Right-to-Left Code Generation for Arithmetic Expressions

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This paper presents a method of right-to-left code generation for arithmetic expressions given in the postfix notation. The number of generated instruction lines is equal to the one obtained from the binary tree structure. However, the right-to-left code generator is faster and requires less memory than the code generator from the binary tree. These results were obtained by introducing a vector, called vector-generatrice, assigned to every postfix string. A translation grammar which generates the postfix string and its associated vector-generatrice is defined. An experiment has been performed over a set of arithmetic expressions to compare the right-to-left code generator and the code generator from the binary tree.

INTRODUCTION

In this paper, we shall concentrate on the design of an efficient code generator which produces an assembly language code for arithmetic expressions. The input to the code generator is an arithmetic expression. The output is an equivalent assembly language program. We would like the resulting assembly language program to be good under some cost function such as the number of assembly language instructions, or the number of memory fetches. The cost function of the code generator depends only on the internal representation of expressions in compilers. The well-known internal structures are parenthesized notation, quadruples, triples, postfix and prefix notation, and the binary tree. The parenthesized form of expressions was used in the first FORTRAN compilers. This is not a suitable internal structure for an efficient code generation. In particular, the transformation to such a structure is not compatible with the design of modern compilers, as far as a single processor is concerned. Stone gives the one-pass algorithm which transforms the expressions into a parenthesized form for parallel processors. In quadruple notation, the operations appear in the order in which they are to be executed. The main problem is to keep track of the contents of the accumulator, in which all arithmetic is done at run-time, in order to eliminate unnecessary load and store instructions. The main disadvantage of quadruples is that a description of each temporary value is maintained throughout the compile-time. This problem does not exist in the triple notation first introduced by Sheridan. We do not need a description of each temporary when using triples; it need only be maintained while code which references it is being generated. If the ranges of temporaries are pairwise disjoint or nested, we can use a compile-time stack to hold descriptions of temporaries; otherwise, a more complex scheme will be necessary to allocate and delete space for them. If the triples are not going to be processed once the code has been generated, we can replace the triple by a description of its result. Consequently, we would not need a stack, and we would not have to delete descriptions. Obviously, the handling of temporaries in triple notation is more complex than in the quadruple notation. Thus, the code generator from the quadruple notation is more efficient. On the other hand, the memory space for triples is smaller since they require three fields per entry. The triples are more suitable for the code optimization since they can easily be rearranged for this purpose. Furthermore, the code generated from the triple notation generally uses fewer temporaries.

A number of languages are based on a concept known as a Polish notation; this has advantages for machine but it is difficult for human digestion. It is so called because it was first introduced by the Polish philosopher Jan Łukasiewicz in connection with the formulae of symbolic logic. A variation of it is called the reverse Polish notation. These notations are also known as the prefix and postfix notation, respectively. The transformation to prefix notation, and the code generation from it, requires the analysis of expressions from right to left. This differs from the previously mentioned methods where the analysis is performed from left to right. In postfix notation, the analysis is also performed from left to right. Formally, the difference between postfix and prefix notation lies in the operator structure; reverse Polish notation is based on postfix operators—<operand> <operator> <operand>—while direct Polish notation is based in a similar way on prefix operators—<operator> <operand> <operand>. Since the writing and interpretation of expressions are usually performed from left to right, the prefix notation is inappropriate for the code generation (with the exception of APL, for example). Compared to the triple notation, the postfix notation requires less space and generates fewer temporaries; the code generation from it is very simple. However, the postfix notation is not a structure particularly suitable for code optimization either at the single expression level or at the level of a group of expressions.

Code generation from a binary tree is probably the most discussed method in this field. Anderson has described an algorithm for the code generation for a one-register machine. Nakata proposed a similar algorithm. The number of registers required to generate code for an expression tree has been investigated by Nakata, Redziejowski, and Sethi and Ullman. Beatty and Frailey discuss extensions involving the unary minus operator. The code generated from the binary tree is the shortest-length program to compute a given expression.
This was shown by Aho and Ullman.\textsuperscript{12} Besides the shortest-length program, the binary tree uses fewer temporaries and offers a more suitable structure for the straight-line code optimization than the postfix notation. On the other hand, the postfix notation requires less space and is more efficient from the transformation and code generation point of view.

There are other works dealing with the problem of register allocation in a sequence of expression evaluations (e.g. Refs 13-15), translating arithmetic expressions into code for parallel computers (e.g. Refs 2, 16-19), or basic algorithms for the code generation.\textsuperscript{20-23} This paper presents a new algorithm for the code generation without optimization. The work was motivated by the results of the investigation of the distribution of executable statements,\textsuperscript{24} and by the examination of works concerning the code optimization. It was found that the assignment and IF statements together have over 60\% of static distribution.\textsuperscript{24} Furthermore, the existing internal structures of expressions are not particularly suitable for the code optimization and register allocation at the single expression level or at the level of a group of expressions. With respect to other algorithms in this field, the proposed algorithm gives faster code generation than the binary tree but for the same length of the code. Nevertheless, the internal structure of expressions is suitable for the code optimization and register allocation. It offers an opportunity to investigate the efficient code optimization techniques.

The internal structure of an expression is composed of two substructures: (1) well-known postfix notation, and (2) vector-generatrice (VG), describing the postfix notation in a certain way. Its generation is discussed through a translation grammar for arithmetic expressions.\textsuperscript{20} Although the transformation to such an internal structure is performed from left to right, the code is generated from right to left. The algorithm is presented in Algol-like form and discussed. It is proved that the algorithm produces the code of the same length as the binary tree. All considerations are based on a single accumulator machine.

Theoretical results are illustrated by a worked and output example. The output example is extracted from an experiment done for a set of arithmetic expressions to examine the characteristics of the algorithm and compare them to that obtained with the binary tree. It was found that the proposed algorithm is about 20\% faster. When the transformation to internal structure is taken into account, this time gain reduces to 13\%. The required memory space and number of instructions necessary to realize the transformation and code generation are approximately the same.

