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JaBUTi – Java Bytecode Understanding and Testing

User's Guide
Version 1.0 – Java

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Abstract

This report describes the main functionalities of JaBUTi (Java Bytecode Understanding and Testing) toolsuite. JaBUTi is designed to work with Java bytecode such that no source code is required to perform its activities. It is composed by a coverage analysis tool, by a slicing tool, and by a complexity metric's measure tool. The coverage tool can be used to assess the quality of a given test set or to generate test set based on different control-flow and data-flow testing criteria. The slicing tool can be used to identify fault-prone regions in the code, being useful for debugging and also for program understanding. The complexity metric's measure tool can be used to identify the complexity and the size of each class under testing, based on static information. A simple example that simulates the behavior of a vending machine is used to illustrate such tools.

1 Introduction

JaBUTi is a set of tools designed for understanding and testing of Java programs. The main advantage of JaBUTi is that it does not require the Java source code to perform its activities. Such a characteristic allows, for instance, to use the tool for testing Java-based components.

This report describes the functionalities of JaBUTi – Version 1.0 and how the tester can use it to create testing projects through its graphical interface. Although JaBUTi can be run using scripts, in this report this aspect is not addressed. To illustrate the operational aspects of JaBUTi, through its graphical interface, we are using a simple example, adapted from Orso *et al.* [15], that simulates the behavior of a vending machine.

The rest of this report is organized as follows. Section 2 presents some background information about Java bytecode and a detailed description about the underlying models used by JaBUTi to derive intra-method testing requirements. A brief description of program slicing and complexity metrics are also presented in Section 2. Section 3 describes the example that we will use to illustrate the functionalities of JaBUTi. Section 5 describes how to create a testing project. Section 6 illustrates how to use JaBUTi as a coverage analysis testing tool for Java programs/components. Section 7 shows how to use JaBUTi functionalities to localize faults. In Section 8 describes the set of static metrics implemented in JaBUTi. Finally, in Section 10, we present the perspectives for JaBUTi evolution.

2 Background

In this section we give an overview on Java bytecode, a brief overview on dependence analysis, including control-flow and data-flow testing criteria, and also a brief overview on program slicing and on static metrics. In case of Java bytecode, the interested reader can consult [11] for a complete reference about the JVM specification, as well as, the bytecode instruction set. Considering dependence analysis on Java bytecode, the interested reader can refer to [34]. More details on control-flow and data-flow testing criteria can be found in [19, 22]. A good survey on program slicing can be found in [23]. The static metrics implemented in JaBUTi can be found elsewhere [12, 4].

2.1 Java Bytecode

One of the main reasons why Java has become so popular is the platform independence provided by its runtime environment, the Java Virtual Machine (JVM). The so called *class* file is a portable binary representation that contains class related data such as the class name, its superclass name, information about the variables and constants and the bytecode instructions of each method.

Bytecode instructions can be seen as an assembly-like language that retains high-level information about the program. A bytecode instruction is represented by a one-byte opcode followed by operand values, if any. Each one-byte opcode has a mnemonic that is more meaningful than the opcode itself. The instructions are typed and a letter preceding the mnemonic name represents the data type handled by each instruction explicitly. The convention is to use the letter `i` for integer, `l` for long, `s` for short, `b` for byte, `c` for char, `f` for float, `d` for double, and `a` for reference (objects and arrays). For example, the instruction that pushes a one-byte integer value onto the top of the JVM operand stack has the

opcode 16, mnemonic bipush, and requires one operand (the one-byte integer value). The instruction bipush 9 pushes the value 9 onto the top of the JVM operand stack.

The JVM has a stack frame on which a frame is inserted for every method invocation. Such a frame is composed by a local variable vector, which contains all the local variables used in the current method, and by an operand stack to perform the execution of the bytecode instructions. For instance, considering the statement "a = b + c", part of the local variable vector and part of the operand stack required to execute such a statement are illustrated in Figure 1.

Slot	Variable
...	...
2	a
3	b
4	c
...	...

(a) Local Variable Vector

Bytecode Instruction	Operand Stack
12: iload_3	Value of b ...
13: iload_4	Value of c Value of b ...
14: iadd	Value of b + c ...
15: istore_2	...

(b) Operand Stack Simulation

Figure 1: Simple bytecode instruction execution.

Considering our example, variables a, b and c correspond to local variables 2, 3 and 4, respectively. The bytecode instructions iload_3 and iload_4 load the value of b and c onto the top of the operand stack. The instruction iadd pops two operands from the stack, executes the additions of such operands, and pushes back the result onto the top of the stack. Finally, the instruction istore_2 pops the result from the top of the stack, storing it into local variable 2 (variable a).

The complete set of bytecode instructions, illustrated in Table 1 is composed by 204 instruction. From this set, there are 3 reserved instructions and 43 that may raise an exception (bytecode instructions highlighted in **bold**). Only athrow can throw an exception explicitly, all the others 42 instructions may throw exceptions implicitly.

