Static Type Assignment for SSA Form in CTOC

Ki-Tae Kim* and Weon-Hee Yoo*

Abstract: Although the Java bytecode has numerous advantages, it also has certain shortcomings such as its slow execution speed and difficulty of analysis. In order to overcome such disadvantages, a bytecode analysis and optimization must be performed. The control flow of the bytecode should be analyzed; next, information is required regarding where the variables are defined and used to conduct a dataflow analysis and optimization. There may be cases where variables with an identical name contain different values at different locations during execution, according to the value assigned to a given variable in each location. Therefore, in order to statically determine the value and type, the variables must be separated according to allocation. In order to achieve this, variables can be expressed using a static single assignment form. After transformation into a static single assignment form, the type information of each node expressed by each variable and expression must be configured to perform a static analysis and optimization. Based on the basic type information, this paper proposes a method for finding the related equivalent nodes, setting nodes with strong connection components, and efficiently assigning each node type.

Keywords: Bytecode, control flow graph, Static Single Assignment, Static Type Assignment

1. Introduction

Although a bytecode has numerous useful features, it is a stack-based code [1,2]. With a slow execution speed, it has the disadvantage of not being an adequate expression for program analysis or optimization. There is also the problem of a relatively large size of constant pool – which was designed to support dynamic linking in the JVM. Therefore, in order for the Java class file to be effectively executed under an execution environment such as a network, it is necessary to convert it into an optimized code.

A control flow analysis of the bytecode should first be performed for bytecode analysis and optimization [3,4]. After performing a control flow analysis, there is a requirement of which one should be aware, wherein the variables are defined and used in order to perform the data flow analysis and optimization. There may be cases where variables with an identical name contain different values at different locations, according to the value assigned to a variable in each location. Therefore, in order to statically determine the value and type, variables must be separated according to allocation. In order to achieve this, the Static Single Assignment (SSA) Form is used [5]. After transformation into an SSA Form, the information must be configured for each node displaying each variable and expression, in order to perform a static analysis and optimization. This paper describes the process of finding the related nodes and setting a type for each node, based on the basic type of information.

The structure of this paper is as follows. Chapter 2 explains the process of creating a CFG as well as the BNF for expressing the tree within the block; Chapter 3 describes the process of generating the SSA Form; Chapter 4 describes the process of establishing types; Chapter 5 describes the experiment and its results, and, finally, Chapter 6 contains the conclusion as well as suggestions for future research.

2. Control Flow Graph

Fig. 1 displays the example source program used in this paper. The implementations of the CFG, SSA Form and Type settings are presented using this example.

| 1: int f(boolean b){  | 1: int f(boolean); |
| 2: int x;            | Code: |
| 3: x = 1;           | 0: iconst_1   |
| 4: if(b)            | 1: istore_2   |
| 5: x = 2;           | 2: iload_1    |
| 6: else             | 3: ifeq 11    |
| 7: x = 3;           | 4: iconst_2   |
| 8: return x;        | 5: istore_2   |
| 9: }                | 6: goto 13    |

Fig. 1. (a) Source (b) Bytecode

Decompiling Fig. 1(a) using javap -c yields the results displayed in Fig. 1(b). ifeq 11 in Fig. 1(b) is the bytecode command to the branch to where Label 11 is "if equal". 11: is the label indicating the command offset.

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2.1 Basic Block

The Basic Block is created for generating the CFG. The Basic Block consists of commands that do not affect the control flow in the CFG. A label that affects the control flow within the program is found to create the Basic Block. The Basic Block has the form of locating a label that can identify each block in the first statement, and a branch statement is located in the last statement for transferring control to another block. The location where the label is added refers to the lineNumbers array that exists in the .class file. The line number information of the source program that has been in the Line Number Table, as well as information regarding the start location, is recorded within the lineNumbers array. In order to create a block with label information, a new block is created using label information.

The created CFG is written with a directed graph, and each node in the graph consists of a Basic Block. In order to create the CFG efficiently, the entry node, exit node and initial node are added as three basic nodes. The entry node is used to notify the entry point of the graph, and the exit node is used to alert the graph's exit point. The initial node is used to initialize information such as the parameters used in the graph. Each block used in the CFG includes label information.