**VECTOR-GENERATRICE**

In the generation of VG-based data structure we shall use the concept of the translation grammar.\textsuperscript{25} A translation grammar is a context-free grammar in which the set of terminal symbols is partitioned into a set of input symbols and a set of action symbols. The action symbols are used to represent more general ad hoc routines. The strings in the language specified by a translation grammar are called activity sequences.

Let a translation grammar \( G^T \) be given generally by

\[
G^T = ( \text{IS}, \text{AS}, \text{NS}, P, \text{SN})
\]

where \( \text{IS} = \) input symbols, \( \text{AS} = \) action symbols, \( \text{NS} = \) nonterminal symbols, \( P = \) productions and \( \text{SN} = \) starting nonterminal.

The following metanotation is used for \( G^T \):

\[
\langle, \rangle = \text{matched pair of angle brackets enclosing a nonterminal},
\]

\[
\rightarrow = \text{production operator},
\]

\[
\{,\} = \text{matched pair of curly brackets enclosing an action symbol}
\]

An example of a translation grammar is:

\[
\text{IS} = a, b, c
\]

\[
\text{AS} = x, y, z
\]

\[
\text{NS} = \langle A \rangle, \langle B \rangle
\]

\[
\text{SN} = \langle A \rangle
\]

\[
\begin{align*}
(1) \ P &= \langle A \rangle \rightarrow a \langle A \rangle \langle x \rangle \langle B \rangle \\
(2) \ &\langle A \rangle \rightarrow x \\
(3) \ &\langle B \rangle \rightarrow \langle B \rangle c \\
(4) \ &\langle B \rangle \rightarrow b \langle y \rangle
\end{align*}
\]

For the input sequence \( abc \), the activity sequence is:

\[
a\{z\}\{x\}b\{y\}c.
\]

It is obtained by the following parsing:

\[
\begin{align*}
(1) \ &\langle A \rangle \rightarrow a \langle A \rangle \langle x \rangle \langle B \rangle \\
(2) \ &\langle A \rangle \rightarrow a \langle z \rangle \langle x \rangle \langle B \rangle \\
(3) \ &\langle A \rangle \rightarrow a \langle z \rangle \langle x \rangle \langle B \rangle c \\
(4) \ &\langle A \rangle \rightarrow a \langle z \rangle \langle x \rangle \langle b \rangle \langle y \rangle c
\end{align*}
\]

If each action symbol represents a routine which outputs the symbol within the curly brackets (and possibly performs anything else), then a given translation grammar is intended to describe the translation of input strings into output strings. For the given example, the output string is \( xzyc \). It is readily derived from the obtained activity sequence. This concept of the translation grammar will be used in the derivation of VG-based data structure.

As the first step toward this goal, we devise a simplified translation grammar for arithmetic expressions:

\[
\text{IS} = I, N, +, -, *, /, \$
\]

\[
\text{AS} = I, N, +, -, #, *, /, \$
\]

\[
\text{NS} = \langle S \rangle = \text{(start expression)}
\]

\[
\langle E \rangle = \text{(expression)}
\]

\[
\langle T \rangle = \text{(term)}
\]

\[
\langle P \rangle = \text{(primary)}
\]

\[
\langle V \rangle = \text{(variable)}
\]

\[
\langle N \rangle = \text{(unsigned number)}
\]

\[
\text{SN} = \langle S \rangle
\]

\[
\begin{align*}
(1) \ P &= \langle S \rangle \rightarrow \{ \langle E \rangle \} \$ \$
(2) \ &\langle E \rangle \rightarrow \langle E \rangle + \langle T \rangle \{ + \}
(3) \ &\langle E \rangle \rightarrow \langle E \rangle - \langle T \rangle \{ - \}
(4) \ &\langle E \rangle \rightarrow \langle T \rangle
(5) \ &\langle T \rangle \rightarrow \langle T \rangle \times \langle P \rangle \{ * \}
(6) \ &\langle T \rangle \rightarrow \langle T \rangle / \langle P \rangle \{ / \}
(7) \ &\langle T \rangle \rightarrow \langle P \rangle
(8) \ &\langle P \rangle \rightarrow + \langle P \rangle
(9) \ &\langle P \rangle \rightarrow - \langle P \rangle \{ # \}
(10) \ &\langle P \rangle \rightarrow \langle V \rangle \{ I \}
(11) \ &\langle P \rangle \rightarrow \langle N \rangle \{ N \}
(12) \ &\langle P \rangle \rightarrow \langle E \rangle
(13) \ &\langle V \rangle \rightarrow I
(14) \ &\langle N \rangle \rightarrow N
\end{align*}
\]
It should be noted that the unary operators + and # (unary minus) are given the highest precedence. Each operator can be followed by a string of unary operators. The input sequences are restricted to symbols \( I \) (representing a variable), \( N \) (representing an unsigned number), (,) and +, -, *, / only for the sake of the clear and concise presentation of the algorithm. The function designer and the operator \( \uparrow \) could be readily included in the grammar. Their presence or absence does not influence the final conclusion on the algorithm characteristics.

If we assign to each action symbol an action routine for performing special functions, then the application of the translation grammar given by Eqn (2) to an input sequence will produce a standard postfix string with associated VG. There is a very simple practical explanation of VG. Let \( E_p \) be an arithmetic expression in the infix notation, transformed to postfix string \( E_p \):

\[
E_p = a_1 a_2 \ldots a_m b_1 b_2 \ldots b_j a_{m+i} a_{m+i+2} \ldots a_{m+i+b_j b_{j+1}} \ldots \cdot b_{j+k} \ldots a_{m+i+j+b_{j+k+1}} \ldots b_{j+k+n} a_{m+i+j+n+1} \ldots
\]

where \( a_1, a_2, a_3, \ldots, a_{m+i+j+n+1} \) are the operands (or their indices in delimiter table), and \( b_1, b_2, b_3, \ldots, b_{j+k+n} \) the operators (or their indices in delimiter table). The dollar sign \$\) denotes the end of \( E_p \), i.e.

