the folding rule to $P_l$. Let $C$ and $D$ be the folded and the folding clauses respectively. Let $[d_C, b_C]$ be the unfolding state of $C$, and let $l_D$ be the level of $D$. The folding of $C$ using $D$ is said to be valid iff $l_D > d_C$ or $(l_D = d_C$ and $b_C > 1)$.

Theorem 4.1 (Total Correctness). Let $P_0$ be an initial program in a transformation sequence, and $P_l$, with $l > 0$, a program obtained from $P_0$ by applying a sequence of transformation steps. Then, $M(P_l) = M(P_0)$.

5 A continuation passing style transformation for Cactus programs

The transformation system presented in section 3 can be used to define a continuation passing style (CPS) transformation algorithm for Cactus programs. This algorithm is an extension of the algorithm presented in [ST89] for definite clause programs. As in [ST89] each argument of a program predicate is classified either as input or as output argument. For each program predicate\footnote{X and Y are mutually disjoint tuples of variables such that X corresponds to the arguments specified as input and Y corresponds to the arguments specified as output.} $p(X, Y)$ we introduce a corresponding continuation passing style
predicate \( p.C(\bar{x}, C) \) called a \textit{closure predicate} pairing with an auxiliary predicate \( cont.p(\bar{y}, C) \) called a \textit{continuation predicate}. Using these predicates we define a clause called an \textit{existential continuation form} for \( p(\bar{x}, \bar{y}) \) as follows:

\[
p.C(\bar{x}, C) \leftarrow p(\bar{x}, \bar{y}), cont.p(\bar{y}, C)
\]

The variable \( C \) is called the \textit{continuation variable}. Using these notions we can now define the CPS algorithm. The input of the algorithm is a Cactus program \( P \) while its output is a program \( P_{CPS} \) in continuation passing style form.

**CPS transformation algorithm:**

**Step 1:** Let \( Def_x \) be the set of existential continuation forms for the predicates in \( P \).

**Step 2:** For every clause \((Cl)\) in \( Def_x \):

\[
(Cl) \quad p.C(\bar{x}, C) \leftarrow p(\bar{x}, \bar{y}), cont.p(\bar{y}, C)
\]

apply the following process. Unfold \((Cl)\) at \( p(\bar{x}, \bar{y}) \) obtaining a set of clauses of the form:

\[
(Cl_i) \quad p.C(S_i, C) \leftarrow E_i, cont.p(T_i, C)
\]

with \( 1 \leq i \leq n \), where \( n \) is the number of program clauses whose head is unifiable with \( p(\bar{x}, \bar{y}) \), and \( S_i, T_i \) are instances of \( \bar{x} \) and \( \bar{y} \) respectively.

For each \( i : 1 \leq i \leq n \), do

**Case 1:** If \( E_i \) is empty add \((Cl_i)\) to \( P_{CPS} \).

**Case 2:** If \( E_i \) is non empty, write \((Cl_i)\) as

\[
(Cl_i) \quad p.C(S_i, C) \leftarrow R q(S, T), F_i, cont.p(T_i, C)
\]

where \( R \) is a temporal reference and \( q(S, T) \) is a classical atom. Then introduce and add to \( Def_x \) a new clause, called a \textit{continuation definition}:

\[
(D_j) \quad R cont.q(T, f(\bar{w}, C)) \leftarrow F_i, cont.p(T_i, C)
\]

where \( \bar{w} \) is a tuple of variables such that \( \bar{w} = FreeVars(S_i, S) \cap FreeVars(T, F_i, T_i) \) and \( f \) is a fresh function symbol. Fold \((Cl_i)\) using by the definition \((D_j)\) to get

\[
(Cl'_i) \quad p.C(S_i, C) \leftarrow R q(S, T), R cont.q(T, f(\bar{w}, C))
\]

Fold further \((Cl'_i)\) using the existential continuation form for the predicate \( q \) to get:

\[
(Cl''_i) \quad p.C(S_i, C) \leftarrow R q.C(S, f(\bar{w}, C))
\]

Add \((Cl''_i)\) to \( P_{CPS} \).

