Static and Dynamic JVM Operand Stack Visualization And Verification

Sergej Alekseev, Andreas Karoly, Duc Thanh Nguyen and Sebastian Reschke

Abstract—**The bytecode verification is an important task of the Java architecture that the JVM specification suggests. This paper presents graph theoretical algorithms and their implementation for the data flow analysis of Java bytecode. The algorithms mainly address the extended static visualization and verification of the JVMs operand stack to allow a deeper understanding in bytecode behavior. Compared to the well known algorithms, the focus of our approach is the visualization of the operand stack and a graph theoretical extension of the verification algorithms. Additionally we present a method for dynamic operand stack visualization and verification.**

We also show some experimental results to illustrate the effectiveness of our algorithms. All presented algorithms in this paper have been implemented in the Dr. Garbage tool suite. The Dr. Garbage project resulted from research work at the University of Oldenburg and is now further maintained at the University of Applied Sciences Frankfurt am Main. The tool suite is available for download under the Apache Open Source license.

Index Terms—**java virtual machine, operand stack, verification, visualization, data flow analysis.**

I. INTRODUCTION

THE computational model of the Java Virtual Machine (JVM) corresponds to a stack machine [4]. Some other programming languages are also based on the computer model of a stack machine, for example *Forth* [6] and *PostScript* [5]. The algorithms and approaches presented in this paper are applicable to any stack based language, although we present our algorithms based on the JVM.

All bytecode instructions of the JVM take operands from the stack, operate on them and return results to the stack. Each method in a java class file has a stack frame. Each frame contains a last-in-first-out (LIFO) stack known as its operand stack [2, The Java® Virtual Machine Specification]. The stack frame of a method in the JVM holds the method's local variables and the method's operand stack. Although the sizes of the local variables get predetermined at the start of the method and always stay constant, the size of the operand stack dynamically changes as the method's bytecode instructions are executed. The maximum depth of a frame's operand stack is determined at compile-time and is supplied along with the code for the method associated with the frame. Additionally, if a class is loaded by the JVM, the JVM verifies its content and makes sure there is no over- or underflow of the operand stack. But neither the Java compiler nor the JVM verifier perform a deep content analysis of the operand stack because such analyses are very time consuming and usually unnecessary, because the Java compiler generates reliable bytecode. Nevertheless, there are many tools that modify bytecode at runtime or generate it from different sources other than Java. In such cases, a more precise and detailed analysis of the operand stack is needed to localize potential runtime errors. The operand stack errors are very hard to track and most of them do not arise until many bytecode instructions have already been executed.

In this paper we present graph theoretical algorithms for extended static verification and visualization of the operand stack. The algorithm *ASSIGN_OPSTACK_STATES* (section III-A) computes all possible contents of a method's operand stack. The following sections describe possible methods of analysis (size, type and content based) which can be performed on the calculated operand stack contents.

Section III-E describes a *LOOP_ANALYSIS* algorithm to handle the operand stacks of methods which contain cycles.

In section IV we propose a graph theoretical transformation algorithm to represent the operand stack structure and define a very simple grammar which includes the mathematical and logical operations in java similar syntax to visualize the contents and conditions of operand stacks based on the operand stack computation algorithm in section III-A.

The section V presents an approach for the dynamic operand stack visualization and verification.

All presented algorithms have been implemented in the context of the Dr. Garbage tool suite project [8] and we present some experimental results in section VI which can be obtained from the Dr. Garbage tool suite project [8].

Furthermore, these algorithms are suitable as an extension of the Java compiler and JVM verifier.

II. RELATED WORK

Klein and Wildmoser explain improvements of Java bytecode verification in their papers [14, Verified lightweight bytecode verification], [16, Verified Bytecode Subroutines] and [15, Verified bytecode verifiers]. There the purpose of a verifier for bytecode regarding the Java operand stack and the possible misbehaviour like underflow and overflow are mentioned. The operand stack is shown as an array of types (e.g. int) per bytecode instruction. The described verification includes the type checking of operand stack entries. Stephen N. Freund and John C. Mitchell present in their paper [13, A Type System for the Java Bytecode Language and Verifier] a specification in the form of a type system for a subset of the bytecode language. And they developed a type checking algorithm and prototype bytecode verifier implementation.

The approach of Klein and Wildmoser, as well as the approach of Freund and Mitchell are partially related to our algorithm for the type based analysis in section III-C. But in addition to these algorithms we present a graph theoretical extension of the type based analysis.

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Some other papers that deal with this subject are [19, Simple verification technique for complex Java bytecode subroutine], [20, Java and the Java Virtual Machine - Definition, Verification, Validation], [21, A type system for Java bytecode subroutines] and [22, Subroutines and java bytecode verification].

Eva Rose deals in her paper [17, Lightweight Bytecode Verification] with the verification algorithms on embedded computing devices. Xavier Leroy's papers [11, Java bytecode verification: an overview] and [12, Java bytecode verification: algorithms and formalizations] review the various bytecode verification algorithms for crucial security Java components on the Web. The application field of our algorithm is not limited, but in view of the memory consumption (section III-A Algorithm) our approach in its pure form is not suitable for using on embedded devices.

In the paper [18, Analyzing Stack Flows to Compare Java Programs] of Lim and Han the Java operand stack is used by algorithms to identify clones of Java programs. They describe how the JVM specification defines the operand stack before and after each bytecode of a Java program. For visualization of the stack an array of dots with one dot per entry of the operand stack is used. Our approach provides a more versatile form of the operand stack representation.