\[
a_{m+i+j+n+1} = \$
\]

Using Eqn (3), VG can be generated in the following way. Firstly, we define the substrings of \( E_p \). A substring is a sequence of all successive operands or operators. If the number of operand substrings is \( N_1 \), the number of operator substrings \( N_2 \) must be

\[
N_2 = N_1
\]

The substrings of \( E_p \) in Eqn (3) are:

\[
a_1, a_2, \ldots, a_m \quad \text{(operands)}
\]

\[
b_1, b_2, \ldots, b_j \quad \text{(operators)}
\]

\[
a_{m+1}, a_{m+2}, \ldots, a_{m+i+1} \quad \text{(operands)}
\]

\[
b_{j+1}, b_{j+2}, \ldots, b_{j+k} \quad \text{(operators)}
\]

\[
a_{m+i+j+n+1}, \ldots, a_{m+i+j+n} \quad \text{(operands)}
\]

\[
b_{j+k+1}, b_{j+k+2}, \ldots, b_{j+k+n} \quad \text{(operators)}
\]

\[
a_{m+i+j+n+1} \quad \text{(operand)}
\]

The total number of substrings \( N_3 \) (including the endmarker as an operand substring) is

\[
N_3 = 2N_1 + 1
\]

By assigning to each substring of operands a successor substring of operators, one obtains a pair of connected substrings \( C_S \), where \( i \) is its ordinal number.

For example, \( a_1 a_2 \ldots a_m b_1 b_2 \ldots b_j \) forms a pair of connected substrings \( C_S \), \( a_1, a_2, \ldots, a_m \) represents a substring of operands followed by a successor substring of operators \( b_1, b_2, \ldots, b_j \). The number of pairs \( N_{CS} \) is

\[
N_{CS} = \lfloor N_3 / 2 \rfloor = N_1
\]

For each pair of connected substrings we create a 3-tuple \(( N_i, N_i^0, P_i ) \), where \( N_i \) = number of operands in \( C_S \), \( N_i^0 \) = number of operators in \( C_S \), \( P_i \) = pointer to beginning of \( C_S \) in \( E_p \). For \( C_S \), the 3-tuple is \(( m, j, 1 ) \) because \( N_i = m, N_i = j \) and \( P_i = 1 \). VG is formed now by concatenating all 3-tuples of connected substrings by their ordinal numbers into a vector of dimension \(( N_{CS} + 1 ) \times 3 \):

\[
VG \cdot catVG \cdot catVG_{N_{CS} + 1}
\]

where \( cat \) is the concatenation operator. The endmarker is considered as an operand substring connected to a dummy operator substring. Its corresponding 3-tuple is given by \(( 1, 0, P_{N_{CS} + 1} ) \).

**ACTION ROUTINES**

In generating VG-based data structure, the action routines play the principal role. In order to describe them, we associate with each action symbol a mnemonic name representing a routine intended to perform a particular function:

<table>
<thead>
<tr>
<th>Action symbol</th>
<th>Name of routine</th>
</tr>
</thead>
<tbody>
<tr>
<td>( / )</td>
<td>VARIABLE</td>
</tr>
<tr>
<td>( N )</td>
<td>UNSIGNED_NUMBER</td>
</tr>
<tr>
<td>+</td>
<td>PLUS</td>
</tr>
<tr>
<td>-</td>
<td>MINUS</td>
</tr>
<tr>
<td>#</td>
<td>UNARY_MINUS</td>
</tr>
<tr>
<td>*</td>
<td>MULTIPLY</td>
</tr>
<tr>
<td>( / )</td>
<td>DIVIDE</td>
</tr>
<tr>
<td>$</td>
<td>END MARKER</td>
</tr>
</tbody>
</table>

We shall proceed now with the presentation of these routines as Algol procedures.

**NULL**

```algol
procedure NULL (VG, current_VG_index, current_index_of_output_string); integer array VG; integer current_VG_index, current_index_of_output_string; begin integer i, n; comment: because the empty symbol is to be outputted, no output operation is performed; current_VG_index := 1; current_index_of_output_string := 1; comment: reset VG array; for i := 1 step 1 until n do begin output_string[current_index_of_output_string] := current_INDEX_of_output_string; current_INDEX_of_output_string := current_INDEX_of_output_string + 1; end; end NULL;
```

The routine NULL resets the space allocated to \( VG \) (defined as a vector), and initializes the indices of the \( VG \) and output string array \( (E_p) \).

**VAR**

```algol
procedure VARIABLE (VG, current_VG_index, class_of_previously_outputted_symbol, output_string, current_index_of_output_string); integer array VG; string array output_string; integer current_VG_index, class_of_previously_outputted_symbol, current_index_of_output_string; begin if current_VG_index = 1 \&\& class_of_previously_outputted_symbol = 0 then begin VG[current_VG_index + 5] := VG[current_VG_index] + VG[current_VG_index + 1] + VG[current_VG_index + 2]; current_VG_index := current_VG_index + 3; end; comment: output the action symbol \( f \) into the output string array; output_string[current_index_of_output_string] := f; current_index_of_output_string := current_index_of_output_string + 1; comment: count the number of outputted symbols of the class 0; VG[current_VG_index] := VG[current_VG_index] + 1; class_of_previously_outputted_symbol := 0; end VARIABLE;
```

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THE COMPUTER JOURNAL, VOL. 25, NO. 3, 1982
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The routine VARIABLE performs three functions: (1) compares the class of the previously outputted symbol to the current one \( i \) or \( N \) for \( current\_VG\_index \neq 1 \); the class of outputted symbol is \( class\_of \( i \) = 0, class\_of \( N \) = 0, class\_of (other action symbols) = 1; (2) outputs the action symbol \( i \) into the output string array (defined as a vector); (3) counts the number of outputted symbols of the class 0.