Although bytecode instructions resemble an assembly-like language, a class file retains very high-level information about a program. The idea behind JaBUTi is to provide as much information as possible, such that the user can have a better understanding of the program, even if the original source code is not available. In the next section we explain how to collect control-flow and data-flow information from the bytecode and how to use this information to provide intra-method coverage criteria for Java programs at bytecode level.

2.2 Dependence Analysis for Java Bytecode

The section below was extracted from [27] and is replicated here with minor changes.

The most common underlying model to establish control-flow testing criteria [14, 20] is the control-flow graph (CFG), from which the testing requirements are derived. Data-flow testing criteria [8, 19, 13] use the Def-Use graph (DUG), which is an extension of the CFG with information about the set of variables defined and used in each node and each edge of the CFG. In this report, the DUG for Java bytecode is called *data-flow block graph* ($\mathcal{BG}$). From the $\mathcal{BG}$ both control and data-flow testing requirements can be derived.

Before constructing the $\mathcal{BG}$ for a method, we construct its *data-flow instruction graph* ($\mathcal{IG}$). Informally, an $\mathcal{IG}$ is a graph where each node contains a single bytecode instruction and the edges connect instructions that might be executed in sequence. $\mathcal{IG}$ also contains information about the kind of ac-

Table 1: Bytecode instruction set

Group	Subgroup	Instruction Set
Do nothing	-	nop
Load and Store	Load a local variable onto the operand stack	aload, aload_⟨n⟩†, dload, dload_⟨n⟩, fload, fload_⟨n⟩, iload, iload_⟨n⟩, lload, lload_⟨n⟩
	Store a value from the operand stack into a local variable	astore, astore_⟨n⟩, dstore, dstore_⟨n⟩, fstore, fstore_⟨n⟩, istore, istore_⟨n⟩, lstore, lstore_⟨n⟩
	Load a constant onto the operand stack	bipush, sipush, ldc, ldc_w, ldc2_w, aconst_null, dconst_⟨d⟩, fconst_⟨f⟩, iconst_m1, iconst_⟨i⟩, lconst_⟨l⟩
	Giving access to more local variables using a wider index or to a larger immediate operand	wide
Arithmetic	Add	dadd, fadd, iadd, ladd
	Subtract	dsub, fsub, isub, lsub
	Multiply	dmul, fmul, imul, lmul
	Divide	ddiv, fdiv, **idiv**, **ldiv**
	Remainder	drem, frem, **irem**, **lrem**
	Negate	dneg, fneg, ineg, lneg
	Shift	ishl, ishr, iushr, lshl, lshr, lushr
	Bitwise	iand, ior, ixor, land, lor, lxor
	Local Variable Increment	iinc
	Comparison	dcmpg, dcmpl, fcmpg, fcmpl, lcmp
Type Conversion	-	d2f, d2i, d2l, f2d, f2i, f2l, i2b, i2c, i2d, i2f, i2l, i2s, l2d, l2f, l2i
Object Creation and Manipulation	Create Class Instance	**new**
	Create Array	**newarray**, **anewarray**, **multianewarray**
	Access Fields of Classes	**getfield**, **getstatic**, **putfield**, **putstatic**
	Load an array component onto the operand stack	**aaload**, **baload**, **caload**, **daload**, **faload**, **iaload**, **laload**, **saload**
	Store a value from the operand stack as an array component	**aastore**, **bastore**, **castore**, **dastore**, **fastore**, **iastore**, **lastore**, **sastore**
	Get the array length	**arraylength**
	Check properties of class instances or arrays	**checkcast**, **instanceof**
Control Transfer	Unconditional Branch	goto, goto_w, jsr, jsr_w, ret, **athrow**
	Conditional Branch	if_acmpeq, if_acmpne, if_icmpeq, if_icmpge, if_icmpgt, if_icmple, if_icmplt, if_icmpne, ifeq, ifge, ifgt, ifle, iflt, ifne, ifnonnull, ifnull
	Compound Conditional Branch	lookupswitch, tableswitch
Method Access	Invocation	**invokeinterface**, **invokespecial**, **invokestatic**, **invokevirtual**
	Return	**areturn**, **dreturn**, **freturn**, **ireturn**, **lreturn**, **return**
Stack Management	-	dup, dup_x1, dup_x2, dup2, dup2_x1, dup2_x2, pop, pop2, swap
Synchronization	-	**monitorenter**, **monitorexit**
Reserved	-	breakpoint, impdep1, impdep2

†⟨n⟩ represents a valid index into the local variable array of the current frame [11].

cesses (definition or use) the bytecode instructions make. The $\mathcal{BG}$ is obtained by applying a reduction algorithm to the $\mathcal{IG}$. Such an algorithm combines several $\mathcal{IG}$ nodes in a single $\mathcal{BG}$ node by identifying blocks of bytecode instructions that are always executed in sequence. The construction of $\mathcal{IG}$ and $\mathcal{BG}$ requires static analysis of Java bytecode instructions. In Sections 2.2.1 and 2.2.2 we explain how to construct the $\mathcal{IG}$ and how the data-flow information is collected, respectively. In Section 2.2.3 the algorithm to generate the $\mathcal{BG}$ from the $\mathcal{IG}$ is described.