III. Static operand stack analysis

An essential idea behind the static operand stack analysis is to identify a set of potential control flow paths in a method, to calculate all possible operand stack states by interpreting the bytecode instructions for each path and to identify inconsistencies of the operand stack by comparing these states.

In the next subsection a graph theoretical algorithm is presented which traverses all control flow paths of a method and assigns the calculated operand stack states to each bytecode instruction in each control flow path.

The control flow path analysis is based on a control flow graph (CFG) of a method. The CFG is defined as a tuple $G = (V, A)$, where V is a nonempty set of *vertices* representing bytecode instructions of a method, A is a (possibly empty) set of *arcs* (or edges) representing transitions between the bytecode instructions. Formally, A is the finite set of ordered pairs of vertices (a, b), where $a, b \in V$.

As a CFG containing loops has unlimited numbers of potential paths, the CFG has to be transformed into a directed acyclic graph (DAG) with a limited number of paths by removing loop backedges (as identified by a depth-first search of the CFG). The number of operand stack states in each acyclic path always equals the number of vertices (or number of corresponding bytecode instructions) in this path.

The subsections III-B, III-C and III-D present techniques for a static operand stack analysis in acyclic graphs based on the operand stack size, type of stack variables and operand stack content. The subsection III-E extends operand stack analysis to arbitrary control flow graphs that contain cycles.

A. Algorithm for assigning stack states to vertices in a DAG

The algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 identifies all possible control flow paths by visiting vertices of the DAG in topological order. This order ensures that all the predecessors of a vertex v are visited before v itself.

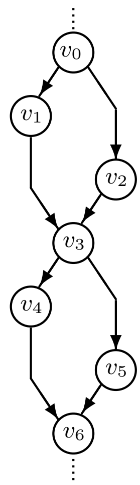
```
/* G is a directed acyclic graph G = (V, E)          */
ASSIGN_OPSTACK_STATES (G)
1   for (each vertex v ∈ V in topological order ){
2       S[] = NULL;
3       for (all incoming edges l of v ){
4           v' = otherend(l, v);
5           S = S ∪ v'.stack;
6       }
7       for (each stack state s ∈ S ){
8           updateStack(s, v);
9       }
10      v.stack = S;
11  }
```

Fig. 1. Algorithm for assigning stack states to vertices in a DAG

The algorithm calculates a list of all possible operand stack states for the current vertex v (fig. 1: lines 2-6) by iterating all the predecessors of the vertex v and building the set of stack states S as a disjunct union of all predecessors operand stack lists.

All stack states of the list S are updated by pop or push operations corresponding to the byte code instruction of the vertex v (fig. 1: lines 7-9).

After execution of the algorithm a list of all possible operand stack states is assigned to each vertex of the DAG.



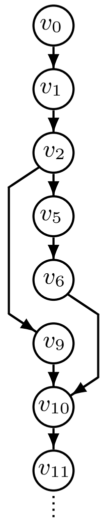
Stack operation	Stack states
-	-
push a;	a
push b;	b
-	a | b
push c;	a, c | b, c
push d;	a, d | b, d
-	a, c | a, d | b, c | b, d

Fig. 2. CFG with operand stack states computed by the algorithm.

Theorem 3.1: (Operand Stack Algorithm) Given a directed acyclic graph $G = (V, E)$, after the algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 visits a vertex $v \in V$, the property variable $stack$ of v contains a list of all possible operand stack states in the vertex v.

Proof: By induction on the depth of a vertex $v \in V$ and paths from the $START$ vertex to v.

Base Case: v depth is 0 ($v = START$). The theorem is trivially satisfied.



Bytecode	Stack size	List of variable types	List of variables on the stack
0 iload_1;	1	I	a
1 iload_2;	2	I,I	a, b
2 if_icmple 7;	0	–	–
5 iload_1;	1	I	a
6 goto 4;	1	I	a
9 iload_2;	1	I	b
10 iconst_2;	2	I,I	a, 2	b, 2
11 invokestatic 16;	0	–	–

Fig. 3. CFG, corresponding bytecode and the operand stack representation.

Induction Step: The list of all possible operand stack states S for the vertex v with $d > 0$ is calculated by updating all elements of the list $S = \{\forall s \in S | update(s)\}$ (lines 7-9). The list S is a set of all operand stack states of all immediate predecessors $v_0 ... v_n$ of v with the depth $d - 1$, so $\bigcup_{i=0}^{n} v_i.stack$ (lines 3-5). By induction hypothesis, each path section from the $START$ to v_i must be visited and all operand stack states are assigned to the property variable $v_i.stack$.

All successors $v_0 ... v_n$ of v must have a depth greater than d, because the graph is a DAG. So the theorem holds for all $v \in V$ with depth $d > 0$. ■

Fig. 2 illustrates how the algorithm operates on the example CFG. The vertices in this example are labeled in topological order. The following control paths exist:

- $p_1 = \{..., v_0, v_1, v_3, v_4, v_6, ...\}$
- $p_2 = \{..., v_0, v_1, v_3, v_5, v_6, ...\}$
- $p_3 = \{..., v_0, v_2, v_3, v_4, v_6, ...\}$
- $p_4 = \{..., v_0, v_2, v_3, v_5, v_6, ...\}$

In path p_1 the vertex v_1 pushes the variable a and the vertex v_4 pushes the variable c onto the stack. The operand stack states can be assigned to each vertex of path p_1 as follows: $p_1 = \{..., v_0(-), v_1(a), v_3(a), v_4(a, c), v_6(a, c), ...\}$. According to these steps, the stack states in all paths can be calculated and assigned to the vertices in the DAG. But this procedure is not efficiently in terms of runtime complexity. To calculate all possible stack states in each vertex of a DAG it is not necessary to traverse each control path separately. Instead our algorithm calculates the stack states step by step for all paths by visiting the vertices of a DAG in topological order.