UNSIGNED_NUMBER

The body of this procedure is identical to VARIABLE except for the statement

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`I'};
\]

which has to be replaced by

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`N'};
\]

PLUS

procedure PLUS(VG, current\_VG\_index, output\_string, current\_index\_of\_output\_string, class\_of\_previously\_outputted\_symbol);
integer array VG; string array output\_string; integer current\_VG\_index, current\_index\_of\_output\_string, class\_of\_previously\_outputted\_symbol;

begin
comment: output the action symbol $ + $ into the output string array;
output\_string[\text{current\_index\_of\_output\_string}] = \text{`$'};
comment: terminate VG by a special three words marker;
current\_VG\_index = current\_VG\_index + 3;
VG[current\_VG\_index] = 1;
VG[current\_VG\_index + 1] = 0;
VG[current\_VG\_index + 2] = VG[current\_VG\_index - 1] +
+ VG[current\_VG\_index - 2] +
+ VG[current\_VG\_index - 3];
end PLUS;

The routine PLUS performs two functions: (1) outputs the action symbol $ + $ into the output string array, and (2) counts the number of outputted symbols of the class 1.

MINUS

The body of this procedure is identical to PLUS except for the statement

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`-'};
\]

which has to be replaced by

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`#'};
\]

UNARY MINUS

The body of this procedure is identical to PLUS except for the statement

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`+'};
\]

which has to be replaced by

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`#'};
\]

MULTIPLY

The body of this procedure is identical to PLUS except for the statement

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`*'};
\]

which has to be replaced by

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`1'};
\]

DIVIDE

The body of this procedure is identical to PLUS except for the statement

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`/'};
\]

which has to be replaced by

\[
output\_string[\text{current\_index\_of\_output\_string}] = \text{`/'};
\]

END MARKER

procedure END\_MARKER(VG, current\_VG\_index, output\_string, current\_index\_of\_output\_string);
integer array VG; string array output\_string; integer current\_VG\_index, current\_index\_of\_output\_string, current\_VG\_symbol;

begin
comment: output the action symbol $ \times $ into the output string array;
output\_string[\text{current\_index\_of\_output\_string}] = \text{`$'};
comment: terminate VG by a special three words marker;
current\_VG\_index = current\_VG\_index + 3;
VG[current\_VG\_index] = 1;
VG[current\_VG\_index + 1] = 0;
VG[current\_VG\_index + 2] = VG[current\_VG\_index - 1] +
+ VG[current\_VG\_index - 2] +
+ VG[current\_VG\_index - 3];
end END\_MARKER;

It is obvious that the procedures VARIABLE, UNARY\_MINUS, MULTIPLY, DIVIDE can be replaced (in the domain of realization) by two procedures: (1) OPERAND, and (2) OPERATOR. This is obtained easily by including the output symbol in the list of formal parameters.

OPERAND

procedure OPERAND(VG, current\_VG\_index, class\_of\_previously\_outputted\_symbol, output\_string, current\_index\_of\_output\_string, output\_symbol);
integer array VG; string array output\_string; integer current\_VG\_index, current\_index\_of\_output\_string, class\_of\_previously\_outputted\_symbol, current\_index\_of\_output\_string;

string (1) output\_symbol;
begin
if current\_VG\_index \neq 1 \land class\_of\_previously\_outputted\_symbol \neq 0 then
begin
VG[current\_VG\_index + 1] = VG[current\_VG\_index] +
+ VG[current\_VG\_index + 1] +
+ VG[current\_VG\_index + 2];
current\_VG\_index = current\_VG\_index + 3;
end;
comment: output the action symbol (output\_symbol) into the output string array;
output\_string[\text{current\_index\_of\_output\_string}] = output\_symbol;
current\_index\_of\_output\_string = current\_index\_of\_output\_string + 1;
comment: count the number of outputted symbols of the class 0;
VG[current\_VG\_index] = VG[current\_VG\_index + 1];
class\_of\_previously\_outputted\_symbol = 0;
end OPERAND;

The procedure OPERAND replaces the procedures VARIABLE and UNSIGNED\_NUMBER.

OPERATOR

procedure OPERATOR(VG, current\_VG\_index, output\_string, current\_index\_of\_output\_string, output\_symbol, class\_of\_previously\_outputted\_symbol);
integer array VG; string array output\_string; integer current\_VG\_index, current\_index\_of\_output\_string, class\_of\_previously\_outputted\_symbol;
As an illustration, consider the following arithmetic expression
\[ I + N - (-(-N+I))\left(I \cdot I - N/I\right)I \cdot I + S \] (9)
whose VG-based data structure is to be found. The parsing sequence is:

1. \( \langle E \rangle \rightarrow \langle S \rangle \# \)
2. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
3. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
4. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
5. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
6. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
7. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
8. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
9. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
10. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
11. \( \langle E \rangle \rightarrow \langle T \rangle \# \)
12. \( \langle E \rangle \rightarrow \langle T \rangle \# \)

Applying now to each nonterminal \( \langle E \rangle \) the production sequence (4), (7), (10), (11), (13) or (14) (depending on the operand type), to each nonterminal \( \langle T \rangle \) the production sequence (7), (10), (11), (13) or (14) (depending on the operand type), and to each nonterminal \( \langle P \rangle \) the production sequence (10), (11), (13) or (14) (depending on the operand type), one obtains the following activity sequence:

\[
\{1\} I[I + N[N\{+\} - (-(-N[I] + I[I]\{+\})))\#\}\{\#\}/(I[I] + I[I]\{+\})\#\# - N[N]/I[I]\{+\} - (-(-I[I] + I[I]\{+\})\#\} + I[I]\{+\} + I[I]\{+\} + S\$. ]

If we extract from the activity sequence all input symbols by the order of their appearance, we obtain Eqn (9). The application of the action routines for each action symbol by the order of its appearance in the activity sequence, gives, finally, VG-based data structure (see Table 1).

Each underlined substring in the output_string (\( E_0 \)), in Table 1, corresponds to one connected substring; i.e., \(+\,\#\,\#\). Two substrings form \( CS_2 \) if they are continuous in \( E_0 \), and the first substring consists of operands; i.e., \( CS_2 = NI + \#\,\#\), 3-tuple is (2, 3, 4). Each underlined 3-tuple in VG corresponds to a \( CS_2 \) in \( E_0 \) by the order of its appearance.