2.2 Tree-Type Statements

Statements that exist in the block are added in Tree Form. The Tree used for this experiment is called the "expression tree". The expression tree is largely categorized into expressions derived from the Expr class, an abstract class, and into statements derived from the Stmt class, which also represents an abstract class. Fig. 2 displays a part of the BNF that constructs the expression tree.

```
Stmnt -> ExprStmnt | InitStmnt | JumpStmnt | LabelStmnt
LabelStmnt -> Label
InitStmnt -> INIT LocalExp[ ]
ExprStmnt -> eval Expr
JumpStmnt -> goto Block
LabelStmnt -> label Block
ExprStmnt = if ZeroStmnt
  ifZeroStmnt -> i0 ( Expr (== || |) ) (null | 0 )
then Block else Block
ReturnExprStmnt -> return Exp
Block = <block Label>
Label = <label Num>
Expr = ConstantExp | DefExpr | StoreExpr
DefExpr = MemExp
StoreExp -> ( MemExp : Expr )
MemExp -> MemRefExpr | VarExp
VarExp -> LocalExp | StackExp
LocalExp -> ( Stack | Local ) Type Num ( _undef ) Num
ConstantExp -> ID | Num F | Num L | Num
```

Fig. 2. BNF

The derivative classes of Expr and Stmnt are created through the BNF shown in Fig. 2. The difference between the two class types is that the classes derived from Expr contain the val field for maintaining values. Moreover, each Expr has a type field for expressing the type. In this paper, static types are configured for each field. In order to propagate the node type using the type field, Stmt simply expresses the Tree Form.

Fig. 3 displays the created CFG.

```
<block_16 entry>
  label_16
  <block_17 init>
    label_17
    INIT Local_ref0_0 Local_i1_1
    goto label_0
    <block_0>
      label_0
      eval ( Local_ref2_2 := 1 )
      label_2
      i0 ( Local_ref1_UDef == 0 ) then <block_11> else <block_6>
    <block_6>
      label_6
      eval ( Local_ref2_6 := 2 )
      goto label_13
    <block_11>
      label_11
      eval ( Local_ref2_4 := 3 )
      goto label_13
    <block_13>
      label_13
      return Local_ref2_UDef
  <block_18 exit>
    label_18
```

Fig. 3. The created CFG

The CFG in Fig. 3 is created by a total of seven Basic Blocks, and the statements inside the blocks are added in Tree Form. The CFG is used as input in the SSA Form.

3. Implementation of the SSA Form

Generally, in order to statically handle a variable, the variable has to be split according to its definition and type, since a single variable may contain different values or types at different locations according to its definition and use. Therefore, in order to statically determine the value and type, the variable must be split according to its assignment.

3.1 Variable Information and Dominator Tree

In order to execute conversion to the SSA Form, the CFG created earlier must be visited to collect information regarding the variables def and use in the program. To achieve this, the tree created for the corresponding statement for each block in the CFG must be visited in the depth-first to find the variables def and use in each block.

The dominance frontier must be acquired to insert the φ function into the join node of the CFG. The dominator tree must first be created in order to obtain the dominance frontier.
Furthermore, to obtain the dominance frontier, the dominance relationship between the blocks must be known, to which end the index for the current block must be acquired and the search for the immediate dominator of the current block performed.

To find the immediate dominator, the blocks corresponding to the graph nodes are sought to retrieve the pre-order of the current block to the variable $i$. Check if $i$ is currently the root. If not, directly find the dominator. The formula for calculating the dominator is presented in (1). From the dominator of the current block, eliminate what is dominating the current block’s dominator, from which the current block is eliminated.

\[
\text{idom := dom(block) - dom(dom(block)) - block (1)}
\]

### 3.2 Dominance Frontier

After the CFG and the dominator tree have been created, the dominance frontier is calculated by inserting the $\phi$-function. The location of $\phi$-function insertion is called the dominance frontier. If the dominance frontier is denoted as $DF[n]$, it can be expressed by (2).

\[
DF[n] = DF_{local}[n] \cup DF_{opt}[c] \quad (2)
\]

$DF_{local}[n]$ in (2) denotes the set of nodes before $n$ that are not directly dominated by node $n$. $DF_{opt}[c]$ denotes the set of dominance frontier nodes that are not dominated by nodes indirectly dominated by node $n$.

### 3.3 Iterated Dominance Frontier

When the location of insertion for the $\phi$-function is determined through the dominance frontier, the $\phi$-function is inserted. In a structural language, there can be multiple places where $\phi$-functions can be inserted, since in structural language, join nodes are created in specific locations, and the $\phi$-function is generally inserted where the join nodes are located. However, most branches in the Java bytecode consist of conditional if branches and unconditional goto branches that can be expressed simply.