Generally, the runtime complexity of a topological search algorithm for the given directed acyclic graph G with n vertices and m arcs can be found in $O(n + m)$ (see [9] or [10]). The memory allocation complexity to store all possible operand stack combinations in our algorithm grows exponentially. As you can see from the example in fig. 2 the number of combinations N depends on the number of sequential branches in the DAG and equals the multiplication of the number of branches in each branch. In this case:

$$N = 2 \times 2 = 4 \tag{1}$$

So the complexity of the memory allocation can be calculated as $O(n^n)$. To solve this problem a pragmatic approach is used in our implementation. We define the maximum number of combinations which have to be calculated by the algorithm to limit the memory allocation. The number of maximum combinations is variable and can be redefined for each operand stack.

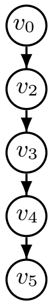
The algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 can be easily adapted to calculate the stack depth (used for size based analysis) and the list of variable types (used for type based analysis) in each node. Instead of the operand stack state combinations, a single value is stored in the property variable $stack$ of each vertex. In this case, both the runtime $O(n + m)$ and the memory allocation $O(n)$ have linear complexity. An example of the operand stack representation is illustrated in the fig. 3.

B. Size based operand stack analysis

A size based analysis can be achieved by simply altering the algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 to calculate the operand stack depth value and store it in the property variable for each vertex in the corresponding CFG. By trivial comparison of the operand stack depth values assigned to the CFG's vertices, the following types of inconsistencies can be determined:

- **Stack over or underflow:** The max operand stack size is calculated as the algorithm visits the vertices of the corresponding CFG in topological order. By comparing the calculated max size with the max stack size, stored in the class file, over- or underflow stack errors can be determined. The overflow verification is generally available in the JVM as specified in [2, The Java® Virtual Machine Specification]. Our approach also allows to determine the bytecode addresses of the instructions which cause the stack overflow.
- **Leaving objects on stack:**

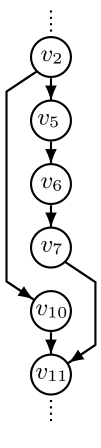
The stack size of each end vertex (e.g. return byte instruction) in the CFG is verified. Herewith is determined if any objects remain on the stack. By the reference to the bytecode instructions of the remained objects a warning is generated about possibly unused bytecode instructions (instructions which push these objects onto the stack).
In fig. 4 one of the three instructions, that pushes an integer value on the stack is obsolete. After the last instruction, the stack should be empty but in the example one unused integer value is left on the stack.



Bytecode	Stack size
0 iload_1;	1
1 iload_2;	2
3 iconst_1;	3
4 iadd;	2
5 ireturn;	1

Fig. 4. Unused objects left on stack

- **Asymmetrical operand stack sizes:** An error in one branch of the CFG could lead to asymmetrical operand stack sizes on the incoming edges of a vertex as illustrated in fig. 5. A simple backtrace algorithm to find unused instructions, is applied in our implementation. A more complex analysis algorithm and a backtrace implementation is planned for the future.



Bytecode	Stack size
2 if_icmple 7;	0
5 iload_1;	1
6 iconst_1;	2
7 goto 4;	2
10 iload_2;	1
11 iconst_2;	2 | 3

Fig. 5. Asymmetrical operand stack size inconsistency

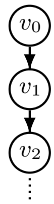
The runtime complexity for this analysis is in $O(n+m)$ and the memory allocation complexity is in $O(n)$, where n is the number of vertices and m number of arcs in the CFG.

C. Type based operand stack analysis

According to the Java® Virtual Machine Specification [2] the JVM supports the operand stack type verification in general. Gerwin Klein and Tobias Nipkow formalize and describe algorithms for an iterative data flow analysis that statically predicts the types of values on the operand stack and in the register set [16], [14], [15] as mentioned in section II. In this section we present a graph-theoretical approach in addition to the well known verification techniques.

A type based analysis is realized by adaptation of the algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 to calculate a list of variable types on the stack and store it in the property variable for each vertex in the corresponding CFG. By comparison of the values assigned to the CFG's vertices the following types of inconsistencies can be determined:

- **Expected type:** To ensure proper code execution at runtime, all operands on the stack have to be type correct in terms of what operand type the bytecode instruction expects. For example an `istore` instruction can not handle a `float` operand. Another example, as visualized in fig. 6 an `iadd` instruction can not operate on `integer` and `double` operands on the stack.



Bytecode	Stack size
0 iload_1;	1
1 dload_2;	2
2 iadd;	ERROR

Fig. 6. Wrong type for instruction

- **Asymmetrical type lists:** The types of operands on a stack can differ on the incoming edges of a vertex. The backtrace algorithm allows to reference the bytecode instructions which pushed operands with different types onto the stack.

The runtime complexity for this analysis is in $O(n+m)$ and the memory allocation complexity is in $O(n)$, where n is the number of vertices and m number of arcs in the CFG.