### RIGHT-TO-LEFT CODE GENERATION

The term **right-to-left code generation** designates the code generation from the right end of \( E_0 \), One of the key points in introducing the vector-generating scheme is just to enable the right-to-left code generation. The algorithm is based on the following principles: (i) the elementary unit for the code generation is a pair of connected substrings \( CS_1 \), (ii) the code generation from an elementary unit is the same as for any standard postfix string; (iii) the code is generated until \( TV,0 = 1 \) \( v A^B = 0 \); (iv) when the current \( CS_2 \) becomes temporary inactive, i.e. \( N^O = 1 \) \( v N^O = 0 \), the next \( CS_2 \) is taken, where \( l' = l + v l' = l' - 1 \) respectively; (v) the separate stack for operands is not needed; instead, the space for \( CS_1 \) is used for \( CS_2 \) stacks, each preset already with an operand substring in the phase of transformation to \( E_0 \), and (vi) the transition from one \( CS_2 \) to another \( CS_2 \) is performed by means of \( P_i \) given in a 3-tuple for \( CS_2 \).

Before we proceed to detailed presentation of algorithm, we shall explain the procedure for the code generation from an elementary unit \( CS_1 \).

Firstly, we shall define a hypothetical machine, necessary for this purpose, as a single accumulator (ACC) machine with the following basic operations:

- **LDA**; move the contents of the location \( A \) into ACC,
- **STA**; move the contents of ACC into the location \( A \),
- **NEG**; the contents of ACC is two's complemented,
- **ADD**; the contents of the location \( A \) are added to the contents of ACC and the result placed in ACC,
- **SUB**; the contents of the location \( A \) are subtracted from the contents of ACC and the result placed in ACC,
- **MUL**; the contents of ACC are multiplied by the
The space occupied by the operand substring $(b_1, \ldots, b_n)$, the operator substring $(o_1, \ldots, o_n)$, if $#_i$ is the unary operator (#), or if $+,-,*,/ , #_i$ is binary operator $(+, -, *, /)$, where $B.T.OPD = \text{below-the-top element of the stack for } T.OPD$, and OPT is a symbolic representation of operators (ADD, SUB, MUL, DIV, NEG).

If any of succeeding operators is unary, an NEG is generated. Otherwise, the operator is checked for generation of the code

\[
\begin{align*}
\text{if } &b_i \text{ is the unary operator (\#), or} \\
&LDABT.OPD \\
&OPTT.OPD
\end{align*}
\]

and then

\[
\begin{align*}
&\text{LDA } BT.OPD \\
&\text{OPT }T.OPD
\end{align*}
\]

where $T$ is a temporary variable. The code generation is continued in this way until $N_{opt} = 1 \lor N_{opt} = 0$. Then, the next $CS_{i+1} \leftarrow 1$ is taken.

### Table 1. Generation of VG-based data structure for expression $I + N - (-((N + I)/(I*I - N/I))/I*I + 1)$

<table>
<thead>
<tr>
<th>ENTRY</th>
<th>ACTIVITY</th>
<th>OUTPUT_STRING</th>
<th>Current_index_of_operation_string</th>
<th>VG</th>
<th>Class_of_output_symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>{}</td>
<td>NULL</td>
<td></td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>[I]</td>
<td>VARIABLE</td>
<td>I</td>
<td>1</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>[N]</td>
<td>UNSIGNED_NUMBER</td>
<td>IN</td>
<td>2</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>[+1]</td>
<td>PLUS</td>
<td>IN +</td>
<td>3</td>
<td>210</td>
<td>1</td>
</tr>
<tr>
<td>[I-N]</td>
<td>UNSIGNED_NUMBER</td>
<td>IN + N</td>
<td>4</td>
<td>1104</td>
<td>0</td>
</tr>
<tr>
<td>[+2]</td>
<td>PLUS</td>
<td>IN + N +</td>
<td>5</td>
<td>212040</td>
<td>0</td>
</tr>
<tr>
<td>[I]</td>
<td>VARIABLE</td>
<td>IN + N + f</td>
<td>6</td>
<td>212240</td>
<td>0</td>
</tr>
<tr>
<td>[+3]</td>
<td>UNARY_MINUS</td>
<td>IN + N + f</td>
<td>7</td>
<td>212140</td>
<td>1</td>
</tr>
<tr>
<td>[I-N]</td>
<td>UNSIGNED_NUMBER</td>
<td>IN + N + f</td>
<td>8</td>
<td>212240</td>
<td>1</td>
</tr>
<tr>
<td>[+4]</td>
<td>UNARY_MINUS</td>
<td>IN + N + f</td>
<td>9</td>
<td>212140</td>
<td>0</td>
</tr>
<tr>
<td>[I]</td>
<td>VARIABLE</td>
<td>IN + N + f +1</td>
<td>10</td>
<td>212234109</td>
<td>0</td>
</tr>
<tr>
<td>[+5]</td>
<td>VARIABLE</td>
<td>IN + N + f +1</td>
<td>11</td>
<td>212234209</td>
<td>0</td>
</tr>
<tr>
<td>[+6]</td>
<td>MULTIPLE</td>
<td>IN + N + f +1</td>
<td>12</td>
<td>212234219</td>
<td>1</td>
</tr>
<tr>
<td>[N]</td>
<td>UNSIGNED_NUMBER</td>
<td>IN + N + f +1</td>
<td>13</td>
<td>2122342191012</td>
<td>0</td>
</tr>
<tr>
<td>[I-N]</td>
<td>UNSIGNED_NUMBER</td>
<td>IN + N + f +1</td>
<td>14</td>
<td>212234192012</td>
<td>0</td>
</tr>
<tr>
<td>[+7]</td>
<td>DIVIDE</td>
<td>IN + N + f +1</td>
<td>15</td>
<td>212234192112</td>
<td>1</td>
</tr>
<tr>
<td>[I]</td>
<td>MINUS</td>
<td>IN + N + f +1</td>
<td>16</td>
<td>212234219212</td>
<td>0</td>
</tr>
<tr>
<td>[+8]</td>
<td>DIVIDE</td>
<td>IN + N + f +1</td>
<td>17</td>
<td>212234219212</td>
<td>1</td>
</tr>
<tr>
<td>[I]</td>
<td>VARIABLES</td>
<td>IN + N + f +1</td>
<td>18</td>
<td>2122341921921017</td>
<td>0</td>
</tr>
<tr>
<td>[+9]</td>
<td>DIVIDE</td>
<td>IN + N + f +1</td>
<td>19</td>
<td>2122341921921117</td>
<td>0</td>
</tr>
<tr>
<td>[I]</td>
<td>MINUS</td>
<td>IN + N + f +1</td>
<td>20</td>
<td>2122341921921171019</td>
<td>1</td>
</tr>
<tr>
<td>[+10]</td>
<td>MINUS</td>
<td>IN + N + f +1</td>
<td>21</td>
<td>2122341921921171119</td>
<td>1</td>
</tr>
<tr>
<td>[I]</td>
<td>VARIABLES</td>
<td>IN + N + f +1</td>
<td>22</td>
<td>21223419219211711219</td>
<td>1</td>
</tr>
<tr>
<td>[+11]</td>
<td>VARIABLES</td>
<td>IN + N + f +1</td>
<td>23</td>
<td>21223419219211719122</td>
<td>0</td>
</tr>
<tr>
<td>[+12]</td>
<td>PLUS</td>
<td>IN + N + f +1</td>
<td>24</td>
<td>21223419219211719122</td>
<td>1</td>
</tr>
</tbody>
</table>