If the definition for the corresponding variable exists in another block but not in the current block, the variable is defined using information in the other block. In order to achieve this, the iterated dominance frontier is recalculated using the dominance frontier value calculated earlier. The dominance frontier acquired from the iteration is the location where the $\phi$-statement is to be inserted.

### 3.4 Rename

This paper expresses the statement with the $\phi$-function inserted as PHIStmt. Rename the two $Local_{ref2}_{UDef}$ variables present in the PHIStmt created. First check whether there is a definition of the corresponding variable $Local_{i2}$ in each block using the CFG and the dominator tree. In the case of $<\text{block 0}>$, the definition of $Local_{ref2}_{2}$ exists. Configure the information regarding the existing variable on the top of the field to signify the top of the stack. From the block corresponding to the top block’s successor, again find the definition for the corresponding block. If the variable’s definition exists, information regarding the new variable is inserted on top of the stack. For $<\text{block 11}>$, the new value of $Local_{ref2}_{4}$ exists on top of the stack. For $<\text{block 13}>$, $Local_{ref2}_{UDef}$, the operand of one of the PHIStmts is from $<\text{block 11}>$. The corresponding variable is renamed as $Local_{ref2}_{4}$ present in the current stack. The result so far indicates $Local_{ref2}_{10} := \Phi (Local_{ref2}_{4}, Local_{ref2}_{UDef})$. The result of renaming for the variables of all blocks is $Local_{ref2}_{10} := \Phi (Local_{ref2}_{4}, Local_{ref2}_{UDef})$. This process establishes a clear name for each variable of the PHIStmt added.

### 3.5 Adding PHIStmt

Add the corresponding statement to the block where PHIStmt is to be inserted. Currently all statements exist in the form of the linked list. Therefore, add PHIStmt which was created after the label statement label_13. Fig. 4 displays the graph after PHIStmt has been added.

---

**Fig. 4. Static Single Assignment Form**

```plaintext
<brack_label_16 entry>
label_16
<brack_label_17 init>
label_17
    INIT Local_{ref0}_0 Local_{i1}_1
    goto label_0
<brack_label_0>
label_0
    eval (Local_{ref2}_{2} := 1)
label_2
    if0 (Local_{ref1}_1 == 0) then <block_11>
    else <block_6>
<brack_label_6>
label_6
    eval (Local_{ref2}_{6} := 2)
    goto label_13
<brack_label_11>
label_11
    eval (Local_{ref2}_{4} := 3)
    goto label_13
<brack_label_13>
label_13
    Local_{i1}_2 := \Phi (Local_{ref2}_{4}, Local_{ref2}_{6})
    return Local_{ref2}_{10}
<brack_label_18 exit>
label_18
```
As displayed in Fig. 4, all blocks and variables within the blocks are assigned new names, according to the definitions and usage of the variables. The modified version number becomes important data for type inference and optimization.

### 4. Type Assignment

As presented in Fig. 4, in the completed SSA Form, all blocks and block variables are assigned new names according to the variables def and use. However, since not all nodes have type information, types must be assigned to those nodes without types using the existing information.

#### 4.1 Finding the Equivalent Node

In order to assign types to nodes whose variables are present, the Basic Blocks of the CFG with the SSA Form must be visited according to the preorder, to find the equivalent nodes. The Basic Block’s statements are constructed in Tree Form. Therefore, after finding the Basic Block, the corresponding tree must be visited in order to examine the nodes constituting each statement, as presented in Fig. 4. In IfStmt of <block_0> if0(Local_ref1_L == 0) then <block_11> else <block_6>, Local_ref1_L is the case of VarExpr. If the corresponding node is VarExpr, then the corresponding expression should be verified to see if it was defined earlier so as to define the expression and find an equivalent node. For the case in Fig. 4, Local1.L of <block_11> is equivalent with Local_ref1_L, the type of which is not defined in <block_0>. Since <block_11> is an initialization node, it has information regarding the format parameters. Therefore, rather than ref signifying that the type is yet to be determined, it has i signifying the integer type. The algorithm for obtaining an equivalent node is presented in Algorithm 1.

**Algorithm 1. equivalent node**

**Input**: node1, node2 ∈ Node  
**Output**: equiv ∈ HashMap  
**procedure** makeEquiv(node1, node2)  
**begin**  
  s1 ← equivalent(node1);  
  s2 ← equivalent(node2);  
  if s1 != s2 do  
    s1.addAll(s2);  
    iter ← s2.iterator();  
    while iter.hasNext() do  
      n ← iter.next();  
      equiv.put(n, s1);  
  endwhile  
  fi  
**end**

In Algorithm 1, equiv is assigned as HashMap. According to the algorithm, equiv of VarExpr becomes {Local_ref1_L = [Local_ref1.L, Local1.L], Local1.L = [Local_ref1.L, Local1.L]}]. In other words, Local_ref1_L and Local1.L are the equivalent nodes and are assigned identical types in the future.

