An Analysis for Fast Construction of States in the Bottom-Up Tree Pattern Matching Scheme

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SUMMARY In this paper, we propose an efficient method of constructing states in bottom-up tree pattern matching with dynamic programming technique for optimal code generation. This method can be derived from precomputing the analysis which is needed for constructing states. The proposed scheme is more efficient than other scheme because we can avoid unfruitful tests in constructing states at compile time. Furthermore, the relevant analyses needed for this proposal are largely achieved at compile-compile time, which secures actual efficiency at compile time.

key words: compilers, code generator generator, tree grammar, dynamic programming

1. Introduction

Many code generators (CG) accept an intermediate representation (IR) in a tree structure and convert it to an equivalent target program. The tree structure is proper for representing semantic of source program efficiently and its manipulation is considered easy [15]. Since the development of bottom-up tree pattern matching by Hoffman and O’Donnell [5], the bottom-up tree pattern matching has been accepted as a practical technique for CG and a code generator generator (CGG) [1], [2], [4], [6], [7], [11], [14], [15]. The specification of the CGG which is actually the machine specification contains the tree grammar which consists of rules. Each rule has a cost associated with its semantic action.

The bottom-up tree pattern matching scheme is much faster than any other tree pattern matching scheme theoretically [5], [12]. The Bottom-Up Rewrite System (BIRS) theory is efficient because Dynamic Programming (DP) can be done at compile-compile time [11], [15]. However, BURS has the restriction that the costs used in the tree grammar must be constant. The bottom-up tree pattern matching scheme adapting DP at compile time allows the arbitrary cost values [6], which admit a larger class of tree grammars [11] but may cause inefficiency at compile time. This paper describes a program that reads a machine specification and writes a bottom-up tree pattern matching scheme that does DP at compile time.

We emphasize the efficiency of the bottom-up tree pattern matching scheme which allows the arbitrary cost values. The bottom-up tree pattern matching scheme with DP [6] traverses the IR tree twice. In the first traversal, the scheme computes a state at every node of the IR tree in a bottom-up direction. A state can be extracted along the sequence of the rules. In the second traversal, the scheme will find the least-cost cover in a top-down direction. Then a target code is produced by executing the semantic actions for the rules used for the least-cost cover. Previous scheme [6] computes a state using all rules in the given sequence. However, we can infer that only reduced number of rules can be used in computing states, which is our primary intention. To implement our intention, we firstly transform the sequence of rules into several sets called match set and the match set transition tables. A match set is a set of patterns which must be used for construction of a state. The state of a node can be computed using a match set which is determined from the match sets of its child nodes using the transition tables. In this paper, the transition tables are hard coded into code generator which uses bottom-up tree pattern matching scheme with dynamic programming.

In Sect. 2, definitions and background are introduced. In Sect. 3, we propose an efficient method of constructing states. In Sect. 4, we show experimental results for the scheme. A summary and the concluding remarks are given in Sect. 5.

2. Definitions and Background

We describe a representing scheme for bottom-up tree pattern matching with DP, upon which our study is based. Moreover, necessary definitions for presenting proposals in Sect. 3 will be described.

An alphabet (written as \( \Sigma \)) is a finite set of operators denoted as \( a, b, c, \ldots \). Each operator has a fixed arity (written as \( \text{arity}(a) \geq 0 \)). We write \( \Sigma_n \) for \( \{ a \mid \text{arity}(a) = n \} \). The tree language over \( \Sigma \) (written as \( T_\Sigma \)) is defined as follows:

- \( a \) is a tree in \( T_\Sigma \), if \( a \in \Sigma_0 \).
- \( a(t_1, \ldots, t_n) \) is a tree in \( T_\Sigma \), if \( a \in \Sigma_n \) and \( t_1, \ldots, t_n \)
are trees in $T_{Σ}$.

A subtree of a tree is identified through its position which is a sequence of relative integers from the root of the tree. Position of a node of a tree $t ∈ T_{Σ}$ is defined by a sequence of relative integers from the root to the node. If $t = a(t_1, \ldots, t_n)$, then $\text{Pos}(t) = \{ε\} \cup \{i \cdot p' \mid 1 ≤ i ≤ n, p' ∈ \text{Pos}(t_i)\}$. If $p ∈ \text{Pos}(t)$, then the subtree $t/p$ of $t$ is defined as follows:

- $t/p = t$, if $p = ε$ and $t/p = t_i/p'$, if $t = a(t_1, \ldots, t_n)$ and $p = i \cdot p'$.