The space occupied by the operand substring $d_1d_2d_3 \cdots d_m$ has to be considered as a stack preset with $d_1d_2d_3 \cdots d_m$. Starting from the top element of the stack, $T.OPD(\text{below})$, and the first operator in the connected operator substring $(b_1)$, we generate the following assembly code:

\[\text{LDA } T.OPD; \text{NEG; LDA } BT.OPD; \text{OPT }T.OPD; \text{end}\]

```
procedure code_generator (EP, VG, IL, NCS);
comment: The procedure code_generator generates the assembly code for arithmetic expressions starting from the right end of the postfix string with an associated vector-generatrice.
EP = postfix string, VG = vector-generatrice, IL = generated instruction lines, NCS = number of elementary units, NIO = number of operands in the current elementary unit, NIB = number of operators in the current elementary unit, CSI = current elementary unit, CSPLUSONE = elementary unit right to the current one, CSMINUSONE = elementary unit left to the current one, I = pointer to the beginning of a 3-tuple in VG, l_i = pointer to the ith 3-tuple currently handled, OPT = symbolic representation of operators (ADD, SUB, MUL, DIV, NEG). OPI = standard representation of operator (+, -, +, /, #) in the operator substring, T.OPD = top element of the stack for CSI, T.OPD = below-the-top element of the stack for CSI, T = symbolic representation of temporary variable;

begin
\[I_i := (NCS - 1) + 1;\]
\[NIO := \text{VG}[\text{I}_i];\]
\[NIB := \text{VG}[\text{I}_i + 1];\]
\[\text{if } \text{NIB} = 0 \text{ then } \text{begin};\]
\[\text{generate_code_line } \text{LDA } T.OPD; \text{goto } \text{exit};\]
\[\text{end};\]
\[\text{else if } NIO = 1 \text{ then } \text{begin};\]
\[\text{L1: begin};\]
\[\text{comment: terminate code generation from an elementary unit CSI and access the next one CSMINUSONE; }\]
\[\text{l}_i := \text{l}_i - 3; \text{NIO} := \text{VG}[\text{l}_i]; \text{NIB} := \text{VG}[\text{l}_i + 1];\]
\[\text{goto } \text{L1};\]
\[\text{end};\]
\[\text{end};\]
```