D. Content based operand stack analysis

The algorithm *ASSIGN_OPSTACK_STATES* in fig. 1 calculates a list of variables on the stack for each bytecode instruction and stores it in the property variable of the vertex in the corresponding CFG. In a certain vertex several variable combinations on the stack are possible.

This analysis allows to figure out unnecessary branches in the bytecode. The bytecode example in fig. 7 contains an if-branch. The bytecode instructions (offset `5` and `9`) in both branches push the same variable `b` onto the stack. A backtrace algorithm prints the bytecode addresses of instructions which lead to the duplicated operand stack states.

This kind of analysis is related to compiler optimization techniques, but in our approach the operand stack analysis is used to localize unused instructions. Our approach is partially comparable to the method of Lim and Han described in their paper [18, Analyzing Stack Flows to Compare Java Programs]. Although the goal of their paper is to identify clones of Java programs, the approach is absolutely different.

The runtime complexity for this analysis is in $O(n+m)$, where n is the number of vertices and m number of arcs in the CFG. The memory allocation complexity is in $O(n^n)$ as mentioned in the section III-A.

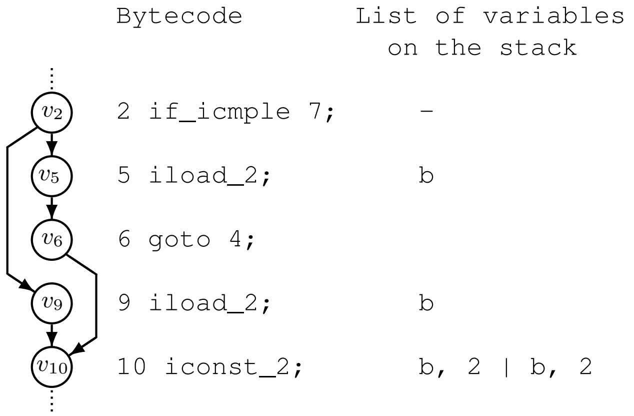


Fig. 7. Operand Stack with the same content in two branches

E. Loop based operand stack analysis

This section extends the analysis algorithms to arbitrary control flow graphs that can contain cycles. The algorithm fig. 1 in section III-A only works for acyclic paths, which correspond to back edge free paths. The main idea of the loop based analysis is that the operand stack states before entering and after leaving a loop have to be equal. Otherwise, each iteration of the loop would push objects onto the stack or pop them from the stack and the state of the stack would be undefined.

A depth-first search algorithm identifies a set of back edges $B \subset E$ in a graph $G = (V, E)$, that contains cycles. The graph G is transformed into a directed acyclic graph (DAG) by removing the back edges $D = (V, E')$, where $E' = E \backslash B$. Each back edge $b \in B$ lies on a loop.

Theorem 3.2: (Loop Analysis Algorithm) The operand stack of a method represented by a control flow graph G that contains cycles is consistent if:

1) Size based analysis (section III-B) and type based analysis (section III-C) have been performed without any error on the directed acyclic graph D transformed from the graph G.
2) and for each back edge $b \in B$ with the start vertex $v_s \in V$ and the end vertex $v_e \in V$: the operand stack state assigned to the start vertex v_s and the states assigned to the start vertices $v_0, ...v_n$ of all incoming edges of the end vertex v_e are equal in size and type.

Proof: The point 1 of the theorem does not need to be proofed, because in case of any errors the stack is inconsistent. The point 2 can be proofed by the contradiction of the operand stack states.

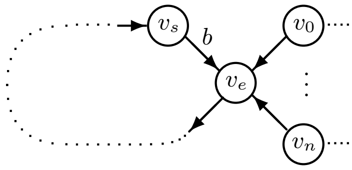


Fig. 8. Loop based analysis

Let us consider the directed acyclic graph D produced by removing the back edges and the set of back edges B. For each $b \in B$ holds:

- Each back edge $b \in B$ lies on one loop.
- There are possibly several forward paths $v_e \to ... \to v_s \to v_e$ in the loop.

Each forward path must have the same operand stack state in the last vertex, because all paths are acyclic and they pass the back edge b. All acyclic paths have already been verified by the point 1 of the theorem.

The back edge b is a single back edge of the vertex v_s, because all other edges are outside the loop and must belong to the DAG. So all states of other incoming edges have been already verified by the point 1 of the theorem.

If the state of the vertex v_e would not be equal to the states of vertices $v_0...v_n$ then the stack would be inconsistent. ■

The following algorithm for the loop based analysis is derived from the theorem 3.2. The algorithm executes the operand stack comparison for all back edges $b \in B$ identified in the previous step of the analysis. The runtime complexity for this analysis is in $O(n + m)$ where n is the number of vertices and m number of arcs in the CFG.

/* $D = (V, E')$ is a directed acyclic graph. B is a */
/* set of back edges, $B \nsubseteq E'$. The back edge $b \in B$, */
/* $b = \{v_s, v_e\}$, where $v_s, v_e \in V$. */
LOOP_ANALYSIS (D, B)
for (each back edge $b \in B$){
    for (all incoming edges l of v_e){
        $v = otherend(l, v_e)$;
        if($v.stack \neq v_s.stack$) {
            print *ERROR*;
} } }

Fig. 9. Loop based analysis algorithm

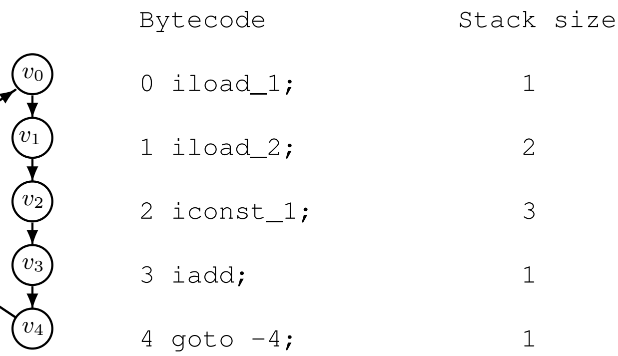


Fig. 10. Loop based analysis example

Fig. 10 shows an example where the loop based analysis tracks down the error in the loop in which a new `integer` stays on the stack after each loop execution.