2.2.1 Constructing the Instruction Graph

Some features of Java bytecode should be carefully handled when performing control-flow analysis:

- The use of intra-method subroutine calls. The JVM has two instructions jsr and ret that allow a piece of the method code to be "called" from several points in the same method. This is used to implement the finally block of Java.

- Exception handlers. Each piece of code inserted in a catch block in a Java program is an exception handler. The execution of such code is not done by ordinary control flow, but by the throwing of an exception.

To deal with the exception-handling mechanism of Java two kinds of edges are used in the $\mathcal{IG}$: **primary edges** representing the regular control-flow, i.e., when no exception is thrown; and **secondary edges** representing the exception-handling control-flow.

Formally, an $\mathcal{IG}$ of a method m is defined as a directed graph $\mathcal{IG}(m) = (NI, EI_p, EI_s, si, TI)$ where each node $n \in NI$ contains a single instruction of m. EI_p represents the set of primary edges and EI_s the set of secondary edges. If an instruction j, corresponding to the node $n_j \in NI$, can be executed after an instruction i, corresponding to the node $n_i \in NI$, then a primary edge from n_i to n_j exists, $(n_i, n_j) \in EI_p$. If an instruction i, corresponding to the node $n_i \in NI$, is in the scope of an exception-handler that begins in an instruction j, corresponding to the node $n_j \in NI$, then a secondary edge exists from n_i to n_j, $(n_i, n_j) \in EI_s$[1]. The start node si corresponds to the node that contains the first instruction of m. Conversely, TI is the set of termination nodes, i.e., nodes that contain an instruction that ends the method execution.

Consider the Java source code presented in Figure 2(a). The class Vet contains a method Vet.average that calculates and returns the average of an array of integer numbers. The bytecode instructions that represent the Vet.average method are presented in Figure 2(b). Each bytecode instruction is preceded by a program counter number (pc) that identifies a single bytecode instruction inside a given method. In our example, the first bytecode instruction aload_0 is located at pc 0 and the last instruction (freturn) at pc 101.

Figure 2(c) illustrates the exception table for Vet.average method. The exception table indicates, for each segment of bytecode instruction (*from* and *to* columns), the beginning of the valid exception-handler (*target* column), and the corresponding type of exceptions caught by such a handler (*type* column). For example, from pc 12 to pc 54 the valid exception-handler begins at pc 60 and it is responsible to catch any exception of the class java.lang.Exception or any one of its subclasses. A registered exception handler with a ⟨Class all⟩'s type catches any kind of exceptions.

The bytecode instructions can be related to source code lines because the class file stores information that maps each bytecode instruction to the source line it appears on. Thus, if the source code is available, analysis applied on the bytecode level can be mapped back to the source code level. The line number table, illustrated in Figure 2(d), gives the correspondence between source line number and bytecode program counter. For example, the statement at the source line number 06 corresponds to the bytecode instructions from pc 0 to pc 2. The bytecode instructions from pc 5 to 7 correspond to the statement at source line 07, and so on.

To construct $\mathcal{IG}$, the bytecode of a given method is read and an interpreter is responsible for analyzing the semantics of each instruction, identifying the set of nodes and edges of the $\mathcal{IG}$. First, a node is created in the $\mathcal{IG}$ for each bytecode instruction, and such nodes are connected by primary edges, considering the existence of control transfer between each instruction, and by secondary edges, considering the exception table. From the complete set of bytecode instructions presented in Table 2 (Section 2.2.2), the instructions in bold from Class 0 and Class 1 (first and second rows) are related with the control-flow aspect of Java bytecode. Figure 2(e) illustrates the resulting $\mathcal{IG}$ of the method presented in Figure 2(b). The $\mathcal{IG}$ nodes are numbered according to the pc number of the bytecode

[1]In this way an exception-handler always begins a new node in the $\mathcal{IG}$ or in the $\mathcal{BG}$ since it is the target of one or more secondary edges.

```
/*01*/public class Vet {
/*02*/    int v[];
/*03*/    float out;
/*04*/
/*05*/    float average(int[] in) {
/*06*/        v = in;
/*07*/        out = 0.0f;
/*08*/        int i = 0;
/*09*/
/*10*/        try {
/*11*/            while (i < v.length) {
/*12*/                out += v[i];
/*13*/                i++;
/*14*/            }
/*15*/            out = out / i;
/*16*/        } catch (Exception e) {
/*17*/            out = 0.0f;
/*18*/            i = 0;
/*19*/        } finally {
/*20*/            v = null;
/*21*/        }
/*22*/        print((float) i);
/*23*/        return out;
/*24*/    }
/*25*/
/*26*/    public void print(float n) {
/*27*/        System.out.print(n + "\n");
/*28*/    }
/*29*/}
```