**Step 3:** For every clause \((D_i)\) in \( Def_x \):

\[
(D_i) \quad R cont.q(T, f(\bar{w}, C)) \leftarrow F_i, cont.p(T_i, C)
\]

apply the following process.

**Case 1:** If \( F_i \) is empty, add \((D_i)\) to \( P_{CPS} \).

**Case 2:** If \( F_i \) is non empty, transform \((D_i)\) following exactly the Case 2 in step 2.

**Step 4:** Supply \( P_{CPS} \) with a set of unit clauses, called \textit{terminators}, constructed as follows:

For each program predicate \( p(\bar{x}, \bar{y}) \) in \( P \), add a unit clause of the form \( cont.p(\bar{y}, f_0(\bar{y})) \).

**Example 5.1.** Let \( P_0 = \{1, 2, 3, 4, 5, 6\} \) be the following Cactus program:
\begin{enumerate}
\item \texttt{first num(0)}.
\item \texttt{next\_0 num(s(X)) \leftarrow num(X)}.
\item \texttt{next\_1 num(s(s(X))) \leftarrow num(X)}.
\item \texttt{next\_2 num(X) \leftarrow next\_0 num(X0), next\_1 num(X1), sum(X0,X1,X)}.
\item \texttt{sum(0,Y,Y)}.
\item \texttt{sum(s(X),Y,s(Z)) \leftarrow sum(X,Y,Z)}.
\end{enumerate}

Suppose that the patterns \texttt{sum(+)} and \texttt{sum(+,+,−)}, reflect the classification of the arguments of the program predicates as input (denoted by ‘+’) or output (denoted by ‘−’).

By applying the step 1 of the CPS algorithm we get the set \(Def_c = \{D1, D2\}\), where:

\begin{enumerate}
\item \texttt{numC(X,C) \leftarrow num(X), cont\_num(C)}.
\item \texttt{sumC(x,Y,C) \leftarrow sum(X,Y,Z), cont\_sum(Z,C)}.
\end{enumerate}

Now we proceed in step 2 and unfold \(D1\) at \texttt{num(X)}. We get

\begin{enumerate}
\item \texttt{first numC(0,C) \leftarrow first cont\_num(C)}.
\item \texttt{next\_0 numC(s(X),C) \leftarrow num(X), next\_0 cont\_num(C)}.
\item \texttt{next\_1 numC(s(s(X)),C) \leftarrow num(X), next\_1 cont\_num(C)}.
\item \texttt{next\_2 numC(X,C) \leftarrow next\_0 num(X0), next\_1 num(X1), sum(X0,X1,X), next\_2 cont\_num(C)}.
\end{enumerate}

We add (7) to \(P_{CPS}\). For clause (8) we introduce:

\begin{enumerate}
\item \texttt{cont\_num(f1(C)) \leftarrow next\_0 cont\_num(C)}.
\end{enumerate}

Folding (8) using (D3) we get

\begin{enumerate}
\item \texttt{next\_0 numC(s(X),C) \leftarrow num(X), cont\_num(f1(C))}.
\end{enumerate}

Folding (11) using (D1) we get clause (12) and add it to \(P_{CPS}\):

\begin{enumerate}
\item \texttt{next\_0 numC(s(X),C) \leftarrow numC(X,f1(C))}.
\end{enumerate}

For clause (9) we introduce:

\begin{enumerate}
\item \texttt{cont\_num(f2(C)) \leftarrow next\_1 cont\_num(C)}.
\end{enumerate}

Folding (9) using (D4) we get:

\begin{enumerate}
\item \texttt{next\_1 numC(s(s(X)),C) \leftarrow num(X), cont\_num(f2(C))}.
\end{enumerate}

Folding (13) using (D1) we get clause (14) which is added to \(P_{CPS}\):

\begin{enumerate}
\item \texttt{next\_1 numC(s(s(X)),C) \leftarrow numC(X,f2(C))}.
\end{enumerate}