IV. Visualization of the Operand Stack

The simplest way to visualize the operand stack is to calculate the state of the operand stack in each instruction of a method and display the complete list of instructions with corresponding states. The calculation of the operand stack states is performed by the algorithm *ASSIGN_OPSTACK_STATES* in section III-A fig. 1. The simple representation of the operand stack is shown in fig. 3, section III-A. To make the operand stack content more comprehensible we have defined a grammar (see appendix A) which includes variable types and names, logical combination and arithmetical operations and developed an algorithm to transform the control flow graph of a method to a tree representation.

```
/* G is a control flow graph, G = (V, E).                */
TRANSFORM_GRAPH (G)
1  G_b = createBasicBlockGraph(G);
2  removeBackEdges(G_b);
3  T = createTree();          /* T is an empty tree. */
4  for (all start basic blocks B ∈ V_b)
5      CREATE_TREE(B, T);
6  };

CREATE_TREE (B, T)
1  add a new tree node n for B to T;
2  for ( all vertices v ∈ B ){
3      add v as child of n to the tree T;
4  }
5  for (all outgoing args l of B ){
6      CREATE_TREE(otherend(l, B), T);
7  }
```

Fig. 11. Transformation algorithm for the operand stack representation

The algorithm *TRANSFORM_GRAPH* in fig. 11 creates a basic block graph G_b for the given control flow graph G (line 1), removes the back edges in G_b (line 2) and starts a *Depth First Search* from each start basic block B, where $indegree(B) = 0$ (line 4). For each basic block B a new tree node n is created (Routine *CREATE_TREE: line 1*) and all vertices of a basic block B (each vertex represents a bytecode instruction) are added as children of B to the tree T (Routine *CREATE_TREE: lines 2-4*). The bytecode instruction tree T is used to represent the operand stack structure in a view.

Offset	Bytecode Instruction	Stack before	Stack after	Size
0	iload_1	<empty>	I a	1
1	iload_2	I a	I a, I b	2
2	if_icmple	I a, I b	<empty>	0
	true			
5	iload_1	<empty>	I a	1
6	iload_2	I a	I a, I b	2
7	iadd	I a, I b	I (a+b)	1
8	goto	I (a+b)	I (a+b)	1
	false			
11	iload_1	<empty>	I a	1
12	iload_2	I a	I a, I b	2
13	isub	I a, I b	I (a-b)	1
14	ireturn	I (a+b) | I (a-b)	<empty>	0

Fig. 12. Operand stack representation

An example representation of a Java bytecode is shown in fig. 12.

V. Dynamic Operand Stack Visualization and Verification

The static representation of the operand stack can be extended by the dynamic visualization. The dynamic representation can only be created during the execution of the program, usually during a debugging session. If the operand stack state at the certain point of the execution has to be analyzed, the task to represent the operand stack is trivial. For this purpose the values on the stack just have to be read from the execution environment, if the runtime environment supports the access to the operand stack. Unfortunately, the JVM-implementation, based on the JVM-specification [2], does not provide any access to the operand stack via debugging interface [3]. Nevertheless, it is possible to visualize the operand stack values by using the local variables.

Let us consider the line `a = b + c;` from the following Java source code example and the corresponding bytecode:

```
int a, b, c;
...                  ...
a = b + c;           iload_2;
                     iload_3;
                     iadd;
                     istore_1;
...                  ...

                     LocalVariableTable:
                     Slot Name Signature
                       1    a        I
                       2    b        I
                       3    c        I
```

Fig. 13. Source code example and the corresponding bytecode

The `iadd` instruction adds two `int` values together. It requires that the `int` values to be added be the top two values of the operand stack, pushed there by previous instructions `iload_2` and `iload_3`. Since the instructions `iload_2` and `iload_3` are linked to the variables `b` and `c`, their values can be obtained via debugging interface. Both of the `int` values are popped from the operand stack by executing the `iadd` instruction and their sum is pushed back onto the operand stack. For visualization purposes the result can be calculated or represented as an arithmetic chain.

```
Bytecode           Stack
...
iload_2;           b =  3
iload_3;           b =  3, c = 1
iadd;              b + c = 4
istore_1;
...
```

Fig. 14. Dynamic operand stack visualization

The operand stack visualization task becomes more complicated if the complete stack history has to be visualized. To record the complete history the operand stack states after execution of each instruction have to be stored. If the bytecode contains loops, the data record can be very large. On the other hand if the bytecode is not executed step by step, a part of the operand stack history is missing. The operand stack state in this case can not be represented. The next subsections describe how to record and verify the operand stack history efficiently.