(a) Vet.java source code

```
0 aload_0
1 aload_1
2 putfield #2 <Field int[] v>
5 aload_0
6 fconst_0
7 putfield #3 <Field float out>
10 iconst_0
11 istore_2
12 goto 34
15 aload_0
16 dup
17 getfield #3 <Field float out>
20 aload_0
21 getfield #2 <Field int[] v>
24 iload_2
25 iaload
26 i2f
27 fadd
28 putfield #3 <Field float out>
31 iinc 2 1
34 iload_2
35 aload_0
36 getfield #2 <Field int[] v>
39 arraylength
40 if_icmplt 15
43 aload_0
44 aload_0
45 getfield #3 <Field float out>
48 iload_2
49 i2f
50 fdiv
51 putfield #3 <Field float out>
54 jsr 82
57 goto 91
60 astore_3
61 aload_0
62 fconst_0
63 putfield #3 <Field float out>
66 iconst_0
67 istore_2
68 jsr 82
71 goto 91
74 astore 4
76 jsr 82
79 aload 4
81 athrow
82 astore 5
84 aload_0
85 aconst_null
86 putfield #2 <Field int[] v>
89 ret 5
91 aload_0
92 iload_2
93 i2f
94 invokevirtual #5 <Method void print(float)>
97 aload_0
98 getfield #3 <Field float out>
101 freturn
```

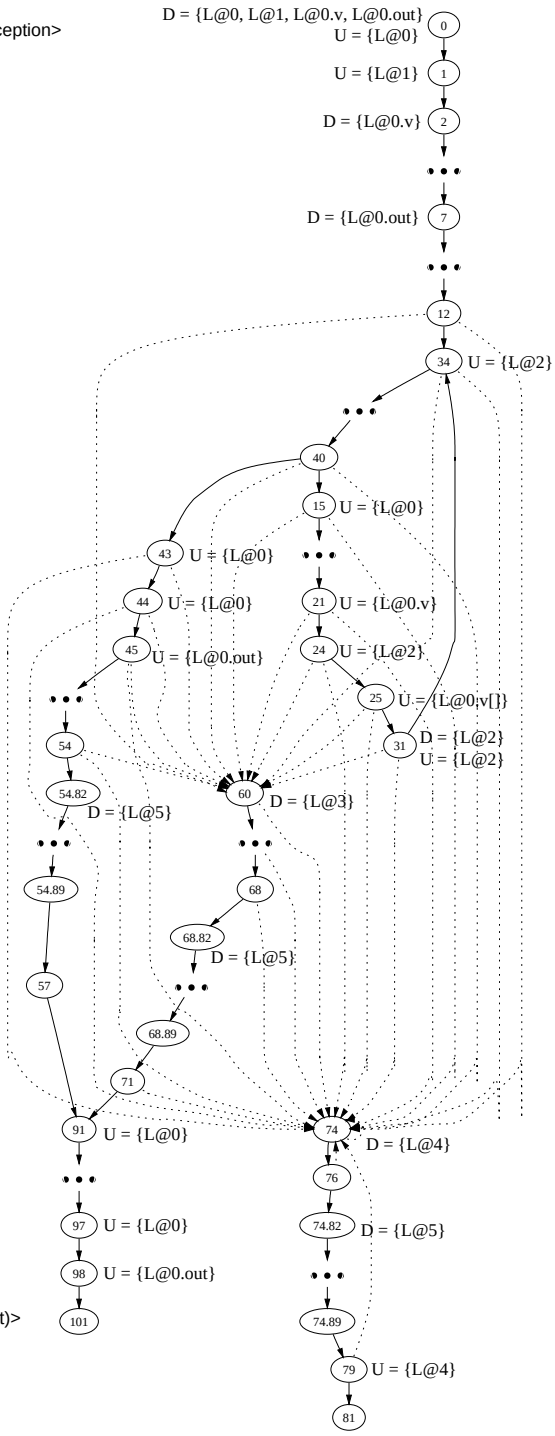
(b) Vet.average bytecode instructions

from	to	target	type
12	54	60	<Class java.lang.Exception>
12	57	74	<Class all>
60	71	74	<Class all>
74	79	74	<Class all>

(c) Exception table

```
Line 6: pc = 0
Line 7: pc = 5
Line 8: pc = 10
Line 11: pc = 12
Line 12: pc = 15
Line 13: pc = 31
Line 11: pc = 34
Line 15: pc = 43
Line 16: pc = 54
Line 17: pc = 60
Line 18: pc = 66
Line 19: pc = 68
Line 20: pc = 74
Line 22: pc = 91
Line 23: pc = 97
```

(d) Line number table



(e) Vet.average data−flow Instruction Graph

Figure 2: Illustration of the data-flow $\mathcal{IG}$.

instruction it represents. Section 2.2.2 describes how to identify the set D_i of defined variables and the set U_i of used variables associated to each node of $\mathcal{IG}$. Observe that at bytecode level it is not possible to distinguish between a *p-use* and a *c-use*. Later, in the computation of the data-flow criteria, nodes with more than one outgoing edge will have the uses associated to such edges, as if they were *p-uses*.