Table 1 displays the entire equiv for the equivalent nodes created according to Algorithm 1.

**Table 1. Information of the equivalent nodes**

<table>
<thead>
<tr>
<th>Node</th>
<th>Equivalent Node</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[2, Local_ref2_6, (Local_ref2_6 := 2), Local_ref2_6]</td>
<td>int</td>
</tr>
<tr>
<td>1</td>
<td>[Local_ref2_10, Local_ref2_10, Local_ref2_10 := Phi(label_6 =Local_ref2_6, label_11=Local_ref2_4)]</td>
<td>var</td>
</tr>
<tr>
<td>2</td>
<td>[2, Local_ref2_6, (Local_ref2_6 := 2), Local_ref2_6]</td>
<td>int</td>
</tr>
<tr>
<td>3</td>
<td>[Local_ref1_1, Local1_1]</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>[Local_ref2_6, (Local_ref2_6 := 2), Local_ref2_6]</td>
<td>int</td>
</tr>
<tr>
<td>5</td>
<td>[Local_ref2_4, (Local_ref2_4 := 3), 3, Local_ref2_4]</td>
<td>int</td>
</tr>
<tr>
<td>6</td>
<td>[Local_ref1_1, Local1_1]</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>[Local_ref2_10, Local_ref2_10, Local_ref2_10 := Phi(label_6 =Local_ref2_6, label_11=Local_ref2_4)]</td>
<td>var</td>
</tr>
<tr>
<td>8</td>
<td>[Local_ref2_4, (Local_ref2_4 := 3), 3, Local_ref2_4]</td>
<td>int</td>
</tr>
<tr>
<td>9</td>
<td>[Local_ref2_6, (Local_ref2_6 := 2), Local_ref2_6]</td>
<td>int</td>
</tr>
<tr>
<td>10</td>
<td>[Local_ref2_4, (Local_ref2_4 := 3), 3, Local_ref2_4]</td>
<td>int</td>
</tr>
<tr>
<td>11</td>
<td>[2, Local_ref2_6, (Local_ref2_6 := 2), Local_ref2_6]</td>
<td>int</td>
</tr>
<tr>
<td>12</td>
<td>[Local_ref2_4, (Local_ref2_4 := 3), 3, Local_ref2_4]</td>
<td>int</td>
</tr>
</tbody>
</table>

The locations where equivalent nodes can be created are trees with nodes having variables or constants. As presented in Fig. 2, these nodes can be created in VarExpr, PhiStmt, and StoreExpr, which include the ExprStmt, IfZeroStmt, PhiJoinStmt, ReturnExprStmt statements in the BNF. The reason for equivalent 1: and 3: being created is to prevent redundant creation, since equivalent nodes can exist in other blocks.

#### 4.2 Assigning a Number to Each Node

After finding the equivalent nodes through the SSA Form, a number is assigned to each node. When setting types, there can be several nodes of the same type, and a number is to be assigned to each node to distinguish the nodes. Based on the TreeVisitor class, all trees of the Basic Blocks are visited depth-first, and the count field value is assigned to each node. For Fig. 4, the entire node is 31. In other words, the tree consists of 31 nodes in total.

#### 4.3 Type Settings

Set a type in an appropriate location. In Fig. 4, examine the statement in <block_11>: ExprStmt : eval (Local_ref2_4 := 3) {15}. {15} denotes the node number, which is the count value. The ExprStmt structure is displayed in Fig. 5.
Fig. 5. ExprStmt

First insert the node currently being visited into the stack. Then find a node equivalent to the current node of ExprStmt. At this point, only the node is the equivalent node. If there is a child node, visit this node to find a node equivalent to the child node. According to Fig. 5, the next child node visited is StoreExpr. If an equivalent node equiv is found with StoreExpr : (LocalRef2_4 := 3){14}, it will be similar to 6: in Table 1. Therefore, an equivalent node of ConstantExpr : 3{12}, StoreExpr : (LocalRef2_4 := 3){14}, LocalExpr : LocalRef2_4[25]. LocalExpr : LocalRef2_4[13] can be obtained. There are two cases of the equivalent type LocalExpr. Since these are different nodes, they are distinguished by attaching an index to the count field value calculated earlier.