A. Operand Stack Visualization of Loops

We assume that the bytecode is executed step by step, and the state of the operand stack is logged for each instruction. Let be V the set of bytecode instructions of a method and R the set of the operand stack records. In order to keep the memory allocation linear, the number of records have to be less than or equal to the number of instructions.

$$|R| \leq |V| \tag{2}$$

Let be $V' \subseteq V$ the set of loop instructions. So the number of the operand stack records can be calculated as

$$|R| = n \times |V'|, \tag{3}$$

where n the number of the loop iterations. As the number of iterations cannot be predicted, the length of the stack history may be very large.

Our proposed solution is to store the state of the stack only once per instruction to satisfy the condition of the equation 2. An additional counter stores information how often an instruction has been executed. According to the theorem 3.2

Bytecode	Iterations	Stack size	Stack
0: iload_1	10	1	a
1: iload_2	10	2	a, b
2: if_icmpge 11	10	0	-
5: iinc 1, 1	9	0	-
8: goto 0	9	0	-
11: return	1	0	-

Fig. 15. Example of the operand stack representation with a loop.

(subsection III-E), the state of the operand stack in each iteration must be the same with the prerequisite that the bytecode is free of errors. To visualize potential errors the stored operand stack state is compared with the current state in the next iteration. If the states are not equal in terms of size and content, an error is reported. This makes it possible

Bytecode	Iterations	Stack size	Stack
0: iload_1	1	1	a
	2	ERROR 1 | 2	
		ERROR	a | a, a
1: iload_2	1	2	a, b
2: if_icmpge 11	1	0	-
5: iload_1	1	1	a
8: goto 0	1	1	a
11: return	-	-	-

Fig. 16. Example of the operand stack representation with a loop.

to determine which iteration of the loop has caused the error. In fig. 16 an example of an error is presented. After the first iteration the variable a, pushed by the instruction `5: iload_1`, remain on the stack. The comparison of the states during the second iteration detects a difference. Such an error can of course be found with the static loop analysis. However, if the bytecode is generated at runtime, such errors can be only found by dynamic stack analysis.

B. Breakpoint Handling

For debugging purposes, the program is not always executed step by step. The developer sets a breakpoint, at which the program execution will be stopped. If the runtime environment, such as JVM [2], [3], allows only limited access to the operand stack, it is not possible to represent the complete content of the operand stack. Our proposed solution is to combine the static representation of the operand stack with the available and accessible operands. The reconstruction algorithm is represented in fig. 17. The input of the algorithm

/* G is a control flow graph, $G = (V, E)$. */
DYN_OPSTACK_REPRESENTATION (G, v_s)
1 $removeBackEdges(G)$;
2 V' = $backwardsDFS(v)$; /* $V' \in V$ */
3 G' = $createSubgraph(G, V')$;
4 $ASSIGN\_OPSTACK\_STATES(G')$;
5 $DYN\_OPSTACK(G', v)$;

DYN_OPSTACK (G, v)
1 if (dynamic opstack state of v not available){
2 return;
3 }
4 replace static by dynamic values;
5 for (all incoming args l of v){
6 v' = $otherend(l, v)$;
7 $DYN\_OPSTACK(G, v')$;
8 }

Fig. 17. Algorithm for the dynamic operand stack representation

DYN_OPSTACK_REPRESENTATION is a control flow graph G representing a method and a vertex $v_s \in V$ representing the instruction, where the execution of the code has been stopped.

The algorithm removes the back edges in the graph G (line 1) to create a DAG. The routine *backwardsDFS* (line 2) is a backward *Depth First Search* which returns the set of all vertices V' (bytecode instructions) reachable via backward paths from the vertex v. In the line 3 a subgraph of G containing the vertices from V' is created. The algorithm *ASSIGN_OPSTACK_STATES* (fig. 1 from the subsection III-A) assigns the static operand stack states to all vertices from the set V'. The routine *DYN_OPSTACK* starts the replacement of statically calculated operand stack states by the available dynamic values as described at the beginning of the section V. The routine is called recursively and it stops as soon as the dynamic value of the operand stack is not available or can not be calculated.

Let us consider the Java source code example in fig. 18. The corresponding bytecode is presented in fig. 19. The bytecode contains three operands representing the variables `a`, `b` and `c`. Lets us assume that a breakpoint is set in line `return c;`. The program stops at he bytecode address `15`

```
  int c =  a < b ? a + b : b - a;
  return c;
```

Fig. 18. Source code example.

and we are able to read the current values of the operands `a`, `b` and `c` via Java debugging interface.

```
  int c = a < b ?  0 iload_0;    /* a */
   a + b :         1 iload_1;    /* b */
                   2 if_icmpge 9;
                   5 iload_0;    /* a */
                   6 iload_1;    /* b */
                   7 iadd;
                   8 goto 6;
   b - a;         11 iload_1;   /* b */
                  12 iload_0;   /* a */
                  13 isub;
                  14 istore_2;  /* c */
 return c;        15 iload_2;   /* c */
                  16 ireturn;
```

Fig. 19. Bytecode to source code example in fig. 18.