if $b_i$ is the unary operator ($\#$), or

```
if $b_i$ is binary operator $(+, -, *, /)$, where $BT.OPD$ designates generally the below-the-top element of the stack, and OPT is a symbolic representation of operators (ADD, SUB, MUL, DIV, NEG).

If any of succeeding operators is unary, an NEG is generated. Otherwise, the operator is checked for the commutativity. If it is a commutative one, an instruction line

OPT T.OPD

is generated. The noncommutative operator requires the generation of the code

STA T

with

T.OPD $\leftarrow$ 'T

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in the resumé of each step. When they are extracted from
there, one obtains the following code:

LDA N
DIV I
STA T
LDA I
MUL I
SUB T
STA T
LDA N
ADD I
NEG
NEG
DIV T
DIV I
MUL I
STA T
LDA I
ADD N
SUB T
ADD I

It should be noted that the algorithm is presented in a
descriptive form. Many irrelevant details are dropped in
order to provide a clear and concise presentation of the
basic idea underlying the algorithm. For example, there
is only one temporary variable (T) although there can be
more. Furthermore, the variables NIO and NIB are
introduced for convenience and readability, although
they were not necessary. Each change of NIO implies, in
fact, the change of VG (K + 1) in an elementary unit
pointed to by l or l. The use of pointers l or l is not given
in explicit form. Instead, their strategic use is described
by comments which make an essential part of the
algorithm description. The algorithm provides an
automatic clearing of VG space with the exception of VG
(K + 2) component in each of its 3-tuples. This is of
significance in the algorithm implementation.

As an example, we shall apply the algorithm to VG-
based data structure whose generation is already de-
scribed. Each step in the code generation corresponds to
the current elementary unit. It includes the starting
values of CS, the part of VG for that elementary unit
(indicated by VG, and CS, t = 1, 2, 3, . . . 8), and the
results of operations performed until the current ele-
mental unit is changed. Due to interdependence of ele-
mental units, every item is denoted by a subscript to provide
the identification of the elementary unit to whom an item
belongs. The generated instruction lines are underlined

(1) VG1 = 1 1 22
CS1 = I+
lc = 19
NIO1 = 1
NIB1 = 1
l = 13
lc = 10

(2) VG8 = 1 2 19
CS8 = I*-
NIO8 = 1
NIB8 = 2
l = 16
lc = 13

(3) VG3 = 1 1 17
CS3 = /I
NIO3 = 1
NIB3 = 1
l = 10
LC = D

(4) VG4 = 2 3 12
CS4 = N|J/-
NIO4 = 2
NIB4 = 3
l = 10
LC = D

(5) VG5 = 2 1 9
CS5 = /I*
NIO5 = 2
NIB5 = 1
l = 7
LC = D

(6) VG4 = 0 2 12
CS4 = T/-
NIO4 = 0
NIB4 = 2
l = 10
LC = D
The binary tree and the postfix string with associated vector-generatrice give the code of the same length.

Proof. Let $CS_i$ be given by Eqn (10). It is evident that $CS_i$ can be represented generally as a partial subtree. The partial subtrees are those subtrees which have not all their nodes resolved. This uncompleteness is the consequence of the fact that the relation

$$N_i^0 = N_i^B + 1$$

is not always satisfied. Bearing in mind the procedure for the binary tree derivation, the graph representation of $CS_i$ must form a partial subtree in the binary tree structure. Thus, the code generated from $CS_i$ is of the same length as that obtained from the corresponding partial subtree belonging to the binary tree. If the following relation for $CS_i$

$$N_i^0 \leq N_i^B$$

is valid, then, according to the given algorithm, $CS_{i-1}$ will be taken, causing an instruction line

$$STA T$$

being generated. We can conclude that the choice of the left or right subtree for commutative operators does not influence the length of code obtained for that node. Thus, the fact that the given algorithm always chooses $CS_{i-1}$, i.e. the nearest (minimum number of nodes to be passed) right partial subtree if Eqn (12) is satisfied, will not influence the number of STA and LDA instructions to be generated. Now, we can state the following: (1) number of instruction lines generated for each $CS_i$ is equal to that obtained from the corresponding partial subtree, and (ii) the number of STA and LDA instruction lines generated due to transition from $CS_i$ to $CS_{i-1}$, $CS_{i-1}$ to $CS_{i-2}$, etc., or due to transition from one to another corresponding partial subtree, etc., are equal as long as Eqn (12) is satisfied.

To finish the proof, we shall prove that for

$$N_i^0 > N_i^B$$

one obtains the same length of code as with the binary tree moving to the right in $VG$ space until $N_i^B = 1 \land N_i^B + 2 = 0 \land \ldots \land N_i^B + i = 0 \land N_i^B + i \neq 0$. It is clear that when a $CS_i$ satisfying Eqn (13) is encountered, one or several partial subtrees satisfying Eqn (12) are already handled. These partial subtrees will complete the partial subtree satisfying Eqn (13) to obtain the resulting subtree satisfying Eqn (11). $CS_i$ which satisfies Eqn (13) corresponds to a left subtree in the binary tree. Thus, moving to the right in $VG$ space will not cause any paired instructions $STA$ and $LDA$ to be generated due to transitions. Because we have to generate the code for a node having as its left side a partial subtree and as its right side the leaves, paired instructions $STA$ and $LDA$
will not be generated, with the exception of the surplus of operands in CS, which can be covered by non-commutative operators left over during the handling of previous CS, satisfying Eqn (12). Thus, the code generated from a CS, satisfying Eqn (13) will be of the same length as the code generated from the corresponding partial left subtree and the leaves. This closes the proof.

In fact, the code generator based on the vector-generatrice simulates the code generation from the binary tree with only one exception that at each node the right subtree is firstly handled independently from the commutativity of operators. The consequence of that can be only the different generated code.

**EXPERIMENTAL RESULTS**

An experiment has been performed over a set of arithmetic expressions transformed to postfix strings, binary trees and postfix strings with associated vector-generatrices in order to examine the time performances of algorithms and the difference in length of the generated code. The set of arithmetic expressions is divided in subsets each comprising arithmetic expressions of the same length. The initial length was 6 and the final one 72. The length is varied in increments of 6. The end marker is accounted for in the length. Each subset contained 15 expressions. Furthermore, two additional subsets are taken into consideration: (1) a subset consisting of a single operand (i.e., A$) and (2) a subset consisting of two operands (i.e., A + B$, A*B$, etc). In order to achieve a uniform distribution in length space, these subsets are filled to also contain 15 expressions (length 2 and 4). The time performances are obtained by evaluating the mean values for each subset. Two classes of comparisons are performed: (1) postfix string–binary tree, and (2) binary tree–postfix string with associated vector-generatrice.

Firstly, the performances of postfix string and binary tree are compared. The comparisons are based on parameters $D_L$, $D_T$ and $D_T$ defined in the following way:

\[
D_L = \frac{L_{bt} - L_{ps}}{L_{bt}} \tag{14}
\]
\[
D_T = \frac{\sum \tau(T_{bt} - T_{ps})}{\sum \tau T_{ps}} \tag{15}
\]
\[
D_T = \frac{\sum \tau(T_{bt} - T_{ps})}{\sum \tau T_{bt}} \tag{16}
\]
\[
D_T = \frac{\sum \tau T_{bt} + T_{bt}}{\sum \tau T_{bt} + T_{ps}} \tag{17}
\]

where $m = \text{number of subsets}$,
$L_{ps} = \text{length of code generated from postfix string}$,
$L_{bt} = \text{length of code generated from binary tree}$,
$D_L = \text{relative difference in length of generated code}$,
$T_{ps} = \text{mean time spent to syntax analysis and transformation to postfix string}$,
$T_{bt} = \text{mean time spent to syntax analysis and transformation to binary tree}$,
$D_T = \text{relative difference in time spent to syntax analysis and transformation}$,

$T_{ps} = \text{mean time spent to code generation from postfix string}$,
$D_T = \text{total relative difference in time spent to code generation, syntax analysis and transformation}$.

It was found that $D_L$ was between about 0–0.4. This fact becomes significant in highly repetitive loops with a large number of calculations. The code obtained from the binary tree is shorter because the whole arithmetic expression is in a form which provides the alternatives in particular points during the code generation. There are no such alternatives in the postfix string, which is scanned strictly sequentially, thus eliminating any possibility of economizing in the code generation.

The results obtained for $D_L$, $D_T$ and $D_T$ (0.15, 0.33 and 0.24 respectively) show that these parameters are practically independent for expression length, in a statistical sense, when evaluated separately for each subset ($m = 1$). The memory requirement for transformation to the binary tree was 50% higher and approximately the same for the phase of the code generation.

The second class of comparisons made between the binary tree and postfix string with the associated vector-generatrice represents the key point in the experiment. The results are presented in Table 2.

**Table 2. The results of the comparison of binary tree to postfix string with vector-generatrice**

<table>
<thead>
<tr>
<th>$D_L$</th>
<th>$D_T$</th>
<th>$D_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>0.13</td>
<td>-0.12</td>
</tr>
<tr>
<td>0.21</td>
<td>0.12</td>
<td>~0</td>
</tr>
<tr>
<td>0.12</td>
<td>0.06</td>
<td>0.024</td>
</tr>
</tbody>
</table>

$D_L$, $D_T$ and $D_T$ are defined analogously to Eqns (14), (15), (16) and (17): $D_L = \frac{L_{bt} - L_{ps}}{L_{bt}}$ (18), $D_T = \frac{\sum \tau(T_{bt} - T_{ps})}{\sum \tau T_{ps}}$ (19), $D_T = \frac{\sum \tau(T_{bt} - T_{ps})}{\sum \tau T_{bt}}$ (20), $D_T = \frac{\sum \tau T_{bt} + T_{bt}}{\sum \tau T_{bt} + T_{ps}}$ (21).

It was found also that the parameters $D_T$, $D_T$ and $D_T$ were independent on expressions length ($m = 1$). $D_L$, $D_L$ and $D_T$ are defined as follows:

\[
D_L = \frac{M_{bt} - M_{ps}}{M_{bt}} \tag{22}
\]
\[
D_L = \frac{M_{bt} - M_{ps}}{M_{bt}} \tag{23}
\]
\[
D_L = \frac{M_{bt} + M_{ps}}{M_{bt}} \tag{24}
\]
\[
D_T = \frac{R_{bt} - R_{ps}}{R_{bt}} \tag{25}
\]
\[ D_1 = \frac{(I_a + I_q) - (I_a + I_q)}{I_a + I_q} \]  
\[ D_2 = \frac{I_a - I_q}{I_a} \]  

where \( M_{va} \) = memory space necessary for syntax analysis and transformation to binary tree,  
\( M_{vo} \) = memory space necessary for syntax analysis and transformation to postfix string with associated vector-generatrice,  
\( M_{vb} \) = memory space necessary for code generation from binary tree,  
\( M_{ve} \) = memory space necessary for code generation from vector-generatrice,  
\( I_a \) = number of instruction lines of syntax analyser (binary tree),  
\( I_q \) = number of instruction lines of syntax analyser (vector-generatrice),  
\( I_b \) = number of instruction lines of code generator (binary tree),  
\( I_e \) = number of instruction lines of code generator (vector-generatrice).

The experimental results obtained show a significant decrease of code generation time (21%) when the vector-generatrice is applied. The overall improvement in time domain is reduced to 13% when the syntax analysis is taken into account. Other improvements, expressed through parameters \( D_1 \) and \( D_2 \) are practically negligible. The code obtained from a vector-generatrice when the syntactic analysis is performed over a binary tree, even for very long expressions (in the case when the left subtrees are chosen for commutative operators).

Because VG space is cleared (with the exception of VG \([K + 2]\) after each execution of the code generator, the action routine NULL reduces only to the initialization of variables \( \text{current}_{.} \text{VG \_index}, \text{current}_{.} \text{index}_{.} \text{of} \_\text{output}_{.} \text{string} \) and VG \([3]\).

In order to obtain an efficient code generator, several changes are done over the postfix string: (1) commutativity of operators is indicated by a special character (blank-operator is commutative, S-operator is not commutative); (2) unary operator is indicated by the numeric # (function call could be also considered as a unary operator); (3) each operator is replaced by a symbolic-machine code during the syntax analysis. The same changes are performed over the binary tree structure.

The postfix string in the example gets the following form after performing these changes:

\[ \text{INFIX STRING IS:} \quad (A + B - (-(-B + C))(D \ast E - G(F))/M \ast N + G) \]

The character Z denotes the symbolic address of a temporary variable.

The same code is generated from the binary tree with the following times:

\[ T1 = 3.012 \text{ MSEC} \]
\[ T2 = 1.961 \text{ MSEC} \]
\[ T = 4.973 \text{ MSEC} \]

Besides this general experiment, a subexperiment is performed over two subsets of expressions of length 2 and 4 (single and two operand subsets) with uniform distribution. The same benefit is observed in the domain of the code generation, but the overall time gain (when the syntax analysis is taken into account) is reduced to 8%.

**CONCLUSION**

The right-to-left generator has demonstrated better characteristics than the ones obtained with a binary tree. The length of the code generated from a vector-generatrice is equal to one obtained from binary tree. The compilation time for arithmetic expressions (syntax analysis + code generation) is appreciably shorter. This benefit is more significant for the stand-alone code generator. The total memory space (syntax analyser + code generator) was approximately the same. The memory space required by the syntax analyser, based on the vector-generatrice, was greater but it was balanced by the decrease of the memory requirement for the corresponding code generator. With respect to programming, the code generator based on the vector-generatrice
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was programmed with a smaller number of instruction lines, but not significantly.

It would be interesting to extend the investigations on the application of the vector-generatrice to all operator precedence grammars and especially to the code optimization.

REFERENCES


Received April 1980

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