The set of positions $\text{Pos}(t)$ of a tree $t$ is partially ordered by $≤$: For $p_1, p_2 ∈ \text{Pos}(t)$ such that $p_1 ≠ ε$ and $p_2 ≠ ε$, $p_1 ≤ p_2 \iff i < j$ or $i = j, p'_1 ≤ p'_2$ where $p_1 = i \cdot p'_1, p_2 = j \cdot p'_2$.

A set $V$ is a countably infinite set of variables denoted as $v_1, v_2, v_3, \ldots$. Each variable is a symbol of arity zero to be replaced by a tree $t ∈ T_{Σ∪V}$. The pattern is a tree in $T_{Σ∪V}$. When there are no constraints between values used to replace any two variables, the pattern is called linear.

A substitution is a map $Θ : V → T_{Σ∪V}$ which can be extended to all trees by defining $a(t_1, \ldots, t_n)Θ = a(t_1Θ, \ldots, t_nΘ)$ for every $n$-ary operator $a$ ($n > 0$). $tΘ$ is also written as $t[θ[v_1, \ldots, t_n];v]$ if the set of the variables occurring in $t$ is $\{v_1, \ldots, v_n\}$ and $v_iΘ = t_i$ for all $i$. Assume that $α$ is a pattern in $T_{Σ∪V}$. $α$ matches a tree $t$ if there exists a substitution $Θ$ such that $αΘ = t$.

**Definition 1:** A tree grammar is a quadruple $G = (N, Σ, R, S)$ where

- $N$ is a finite set of nonterminals denoted as $A, B, \ldots$.
- $Σ$ is the alphabet of terminals denoted as $a, b, \ldots$.
- $R$ is a finite set of rules of the form $A → α$ with $α ∈ T_{Σ∪N}$ and $A ∈ N$. $α$, $A$ are also called pattern.
- Each rule has an associated cost such as $c(A → α)$.
- $S$ is a special nonterminal and it represents start symbol.

A rule $r : A → α$ is of type $(A_1, \ldots, A_n) → A$ if the $i$-th nonterminal in $α$ is $A_i[10]$. For a left side $α$ of the rule $r$, the pattern $α$ is defined as a pattern in $T_{Σ∪V}$ such that $α$ is obtained from $α$ by replacing, for $1 ≤ j ≤ n$, the $j$-th nonterminal by a variable $v_j[10]$. For a tree grammar $G$, we define $a$-rules as the set of rules such that $a$-rules $= \{A → a(t_1, \ldots, t_n) ∈ R \mid a ∈ Σ_n \text{ and for } 1 ≤ i ≤ n, t_i ∈ T_{Σ∪N}\}$. A rule of the form $A → α$ is called normal form if $α$ is a pattern of the form either $X ∈ Σ_0 \cup N$ or $a(A_1, \ldots, A_n)$ where $a ∈ Σ_n$ and $A_1, \ldots, A_n ∈ N$. A tree grammar is called normal form if all rules are in normal form. Any tree grammar can be converted into normal form tree grammar by introducing several nonterminals and rules[1]. In this paper, the tree grammar is assumed to be a normal form.

A cover of $t ∈ T_{Σ∪N}$ to $A$ is a sequence of pairs $(\text{rule}, \text{position}) ∈ R × \text{Pos}(t)$. If $τ$ is a cover of $t/p$ to $X$, then $τ$ satisfy the following conditions:

- If $τ = ε$ then $t = X$
- If $τ = τ_1 \cdots τ_n(r, p)$ for some rule $r : A → α ∈ R$ of type $(X_1, \ldots, X_n) → A$, then $t/p = τ_i[t \setminus v_1, \ldots, t_n \setminus v_n]$ and $τ_i$ is a cover of $t_i$ to $X_i$ for $1 ≤ i ≤ n$.