The strong connection component, which has the form of the array list, must be obtained in order to configure the type. If the stack is not empty, remove the node located on top of the stack, acquire a node equivalent to the eliminated node, and add it to the strongly connected node. In the example above, since StoreExpr : (LocalRef2_4 := 3){14} existed on the current stack, the corresponding node is eliminated from the stack, and LocalRef2_4, LocalRef2_4 := 3, LocalRef2_4, which is an equivalent node to the eliminated node, is added to the strongly connection component. Then, each node that corresponds to each component is visited to set the type. ConstantExpr, VarExpr, StoreExpr, and PhiStmt are nodes that can be assigned a type, as shown in Fig. 2. For example, if the strongly connection component currently visited is ConstantExpr : 3{12}, the value of the expression is first retrieved to the value field. In terms of a constant, a value can be a character or a number. Therefore, they must be processed differently according to the circumstances. The instanceof operator is used to verify which kind of constant it is. In the case where the value of the instanceof Integer is true, the value type is an integer. Consequently, the type can be determined from the value. Once the type has been assigned to the current strongly connection component, the remaining components will also be assigned with types. Therefore, the process of configuring integer types to all of the strongly connection components [LocalRef2_4, LocalRef2_4 := 3], 3, LocalRef2_4 is performed. Similarly, node types can be assigned to the remaining nodes. Fig. 6 displays the final static single assignment form graph with all types assigned.

Fig. 6. Typed Static Single Assignment Form

In Fig. 6, [Type] : type(LocalRef0_0) = LTemp indicates the class type located in the 0th position of the local variable. Since the Java virtual machine expresses the object type as L, this paper also expressed the object type in the form of LTemp as LocalRef0_0. [Type] : type(LocalRef1_0) = Z indicates that the first type of the first local variable is of the boolean type, denoted as Z in the JVM. [Type] : type3 = 1 signifies that node 3 is of the integer type. In turn, types are statically assigned to all documents and nodes.

5. Experiment and Results

The experiment was conducted using a Pentium 4 2.4 GHz processor, with 512MB of RAM, Eclipse 3.1 was used for writing and testing CTOC, Editisplus 2.11 was used to print the bytecode, and a Java compiler j2sdk1.4.2.03 was used.
We analyzed 6 case examples that could be used to compare the control flow. These data—which appeared in Don Lance's paper—are used to compare the experiment results [6]. In Table 1, simple explanations of the program that we used are presented.

### Table 1. Examples

<table>
<thead>
<tr>
<th>Program</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SquareRoot</td>
<td>Finding the square root</td>
</tr>
<tr>
<td>SumOfSquareRoot</td>
<td>Finding the sum of the square root of a number. That is from 1 to n</td>
</tr>
<tr>
<td>Fibonacci</td>
<td>Finding fibonacci number n.</td>
</tr>
<tr>
<td>QuickSort</td>
<td>Sorting the Integer array using Quicksort</td>
</tr>
<tr>
<td>LabelExample</td>
<td>Labeled break and continue program</td>
</tr>
<tr>
<td>Exceptional</td>
<td>Exception handling of try-catch-finally</td>
</tr>
</tbody>
</table>

Experiment items using the example of Table 1 include the number of lines of each program's source code, the number of bytecode lines, the number of lines after transforming the code, the number of basic blocks, the number of edges, and the total number of nodes.

### Table 2. Results of Experiment

<table>
<thead>
<tr>
<th>Program</th>
<th>source</th>
<th>bytecode</th>
<th>after trans</th>
<th>basic blocks</th>
<th>edges</th>
<th>nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SquareRoot</td>
<td>37</td>
<td>94</td>
<td>60</td>
<td>15</td>
<td>18</td>
<td>99</td>
</tr>
<tr>
<td>SumOfSquareRoot</td>
<td>38</td>
<td>103</td>
<td>63</td>
<td>18</td>
<td>19</td>
<td>108</td>
</tr>
<tr>
<td>Fibonacci</td>
<td>42</td>
<td>76</td>
<td>69</td>
<td>18</td>
<td>22</td>
<td>86</td>
</tr>
<tr>
<td>QuickSort</td>
<td>30</td>
<td>79</td>
<td>68</td>
<td>16</td>
<td>21</td>
<td>101</td>
</tr>
<tr>
<td>LabelExample</td>
<td>28</td>
<td>51</td>
<td>59</td>
<td>13</td>
<td>16</td>
<td>58</td>
</tr>
<tr>
<td>Exceptional</td>
<td>41</td>
<td>99</td>
<td>149</td>
<td>26</td>
<td>29</td>
<td>143</td>
</tr>
</tbody>
</table>