Since in the $\mathcal{IG}$ each bytecode instruction corresponds to a node, the number of nodes and edges can be very large, even for methods with a few lines of code. In case of the $\mathcal{IG}$ in Figure 2(e), some

nodes are omitted in order to reduce the size of the $\mathcal{IG}$ and to make it more readable. Ellipsis ("•••") are used to represent omitted nodes.

Primary edges are represented by continuous lines and secondary edges by dotted lines. Observe that there are a large number of secondary edges connecting the nodes in the scope of a given exception-handler to the first node of the handler. For example, according to the exception table of Figure 2(c) the exception-handler located at pc 60 is responsible to catch all exceptions of java.lang.Exception class raised from pc 12 to pc 54. So, there are secondary edges connecting all nodes in this range to node 60. The same applies to the other exception-handlers.

Special care on building the $\mathcal{IG}$ is required to deal with subroutine calls inside the method, used, for example, to implement the finally block of Java. Each jsr instruction causes the execution of an intra-method piece of code (subroutine). After the subroutine has been executed, the execution is resumed at a different point in the program, depending on which jsr caused the execution of the subroutine. In our example, there are three jsr instructions located at pc 54, 68, and 76, all of them representing a branch to pc 82, that is the first instruction of the finally block. Such a finally block goes from pc 82 to pc 89. Observe that at pc 89 there is a ret instruction which returns the execution to pc 57, 71 or 79, depending on which jsr instruction invoked the subroutine. To avoid any misinterpretation about which jsr instruction causes the invocation of the finally block, and at which instruction the execution is resumed, the set of nodes that corresponds to the finally block is replicated for each jsr instruction, and different labels are used to identify the replicated nodes. In our example, nodes 82 to 89 are replicated three times and the labels of such nodes are preceded by "54.", "68.", and "76.", as can be observed in Figure 2(e). Figure 3(a) illustrates the problem if the nodes that compose a finally block are not replicated. Observe that since node 82 has three incoming edges and node 89 three outgoing edges this can lead to the false impression that from any incoming edge there are three outgoing edges while, in the reality, only one exists. By replicating the nodes in the subroutine we avoid such a problem, as illustrated in Figure 3(b).

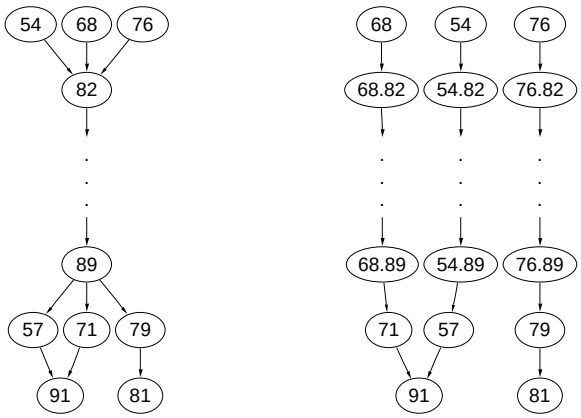


Figure 3: Different approaches to deal with finally block: (a) Single Finally Node (b) Multiple Finally Nodes.

2.2.2 Augmenting the $\mathcal{IG}$: Data-Flow $\mathcal{IG}$

The first thing required to augment the $\mathcal{IG}$ with data-flow information is to precisely define the underlying data-flow model which indicates what kinds of bytecode instructions lead to variable def-

inition/use and also how to consider reference and array variables. By analyzing the set of bytecode instructions obtained from [11] we classify such instructions in eleven different classes, according to their relation with the data-flow at bytecode level. Table 2 illustrates these classes of instructions.

Table 2: Different classes of bytecode instruction.