The last rule (written as last($τ$)) of a cover $τ$ is defined as follows. If $τ = (r_1, p_1) \cdots (r_n, p_n)$ and $r_i ∈ R$ for $1 ≤ i ≤ n$ then last($τ$) = $r_n$. The tree language of $G$ relative to $α$ (written as $L(G, α)$) is:

- $\{t ∈ T_{Σ} \mid \exists ρ : τ$ is a cover of $t$ to $A\}$ if $α = A ∈ N$.
- $\{t ∈ T_{Σ} \mid t = τ_i[t \setminus v_1, \ldots, t_n \setminus v_n]$ and $\exists τ_i : τ_i$ is a cover of $t_i$ to $A_i$ for $1 ≤ i ≤ n\}$ if $α = (A_1, \ldots, A_n)$.

The cost associated with a cover $τ$ is the sum of the costs associated with each rule in the cover (written as $C(τ)$ which is the extension of cost of a rule):

- If $τ = ε$ then $C(τ) = 0$.
- If $τ = \langle r_1, p_1 \rangle \cdots \langle r_n, p_n \rangle$ then $C(τ) = \sum_{i=1}^{n} C(r_i)$.

In covers of $t$ to $A$, one cover with the minimum cost is called least-cost cover of $t$ to $A$ (written as LCV($t$, $A$)). Then the goal of the tree pattern matching scheme is to find $\text{LCV}(t, S)$. Evaluation procedure of $\text{LCV}(t, A)$ consists of two phases. The first phase annotates a state on each node of the IR tree $t$ in a bottom-up way. A state is a set of triples (nonterminal, rule, cost) which is called an item. In an item, rule and cost are computed for nonterminal [6]. The state annotated on the root node of $t = a(t_1, \ldots, t_n)$ is $(\{B, cost(t, B), rule(t, B)\} \mid B ∈ N)$ where

- $cost(t, B) = \text{min}\{\sum_{i=1}^{n} c_i + C(τ) + C(τ) \mid r : B' → α ∈ a$-rules and if $r$ is type $(B_1, \ldots, B_n) → B'$ then $c_i = cost(t_i, B_i)$ for $1 ≤ i ≤ n$ and $τ$ is a cover of $B'$ to $B\}$.
- $\text{rule}(t, B) = \text{last}(τ)$ such that $τ$ is a cover of $t$ to $B$ and $C(τ) = cost(t, B)$.

In the second phase, the scheme finds the least-cost cover of $t$ to $A$ while traversing the IR tree in a top-down direction. If $s$ is the state annotated on the root node of $t/p$, then $\text{LCV}(t, B) = \text{LCV}(t_1, B_1)\cdots \text{LCV}(t_n, B_n) \cdot (r, p)$ where $(B, c, r : B → α) ∈ s$, $r$ is of type $(B_1, \ldots, B_n) → B$ and $t = τ_i[t \setminus v_1, \ldots, t_n \setminus v_n]$.

3. An Efficient Method of Constructing States

In the previous work of [6], the cost ($cost(t, A)$) is evaluated from a sequence of all rules in $a$-rules when computing an item in the state. We can infer that only reduced number of rules can be used in computing states.
This is the point we are claiming in this paper, and we will propose an efficient method of constructing states.

The *match set* of a tree *t* is a set of the patterns \( \alpha \) such that \((A \rightarrow \alpha) \in R \) or \( \alpha \in N \) and \( t \in L(G, \alpha) \). If \( m \) is the match set of \( t \), then \( m \) is calculated as follows: \( m = \{ \alpha | r : A \rightarrow \alpha \in R \) and \( r \) is type \((A_1, \ldots, A_n) \rightarrow A \) then \( Q = m = \{ t_1[v_1, \ldots, t_n[v_n], \exists t_i : t_i \) is a cover of \( t_i \) to \( A_i \) for \( 1 \leq i \leq n \}\} \). Let \( \delta_\alpha(t_1, \ldots, t_n) = \delta_\alpha \) for \( 1 \leq i \leq n \) and \( \delta_\alpha(q_i) = q_i \). We define \( \mu_\alpha(t_1, \ldots, t_n) = q_i \) and \( \delta_\alpha(q_i, \ldots, q_n) = m \).