For (10) we introduce:

\begin{enumerate}
\item \texttt{next\_0 cont\_num(f3(X,X0,C)) \leftarrow next\_1 num(X1), sum(X0,X1,X), next\_2 cont\_num(C)}.
\end{enumerate}

Folding (10) using (D5) we get:

\begin{enumerate}
\item \texttt{next\_2 numC(X,C) \leftarrow next\_0 num(X0), next\_0 cont\_num(f3(X,X0,C))}.
\end{enumerate}

Folding (15) using (D1) we get clause (16) which is added to \(P_{CPS}\):

\begin{enumerate}
\item \texttt{next\_2 numC(X,C) \leftarrow next\_0 numC(X0,f3(X,X0,C))}.
\end{enumerate}

Now we unfold \(D2\) at ‘\texttt{sum(X,Y,Z)}’. We get
(17) \( \text{sumC}(0, Y, C) \leftarrow \text{cont\_sum}(Y, C). \)

(18) \( \text{sumC}(s(X), Y, C) \leftarrow \text{sum}(X, Y, Z), \text{cont\_sum}(s(Z), C). \)

(17) is added to \( P_{CPS} \). For (18) we introduce clause (D6):

(D6) \( \text{cont\_sum}(Z, f_4(C)) \leftarrow \text{cont\_sum}(s(Z), C). \)

Folding (18) using (D6) we get

(19) \( \text{sumC}(s(X), Y, C) \leftarrow \text{sum}(X, Y, Z), \text{cont\_sum}(Z, f_4(C)). \)

Folding (19) using (D2) we get (20) which is added to \( P_{CPS} \):

(20) \( \text{sumC}(s(X), Y, C) \leftarrow \text{sumC}(X, Y, f_4(C)). \)

Going into step 3 we add (D3), (D4) and (D6) to \( P_{CPS} \). For (D5) we introduce:

(D7) \( \text{next}_1 \text{ cont\_num}(f_5(X, X_0, X_1, C)) \leftarrow \text{sum}(X_0, X_1, X), \text{next}_2 \text{ cont\_num}(C). \)

Folding (D5) using (D7) we get:

(21) \( \text{next}_0 \text{ cont\_num}(f_5(X, X_0, C)) \leftarrow \text{next}_1 \text{ num}(X_1), \text{next}_1 \text{ cont\_num}(f_5(X, X_0, X_1, C)). \)

Folding (21) using (D1) we get clause (22) which is added to \( P_{CPS} \):

(22) \( \text{next}_0 \text{ cont\_num}(f_5(X, X_0, C)) \leftarrow \text{next}_1 \text{ numC}(X_1, f_5(X, X_0, X_1, C)). \)

For (D7) we introduce (D8) which is also added to \( P_{CPS} \):

(D8) \( \text{cont\_sum}(X, f_6(X, C)) \leftarrow \text{next}_2 \text{ cont\_num}(C). \)

Folding (D7) using (D8) we get

(23) \( \text{next}_1 \text{ cont\_num}(f_6(X, X_0, X_1, C)) \leftarrow \text{sum}(X_0, X_1, X), \text{cont\_sum}(X, f_6(X, C)). \)

Folding (23) using (D2) we get (24) which is added to \( P_{CPS} \):

(24) \( \text{next}_1 \text{ cont\_num}(f_6(X, X_0, X_1, C)) \leftarrow \text{sumC}(X_0, X_1, f_6(X, C)). \)

Now applying step 4, we add the terminators:

(25) \( \text{cont\_num}(f_0^{\text{num}}). \)

(26) \( \text{cont\_sum}(Y, f_0^{\text{sum}}(Y)). \)

Collecting together all clauses in \( P_{CPS} \) we obtain:

(7) \( \text{first} \text{ numC}(0, C) \leftarrow \text{first} \text{ cont\_num}(C). \)

(12) \( \text{next}_0 \text{ numC}(s(X), C) \leftarrow \text{numC}(X, f_1(C)). \)