Class	Bytecode Instructions	Data-Flow Implication
0	**athrow**, **goto**, **goto_w**, **if_acmpeq**, **if_acmpne**, **if_icmpeq**, **if_icmpge**, **if_icmpgt**, **if_icmple**, **if_icmplt**, **if_icmpne**, **ifeq**, **ifge**, **ifgt**, **ifle**, **iflt**, **ifne**, **ifnonnull**, **ifnull**, **lookupswitch**, **tableswitch**, **areturn**, **dreturn**, **freturn**, **ireturn**, **lreturn**, **return**, **ret**, monitorenter, monitorexit, pop, pop2, breakpoint, impdep1, impdep2, nop, checkcast, wide, swap	Instructions in this class have **no implication** for the flow of data.
1	**invokeinterface**, **invokespecial**, **invokestatic**, **invokevirtual**, **jsr**, **jsr_w**, dadd, ddiv, dmul, dneg, drem, dsub, fadd, fdiv, fmul, fneg, frem, fsub, iadd, iand, idiv, imul, ineg, ior, irem, ishl, ishr, isub, iushr, ixor, ladd, land, ldiv, lmul, lneg, lor, lrem, lshl, lshr, lsub, lushr, lxor, arraylength, instanceof, aconst_null, bipush, dconst, fconst, iconst, lconst, sipush, ldc, ldc_w, ldc2_w, d2f, d2i, d2l, f2d, f2i, f2l, i2b, i2c, i2d, i2f, i2l, i2s, l2d, l2f, l2i, new, multianewarray, anewarray, newarray, dcmpg, dcmpl, fcmpg, fcmpl, lcmp	Instructions in this class have **no implication** for the flow of data. In addition, they leave an unknown element at the top of the operand stack. Accesses to such element will not characterize any use or definition. For example, instruction new pushes an object reference onto the stack. Further use of such reference as a field access is not regarded as a definition or use.
2	aaload, baload, caload, daload, faload, iaload, laload, saload	Loads an array element to the top of the operand stacks and indicating the **use** of the array.
3	aastore, bastore, castore, dastore, fastore, iastore, lastore, sastore	Stores the value on the top of the operand stack into an array element, indicating the **definition** of the array.
4	putfield	Stores the value on the top of the operand stack into an instance field, indicating the **definition** of such an instance field.
5	putstatic	Stores the value on the top of the operand stack into a class field, indicating the **definition** of such a class field.
6	dup, dup2, dup_x1, dup_x2, dup2_x1, dup2_x2	Duplicates the value onto the top of the operand stack and has **no implication** for the flow of data.
7	aload, dload, fload, iload, lload	Loads the value of a given local variable onto the top of the operand stack, indicating a **use** of such a local variable.
8	astore, dstore, fstore, istore, lstore	Stores the value on the top of the operand stack into a local variable, indicating a **definition** of such a variable.
9	getfield	Loads an instance field onto the top of the operand stack, indicating a **use** of such an instance field.
10	getstatic	Loads a class field onto the top of the operand stack, indicating a **use** of such a class field.
11	iinc	Increments the value of a given local variable, indicating a **use** and a **definition** of such a local variable.

The division into such classes was based on the kind of definitions and uses that we would like to identify. In Java and Java bytecode, the variables can be classified in two types: basic or reference types. Fields of a class can be of basic or reference type and are classified as instance or class fields, depending on whether they are unique to each object of the class or unique to the entire class (static fields), respectively. Local variables declared inside a method can also be of basic or reference type. An aggregated variable (array) is of reference type. To deal with aggregated variables we are following the approach proposed by Horgan and London [9], which considers an aggregated variable as a unique storage location such that when a definition (use) of any element of the aggregated variable occurs, what is considered to be defined (used) is the aggregated variable and not a particular element. Moreover, in their data-flow model, a definition of a given variable blocks previous definitions of the

same variable. So, in our data-flow model the following guidelines apply to identify definitions and uses of variables:

1. Aggregated variables are considered as a unique storage location and the definition/use of any element of the aggregated variable a[] is considered to be a definition/use of a[]. So, in the statement "a[i] = a[j] + 1" there is a definition and a use of the aggregated variable a[].

2. If an aggregate variable a[][] is defined, an access to its elements is considered a definition or use of a[][]. Then, in the statement "a[0][0] = 10" there exists a definition of a[][] and in the statement "a[0] = new int[10]" there is a definition of a[].

3. Every time an instance field (or an array element) is used (defined) there is a use of the reference variable used to access the field and a use (definition) of the field itself. Considering ref_1 and ref_2 as reference variables of a class C which contains two instance fields x and y of type int, in the statement "ref_1.x = ref_2.y" there are uses of the reference variables ref_1 and ref_2, a use of the instance field ref_2.y, and a definition of the instance field ref_1.x. Since instance fields are valid in the entire scope of a given class, each instance field used in the context of a given method is considered to have a definition in the first node of the $\mathcal{IG}$.

4. Class fields (static fields) can be considered as global variables and do not require a reference variable to be accessed. Considering a class C with a static fields w and z, in the statement "C.z = C.w + y" there are a use of C.w and a definition of C.z. Even if a static field is accessed using a reference variable ref_1 of class C, such that "ref_1.w = 10", at bytecode level, such a reference is converted to the class name and there is no use of the reference variable in this statement. Since static fields are in the entire scope of a given class, each static field used in the context of a given method is considered to have a definition in the first node of the $\mathcal{IG}$.

5. A method invocation such as ref_1.foo(e_1, e_2, ..., e_n) indicates a use of the reference variable, ref_1. The rules for definition and use identification inside expressions e_1, e_2, ..., e_n are the same as described on items 1 to 4.

6. For instance methods, a definition of this is assigned to the first node of the $\mathcal{IG}$, and also the definition of each local variable corresponding to the formal parameters of such a method, if any. For class methods, only the local variables corresponding to the parameters are considered, no instance is required to invoke such a method.

Based on these guidelines and on the different classes of bytecode instructions, the $\mathcal{IG}$ of a given method is traversed and to each node of such a graph a set D_i of defined variables, and a set U_i of used variables are assigned. Before explaining how these two sets are created, it is important to know how these different kinds of variables are treated at the bytecode level. Method parameters and variables declared inside the method are treated as local variables and are bound to the JVM local variable table as follows: if it is an instance method, local variable zero, referenced here as L@0, is bound to the reference to the current object (this), i.e., the object that caused the method invocation. The formal parameters, if any, are bound to the local variable one (L@1), two (L@2), and so on, depending on the type and on the number of parameters. Finally, the variables declared inside the method are bound to the remaining local variables, also depending on the type and the number of declared variables. For example, considering the source code of the method Vet.average, it can be observed that it is an

instance method which accepts one parameter in and declares one local variable i. L@0 corresponds to reference to the current object. The formal parameter in corresponds to L@1, and the variable i corresponds to L@2. Three other local variables (L@3, L@4 and L@5) are used by the compiler to implement the exception-handling mechanism. The method accesses two instance fields: v, and out. Since they are instance fields, they require a reference to an object of class Vet to be accessed. When no reference is used preceding a field, the reference to the current object is used. So, v and out are referenced in the bytecode of our example as L@0.v and L@0.out.