**Algorithm 1**: Let \( G = (N, \Sigma, P, S) \) be a tree grammar. The sets \( \delta_\alpha \) and \( \mu_\alpha \) are iteratively determined by \( Q = \bigcup_{0 \leq j} Q^{(j)}, \delta_\alpha = \bigcup_{0 \leq j} \delta_{\alpha}^{(j)} \) and \( \mu_\alpha = \bigcup_{0 \leq j} \mu_\alpha^{(j)} \) where

1. \( Q^{(0)} = \emptyset, \delta_{\alpha}^{(0)} = \emptyset \) and \( \mu_\alpha^{(0)} = \emptyset \) for all \( \alpha \in \Sigma \);
2. Assume \( j > 0 \). For \( \alpha \in \Sigma \) and \( m_1, m_2, \ldots, m_n \in Q^{(j-1)} \) such that \( m_i \cap \delta_\alpha \) is not empty, let \( \mu_\alpha^{(j)}(m_i, i) = q_i \) for \( 1 \leq i \leq n \).

Since \( Q^{(j)} \subseteq Q^{(j+1)} \) for \( 0 \leq j \), iteration can be terminated as soon as no new states are generated. Therefore \( Q = Q^{(j)}, \delta_\alpha = \delta_\alpha^{(j)} \) and \( \mu_\alpha = \mu_\alpha^{(j)} \) for the first \( j \) with \( Q^{(j)} = Q^{(j+1)} \).

In this paper, it is a primary intention that we use the set \( Q, \delta_\alpha \) and \( \mu_\alpha \) to evaluate \( \text{cost}(t, A) \) of state efficiently.

**Theorem 1**: Assume that the state annotated on the root node of \( t = a(t_1, \ldots, t_n) \) is \( \{(A, \text{cost}(t, A), \text{rule}(t, A)) | A \in N \} \), \( m \) is the match set of \( t \) and \( m_i \) is the match set of \( t_i \) for \( 1 \leq i \leq n \). Let \( \mu_\alpha(m_i, i) = q_i \) for \( 1 \leq i \leq n \) and \( \delta_\alpha(q_i, \ldots, q_n) = m \). Then \( \text{cost}(t, A) = \min \{ \sum_{i=1}^{n} c_i + C(r) + C(\tau) | r : B \rightarrow \alpha \in Q \} \) where \( \alpha \in m \) and \( r \) is type \((A_1, \ldots, A_n) \rightarrow B \), then \( c_i \) is \( \text{cost}(t_i, A_i) \) for \( 1 \leq i \leq n \) and \( \tau \) is a cover of \( B \) to \( A \).

Also we describe another speed-up technique which can be applied when there is only one pattern in a match set to compute the state. From the definition of the state, it is required that each nonterminal has only one cost, and its value is relative to that of the other nonterminals in the match set. When one pattern of the match set is \( \alpha \), the evaluation of \( \text{cost}(t, A) \) is simplified as follows: \( \text{cost}(t, A) = \min \{ C(r) + C(\tau) | r : B \rightarrow \alpha \in R \} \).

**4. Experimental Results**

Based on the Algorithm 1, the CGG proposed in this paper is implemented for experiment and comparison with the related work iburg. Our CGG is a modified version of iburg which produces a CG of lcc [4]. iburg is a recently developed CGG adopting the bottom-up tree pattern matching with DP technique at compile time. We show improvements in compile time by the experiment on MC68000, x86, mips and sparc CGs. Relevant statistics for the CGs are shown in Table 1. The standard of the comparison is the number of tree patterns checked in computing the state at each node. The C programs which were tested are the test suites of lcc. Table 2 shows amount of time required in compiling C program (5317 lines) by two versions of lcc.

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(original version and our version). Those amounts are required in compilation only; times spent in preprocessing, assembly, and linking time are excluded. Test compilations were executed on on the Sparc2/40 station with 48 MB under SunOS Release 4.1.2. The time in Table 2 means the lowest elapsed time in seconds chosen among the results of several experimentations on a lightly loaded machine (i.e., (user + system)/elapsed ≥ 0.95).

5. Concluding Remarks

In this paper, we proposed an efficient method of constructing states in bottom-up tree pattern matching with DP in the CG. The task of computing a state is divided into two parts: the computation of the match set, the computation of the state. Although the state cannot be computed at compile-compile time because of the evaluation of costs, the match sets can be computed at compile-compile time. We transform the sequence of rules into several match sets and several transition tables. If the match sets and the transition tables is used in constructing the states, then the pattern matcher can avoid about 40% unfruitful tests. However, the size of matcher is larger because the match sets may have common rules. In Addition, we would like to point out that some part of the analyses required in our method can be applied at compile-compile time, which may secure practical efficiency at compile time.

References


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