To visualize the operand stack the algorithm *DYN_OPSTACK_REPRESENTATION* in fig. 17 executes following steps. The input is a Graph G containing all instructions of the bytecode V and the instruction v_s with the bytecode address `15` at which the program has been stopped. The line 1 is ignored because for simplicity our example does not contain any loops. The *backwardsDFS* procedure collects backwards all from v_s reachable instructions and stores them in V'. The set V' includes all instructions of V accept the last one with bytecode address `16`. Based on V' a subgraph G' is generated. The algorithm *ASSIGN_OPSTACK_STATES* from the subsection III-A, fig. 1, will assign statically the following operand stack states (fig. 20). The column *Stack before* represents the state of

```
Bytecode              Stack        Stack
                      before       after
 0 iload_0;           <empty>      a
 1 iload_1;           a            a, b
 2 if_icmpge 9;       a, b         <empty>
 5 iload_0;           <empty>      a
 6 iload_1;           a            a, b
 7 iadd;              a, b         <a + b>
 8 goto 6;            <a + b>      <a + b>
11 iload_1;           <empty>      b
12 iload_0;           b            b, a
13 isub;              b, a         <b - a>
14 istore_2;          <a + b>      <empty>
                      | <b - a>
15 iload_2;           <empty>      c
```

Fig. 20. Static operand stack visualization of the bytecode in fig. 19.

the operand stack before the bytecode instruction has been executed and the column *Stack after* the state of the operand stack after the execution of the bytecode instruction. The recursive routine *DYN_OPSTACK* starts from the vertex v_s representing the bytecode instruction `15 iload_2` and visualize following values. For example the obtained values of the operands a, b and c are: $a = 3$, $b = 2$ and $c = 5$. The dynamic visualization of the operand stack is presented in fig. 21. The value of the operand c is obtained from the

```
Bytecode              Stack        Stack
                      before       after
 0 iload_0;           <empty>      a=3
 1 iload_1;           a=3          a=3, b=2
 2 if_icmpge 9;       a=3, b=2     <empty>
 5 iload_0;           <empty>      a=3
 6 iload_1;           a=3          a=3, b=2
 7 iadd;              a=3, b=2     <a + b>=5
 8 goto 6;            5             5
11 iload_1;           -            -
12 iload_0;           -            -
13 isub;              -            -
14 istore_2;          5            <empty>
15 iload_2;           <empty>      c=5
```

Fig. 21. Dynamic operand stack visualization of the bytecode in fig. 19.

execution environment. So the stack of the instruction with the address 15 and 14 is visualized. To visualize the stack states in the if branches the arithmetic operation has to be interpreted and two equations have to be solved.

$$\left.\begin{array}{l} a+b=c \\ b-a=c \end{array}\right\} \begin{array}{ll} 3+2=5 & true \\ 3-2=1 & false \end{array}$$

After solving the equations we can exclude one branch and replace the mathematical operations by the calculated values as presented in fig. 21.

If not all operand stack states can be dynamically visualized the mix of the static and dynamically calculated states can be represented.

VI. Experimental Results

As stated in section III-A the more combinations of sequential branches are contained in the bytecode of a method, the more memory needs to be allocated. In practice, excessive memory allocation happens very rarely. We analyzed over 500 methods from different Java classes of the Standard Java Library with the implementation based on the Dr. Garbage tools [8], [7]. The most representative methods are listed in the table I which have been selected by the following criteria:

- methods with a large number of bytecode instructions
- methods that contain a large number of `if` or `switch` instructions
- methods with a large stack size
- methods that hold a decent amount of stacks

The column *NS* in the table I represents the number of stack objects generated for a method. Each stack object is assigned to a bytecode instruction and represents the current state of the stack in this instruction. The memory consumption would stay linear if the number of stack objects *NS* is less or equal the number of bytecode instructions *NI* in a method.

$$NS \leq NI \tag{4}$$

TABLE I
EXPERIMENTAL RESULTS: MS - MAX STACK SIZE, MC - MAX NUMBER OF STACK COMBINATIONS, NS - NUMBER OF STACKS, NE - TOTAL NUMBER OF STACK ENTRIES, NI - NUMBER OF BYTECODE INSTRUCTIONS, IF/S - NUMBER OF IF/SWITCH INSTRUCTIONS

No.	Library	Package	Class Name	Method Name	MS	MC	NS	NE	NI	IF/S
01	classes.jar	sun.awt.geom	Curve	compareTo()	31	1	412	913	508	25/0
02	classes.jar	com.sun.imageio.metadata	XmlChars	isCompatibilityChar()	2	2	210	297	309	85/1
03	j3dcore.jar	javax.media.j3d	Font3D	triangulateGlyphs()	6	2	1847	3509	2462	84/0
04	classes.jar	java.util	SimpleTimeZone	makeRulesCompatible()	4	1	153	332	198	8/4
05	vecmath.jar	javax.vecmath	Matrix3d	compute_svd()	10	1	153	332	1558	19/0
06	j3dcore.jar	javax.media.j3d	Alpha	value()	5	1	660	1413	775	39/0
07	classes.jar	sun.tools.tree	BinaryExpression	costInline()	5	4	40	88	26	2/0
08	classes.jar	sun.io	ByteToCharUTF8	convert()	7	1	427	975	522	21/0
09	classes.jar	javax.print	ServiceUI	printDialog()	10	1	149	344	199	19/0

The number of generated stacks could be less than the number of bytecode instructions in the method, because not all instructions operate with the stack or greater if the stack combinations according the algorithm *ASSIGN_OPSTACK_STATES* in fig. 1, section III-A have to be calculated.