To analyze the $\mathcal{IG}$ we implemented a simulator that interprets bytecode instructions and identifies the type and the source of data manipulated by each instruction. For example, suppose the current instruction to be analyzed is iload_2. Such an instruction, when interpreted by the JVM, pushes onto the top of the operand stack an integer value stored in L@2. Our simulator, instead of pushing an actual value, pushes onto the top of the stack an indication in the form "<type> - <data_source>" to be used when interpreting the next bytecode instructions. <type> corresponds to the data type being manipulated, and <data_source> to the source of each data. In this example, instruction iload_2 pushes an indication like "int - L@2", since L@2 is a data source of an integer value. Moreover, the load instruction characterizes a use of L@2 so this variable is inserted in the set of used variables associated to the current node of the $\mathcal{IG}$ graph. Different indications are used to represent the different types of storage places, as described above. In Figure 4(a), second column, there are different kinds of indications placed onto the top of the operand stack when the bytecode instructions in the first column are interpreted. For a class field (static field) the indication is in the form "<type> - S@<class_name>.<field_name>", where <type> is the type of the static field, <class_name> is the class name, and <field_name> is the name of the static field. A detailed description of the interpreter and all kinds of indications can be found in [26].

Considering the $\mathcal{IG}$ presented in Figure 2(e), there are the definitions of L@0, L@1, L@0.v, and L@0.out associated with node 0. Moreover, node 0 also contains a bytecode instruction of Class 7 (aload_0), which indicates a use of the loaded local variable, L@0 in this case. Observe that the bytecode instruction at pc 0 is one of the bytecode instructions that corresponds to the statement "v = in" at source code line 6 of Figure 2(a). The use exists because before initializing such a field, which is carried out when the instruction located at pc 2 is executed, the reference to the current object (L@0) has to be loaded onto the top of the operand stack, characterizing the use of such a local variable.

At node 2, the putfield instruction, which belongs to Class 4, indicates a definition of an instance field, in our case the instance field v, referenced as L@0.v. So, the set of defined variables at node 2 contains the element L@0.v. Finally, the instruction at node 25, iaload, belongs to Class 2 and indicates a use of an element of an array of integers, so the set of used variables at node 25 contains the element L@0.v[].

One important point to be observed is that, when evaluating a given instruction, the current top of the operand stacks can have more that one configuration, depending on the path used to reach the instruction. Since it is possible to reach a given node through different instruction sequences, each different possible stack configuration needs to be evaluated to find the complete set of defined/used variables in a $\mathcal{IG}$ node. This is performed by traversing the $\mathcal{IG}$ as many times as necessary, until all possible combinations have been evaluated, and the complete set of defined/used variables on each node have been found.

As an example of such a situation, consider the bytecode instructions illustrated in Figure 4(b). This set of bytecode instructions corresponds to the piece of source code shown in Figure 4(a). Figure 4(c) shows the corresponding data-flow $\mathcal{IG}$.

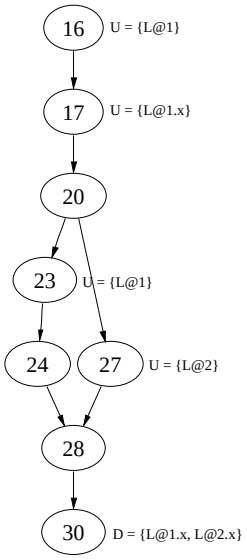
Observe that the bytecode instruction at node 30, can be reached from two different paths: {16, 17, 20, 23, 24, 28, 30} or {16, 17, 20, 27, 28, 30}. Each of them inserts a different indication in the top of the operand stack, the first loads L@1 into the top of the operand stack and the other L@2. When executing the bytecode instruction at pc 30, which stores the value onto the top of the operand stack in a field of an object, two possible combinations can occur, the definition of the field x of L@1, or the definition of field x of L@2. Therefore, the complete set of defined variables at $\mathcal{IG}$ node 30 contains both: L@1.x and L@2.x.

```
r = new Foo();
s = new Foo();
(r.x == 0 ? r : s).x = 20;
```

(a) Piece of Java Source Code

Bytecode Instruction	Operand Stack Configuration
16 aload_1	Foo - L@1 ...
17 getfield #4 <Field int x>	int - L@1.x ...
20 ifne 27	...
23 aload_1	Foo - L@1 ...
24 goto 28	Foo - L@1 ...
27 aload_2	Foo - L@2 ...
28 bipush 20	int - DC **Foo - L@1 or Foo - L@2** ...
30 putfield #4 <Field int x>	**int - L@1.x or int - L@2.x** ...