In Table 2, **source** represents the number of lines of the source code, **bytecode** represents the number of lines of the bytecode generated by javap. **after trans** represents the number of code lines that are added and eliminated in transforming the original code to the basic block in CTAC. **basic block** represents the number of basic blocks generated by the leader for the transformed code and the basic block. **edge** represents the number of edges that show a relationship among the basic blocks. **node** represents the number of nodes used to identify instructions and statements in a basic block.

In Table 3, we can see that the number of lines and the number of nodes increase after conversion into the SSA Form.

### Table 3. SSA Form results

<table>
<thead>
<tr>
<th>Program</th>
<th>CFG lines</th>
<th>SSA lines</th>
<th>%</th>
<th>CFG nodes</th>
<th>SSA nodes</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SquareRoot</td>
<td>60</td>
<td>63</td>
<td>4.76%</td>
<td>99</td>
<td>117</td>
<td>15.38%</td>
</tr>
<tr>
<td>SumOfSquareRoot</td>
<td>63</td>
<td>71</td>
<td>11.27%</td>
<td>108</td>
<td>143</td>
<td>24.48%</td>
</tr>
<tr>
<td>Fibonacci</td>
<td>69</td>
<td>77</td>
<td>10.39%</td>
<td>86</td>
<td>126</td>
<td>31.75%</td>
</tr>
<tr>
<td>QuickSort</td>
<td>68</td>
<td>76</td>
<td>10.53%</td>
<td>101</td>
<td>133</td>
<td>24.06%</td>
</tr>
<tr>
<td>LabelExample</td>
<td>59</td>
<td>63</td>
<td>6.35%</td>
<td>58</td>
<td>74</td>
<td>21.62%</td>
</tr>
<tr>
<td>Exceptional</td>
<td>147</td>
<td>177</td>
<td>15.82%</td>
<td>143</td>
<td>304</td>
<td>52.96%</td>
</tr>
</tbody>
</table>

In Table 4, **Basic block** means the number of basic blocks created in the SSA Form, and **Statements** means the number of statements used in the SSA Graph. **Type** shows each node at process that static type assignment is achieved however many type decisions happen. For example, the SquareRoot program is divided into a basic block of 15, including 42 statements in tree form, and 75 type decisions occur after SSA Form conversion.

### Table 4. Example of Experiment

<table>
<thead>
<tr>
<th>Program</th>
<th>Basic block</th>
<th>Statements</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SquareRoot</td>
<td>15</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>SumOfSquareRoot</td>
<td>18</td>
<td>47</td>
<td>83</td>
</tr>
<tr>
<td>Fibonacci</td>
<td>16</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>QuickSort</td>
<td>16</td>
<td>82</td>
<td>125</td>
</tr>
<tr>
<td>LabelExample</td>
<td>13</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Exceptional</td>
<td>26</td>
<td>89</td>
<td>107</td>
</tr>
</tbody>
</table>

In Table 4, Basic block means the number of basic blocks created in the SSA Form, and Statements means the number of statements used in the SSA Graph. Type shows each node at process that static type assignment is achieved however many type decisions happen. For example, the SquareRoot program is divided into a basic block of 15, including 42 statements in tree form, and 75 type decisions occur after SSA Form conversion.

### 6. Conclusion

The Java bytecode has recently been used as a means of intermediary expression in various fields. However, the disadvantages of a slow execution speed and difficulty in performing analysis exist. Therefore, optimization and program analysis are required to expedite the execution speed and enhance program understanding.

This paper involves the analysis of programs from the bytecode level and preparation for optimization. In order to perform analysis and optimization at the bytecode level, the CFG was first created. However, due to the bytecode characteristics, the existing control-flow analysis techniques were expanded to suit the bytecode. Furthermore, in order to perform a static analysis, the CFG was converted into the SSA form. For conversion into the SSA Form, a considerable level of calculation was carried out regarding the CFG, dominance relationship, dominator tree, immediate dominator, $\phi$-function, rename and dominance frontier.

After conversion into the SSA form, the equivalent nodes were obtained and found, and then configured as strong connection components, and an identical type was assigned to each node. The SSA Form with the type assigned acts as an adequate input to the optimization process to be performed in later stages.

### References


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