The column *NE* in the table I represents the total number of stack entries calculated as defined in equation 5, where *BI* the list of bytecode instructions.

$$NE = \sum_{e \in BI} e.stack.size() \quad (5)$$

To make the collected results relative and to show how the number of generated stacks and stack entries depend on the number of instructions we calculate for each method the relative value R_{ns} as a ration of the number of stacks NS to the number of bytecode instructions NI (equation 6)

$$R_{ns} = \frac{NS}{NI} 100\% \quad (6)$$

and the relative value R_{ne} as a ration of the number o stack entries NE to the number of bytecode instructions NI (equation 7).

$$R_{ne} = \frac{NS}{NI} 100\% \quad (7)$$

The calculated values are summarized in the table II and presented in the chart in fig. 22. The ration of the number of generated stacks to the number of bytecode instructions R_{ns} is under 100% for all methods except the method *BinaryExpression.costInline()*. According the table I the max number of stack combinations for this method is 4 and this is the reason why the R_{ns} value is higher. Nevertheless the value of 154% is acceptable. The memory consumption is still linear, because $O(2n) \Rightarrow O(n)$, where n the number of bytecode instructions.

TABLE II
EXPERIMENTAL RESULTS: RELATIVE VALUES

No.	NS	NE	NI	Rns	Rne
1	412	913	508	81%	178%
2	210	297	309	68%	96%
3	1847	3509	2462	75%	143%
4	153	332	198	77%	130%
5	1318	3642	1558	85%	234%
6	660	1413	775	85%	155%
7	40	88	26	154%	338%
8	427	975	522	82%	187%
9	149	344	199	75%	173%

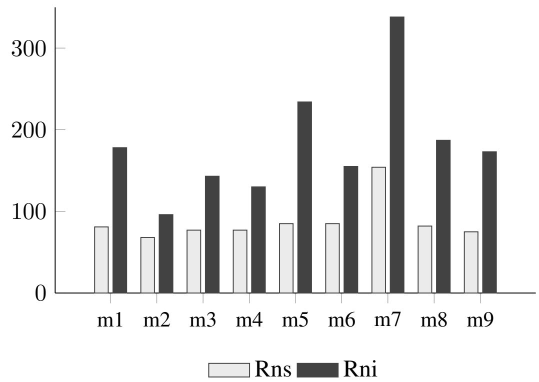


Fig. 22. Ration of the number of stacks NS to the number of bytecode instructions NI

The ration of the number of generated stack entries to the number of bytecode instructions R_{ne} is much more higher than the R_{ns} value, because stack objects may contain more than one entry. The number of stack entries NE depends on the max stack size of a method. Although the R_{ns} value for the method *BinaryExpression.costInline()* is about 350% the memory allocation stays linear. In our implementation the stack entries are reused and only the references are stored in stack objects. In this way the number of allocated stack entries is always equal or less the number of stack objects. The fig. 23 presents an example of the stack allocation.

$$\begin{array}{ll} S_1 & SE_1 \\ S_2 & SE_1, SE_2 \\ S_3 & SE_1, SE_2, SE_3 \\ S_4 & SE_1, SE_2 \\ S_5 & SE_1 \end{array}$$

Fig. 23. Stack allocation

The number of stack objects in this example is five and the number of stack entries is three. The developer have to spend attention on implementation details because in case if all stack entries are stored as separate objects the memory allocation would grow. The number of stack entries fro the example above would get the value nine, according the equation 5.

$$NE = S_1.size + ... + S_5.size = 1+2+2+3+2+1 = 9 \quad (8)$$

The absolute runtime time and memory allocation values of the implemented algorithms are presented in table III.

TABLE III
EXPERIMENTAL RESULTS: TIME AND MEMORY ANALYSIS

No.	Time in ms	Memory in byte
1	524	1280416
2	534	953152
3	821	6265320
4	550	730304
5	742	4100952
6	598	2261472
7	622	399048
8	629	1636984
9	615	835880

The experimental results have shown that despite a number of conditional branch operators or stack entries along with method instructions, the amount of stack combinations stay in limit. The run time and memory allocation measurements shows as well that the implemented algorithms are suitable for usage in developer environments.

VII. CONCLUSION

This paper describes new algorithms for operand stack analysis and visualization based on graph theoretical methods. Although the algorithms partially execute trivial operand stack verifications, they can be obtained as a supplement to the well known algorithms. The operand stack visualization algorithms presented in this paper are the first that can represent the operand stack in such a comprehensive way.

Experimental results showed that the performance and memory consumption do never deviate from linearity, although the theoretical memory consumption has exponential complexity. It is obviously possible with the synthetically generated code to reach the limits, but such code constructs do not occur in practice. We are convinced that a lot of new tools can be designed and implemented based on these algorithms and results

APPENDIX A
OPERAND STACK CONTENT GRAMMAR

```
<Stack> ::= <StackEntry>{"," <StackEntry>}{"|" <Stack>}
<StackEntry> ::= <type> <value>
<type> ::= "B" | "C" | "D" | "F" | "I" | "J" | "S" | "Z"
         | "L" | <array type>
<array type> ::= "[" { "[" }  <type>
<value> ::= <variable name> | <constant> | <array name>
         | <math operation>
<variable name> ::= <char>{<char>}
<char>::= any one of the 128 ASCII characters, but not
any of special characters [, ], (, ), \, /,  ;, ... or
the space character
<constant> ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
                <float_constant>  {<constant>}
<array name> ::= <variable name> [ <numeric> |
                 <variable name> ]
<float_constant> ::= <constant> "."  <constant>
<math operation> ::="("<value>  <operation>  <value>")"
<operation> ::= "+" | "-" | "*" | "/" | "%" | "^" | "|"
              | "<<" | ">>"
```

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