(14) \( \text{next}_1 \text{ numC}(s(X), C) \leftarrow \text{numC}(X, f_2(C)). \)

(16) \( \text{next}_2 \text{ numC}(X, C) \leftarrow \text{next}_0 \text{ numC}(X_0, f_3(X, X_0, C)). \)

(25) \( \text{cont\_num}(f_0^{\text{num}}). \)

(D3) \( \text{cont\_num}(f_1(C)) \leftarrow \text{next}_0 \text{ cont\_num}(C). \)

(D4) \( \text{cont\_num}(f_2(C)) \leftarrow \text{next}_1 \text{ cont\_num}(C). \)

(22) \( \text{next}_0 \text{ cont\_num}(f_3(X, X_0, C)) \leftarrow \text{next}_1 \text{ numC}(X_1, f_5(X, X_0, X_1, C)). \)

(24) \( \text{next}_1 \text{ cont\_num}(f_5(X, X_0, X_1, C)) \leftarrow \text{sumC}(X_0, X_1, f_6(X, C)). \)

(17) \( \text{sumC}(0, Y, C) \leftarrow \text{cont\_sum}(Y, C). \)

(20) \( \text{sumC}(s(X), Y, C) \leftarrow \text{sumC}(X, Y, f_4(C)). \)
Although the CPS algorithm for definite clause programs presented in [ST89] applies to every definite clause program, our algorithm does not apply to every Cactus program. This is due to the restrictions imposed by the definitions of the unfolding and folding transformation rules. Nevertheless, we can show that the algorithm applies to a wide class of Cactus programs. In order to define this class, we will define the notion of 'naughty clauses'.

**Definition 5.1 (Naughty clause).** A clause \(C\) is said to be a naughty clause if there is a canonical atom in the body of \(C\) and there is at least one non canonical atom either in the head or in the body of \(C\).

It is easy to see that our algorithm applies to every Cactus program not containing naughty clauses as in this case the application of the unfolding and folding rules in the algorithm do not violate the restrictions imposed by the corresponding definitions.

**Theorem 5.1 (Correctness of the CPS algorithm).** Let \(P_0\) be a Cactus program not containing naughty clauses and \(P_{CPS}\) be the program obtained by applying the CPS algorithm to \(P_0\). Then, for every ground temporal atom \(\langle p(a), b \rangle\) in the Herbrand base of \(P_0\) where 'a' is a tuple corresponding to the arguments of 'p' specified as input and 'b' the tuple corresponding to the arguments of 'p' specified as output, \(P_0 \models p(a, b)\) iff \(P_{CPS} \models p(a, f_0(b))\).

6 Discussion

Program transformation techniques have been widely used in definite clause logic programming as well as in functional programming. This is why we believe that they will also be proved useful in temporal logic programming languages as well.

In this paper we define a program transformation system for branching-time (Cactus) logic programs and present sufficient conditions for their correctness.

As an application of the transformation system that we propose, we develop an algorithm which can be used to transform a wide class of branching time logic programs into equivalent programs in continuation passing style form. A program obtained by applying the CPS algorithm has a special form i.e. no clause in this program has more than one atoms in its body.

Both the transformation system and the CPS algorithm apply also to Chronolog and Chronolog(\(Z\)) programs [Wad88, OWD93]. Moreover, it is easy to adapt them to apply to multidimensional logic programming languages [OD94] as well.

As in transformation of definite clause programs, transformation strategies are needed to guide the application of the transformation rules. Nevertheless, it seems straightforward to extend the transformation strategies developed in the context of definite clause program transformation [PP93, PP93, PP94b] for the case of branching time logic programs.

It is important to note here that (zero-order) branching-time and multidimensional functional languages have been recognized [RW97, Yag84, Ron94] as appropriate target languages for transforming first-order functional programs. This transformation is very useful since zero-order branching time programs can be efficiently executed using tagged, demand-driven
evaluation [FW87]. We believe that the transformation system that we propose in this paper may be used as a tool in order to define a similar transformation from definite clause programs into multidimensional logic programs.

References