(b) Bytecode instructions



(c) Corresponding $\mathcal{IG}$

Figure 4: Different Stack Configurations.

Once the complete set of defined and used variables have been detected, the instruction CFG can be reduced to originate the $\mathcal{BG}$. The algorithm used to perform such a reduction is explained in the next section.

2.2.3 Constructing Data-Flow Block Graph ($\mathcal{BG}$)

The $\mathcal{IG}$ provides a practical way to traverse the set of statements of a given method to identify the set of variables defined and used by each statement. However, since a node on $\mathcal{IG}$ is created for each statement of a given method m, the number of nodes and edges can be very large, especially considering lower level bytecode instructions. Once all information about each bytecode instruction has been collected, we use the concept of *instruction block* to reduce the number of nodes and edges as much as possible.

An *instruction block* is a set of instructions that are "normally" executed in sequence in a program. When the first instruction of a block is executed, so are the remaining instructions; branching only occurs to the beginning and from the end of the block.

A block graph for a given method m is a directed graph $\mathcal{BG}(m) = (N, E_p, E_s, s, T)$ such that, each node $n \in N$ represents a instruction block, each edge $(n_i, n_j) \in E_p$ represents a primary edge (control transfer) between blocks n_i and n_j, each edge $(n_i, n_j) \in E_s$ represents a secondary edge between blocks

n_i and n_j, s corresponds to the start block, and T is the set of termination blocks. For each block two sets D_i and U_i are assigned. They contain the sets of defined and used variables in the block, respectively.

The algorithm used to reduce a data-flow $\mathcal{IG}$ to a data-flow $\mathcal{BG}$ is presented in Figure 5. In line 14 of the algorithm, a decision is taken whether the current instruction x being analyzed is the last one in the current block or not. It will be the last one if at least one of the following conditions holds:

- x is a jump, goto, ret or invoke instruction;
- x has more than one primary successor;
- the single primary successor of x has more than one (primary or secondary) predecessor;
- the single primary successor of x has not the same set of secondary successors of x.

```
# Input: iG, the instruction-CFG GI = ⟨NI, EI_p, EI_s, si, TI⟩ to be reduced;
# Output: bG, the block CFG bG = ⟨N, E_p, E_s, s, T⟩

01      s := NewNodeTo(si)
02      foreach x ∈ N
03          if x has no successor
04              T := T ∪ {x}

# Auxiliary function: NewNodeTo
# Input: A node y from iG
# Output: A node from bG where y has been inserted

05      ins := the instruction in y
06      if the node y has already been visited
07          return the node w ∈ N that contains ins
08      CurrentNode := new block node
09      N := N ∪ {CurrentNode}
10      x := y
11      repeat
12          Include x as part of CurrentNode
13          Mark x as visited
14          if x should terminated the current block
15              foreach v such that (x, v) ∈ EI_p
16                  E_p := E_p ∪ {(CurrentNode, NewNodeTo(v))}
17              foreach v such that (x, v) ∈ EI_s
18                  E_s := E_s ∪ {(CurrentNode, NewNodeTo(v))}
19              x := null
20          else
21              if there exists a v such that (x, v) ∈ EI_p
22                  x := v
23              else
24                  x := null
25      while x ≠ null
26      return CurrentNode
```

Figure 5: Algorithm to generate the CFG from bytecode.

Zhao [33] proposes a different approach to construct the CFG of a given method. According to Zhao's approach, if an exception-handler is present, a new node is also created for any instruction that may throw an exception explicitly (instruction athrow) or implicitly (other 42 instructions), which can increase significantly the number of nodes in the CFG. Moreover, to correctly implement the approach

to generate the CFG as proposed by Zhao [33] it is necessary to check the subclasses of each exception that may be raised and to identify if there is any exception-handler that can catch this particular exception. In our implementation we decide to use a more pragmatic approach to construct the $\mathcal{BG}$, expecting to obtain simpler and more readable graphs.

As mentioned earlier, two points that should be highlighted are: first, when we have subroutine calls, the set of statement blocks representing the subroutine is expanded for every call, i.e., the statements of a given subroutine may appear more than once in the $\mathcal{BG}$ within different nodes, once for each subroutine call.

Second, observe that since the set of bytecode instructions on each statement block might not throw all kind of handled exceptions, our $\mathcal{BG}$ may have "false" (or spurious) secondary edges. Moreover, the execution of a given block can be interrupted in any place, when an exception is thrown, so in the presence of exceptions the block may not have the "atomicity" characteristic mentioned above. On the other hand, this approach simplifies both the construction of the $\mathcal{BG}$ and also its interpretation, since the number of nodes is reduced. An alternative approach to construct a CFG to deal with exception-handling constructions is described by Sinha and Harrold [21] such that no false edges are generated. Although, the proposed technique considers only exceptions generated explicitly, i.e., the ones originate by the throw statement [21].

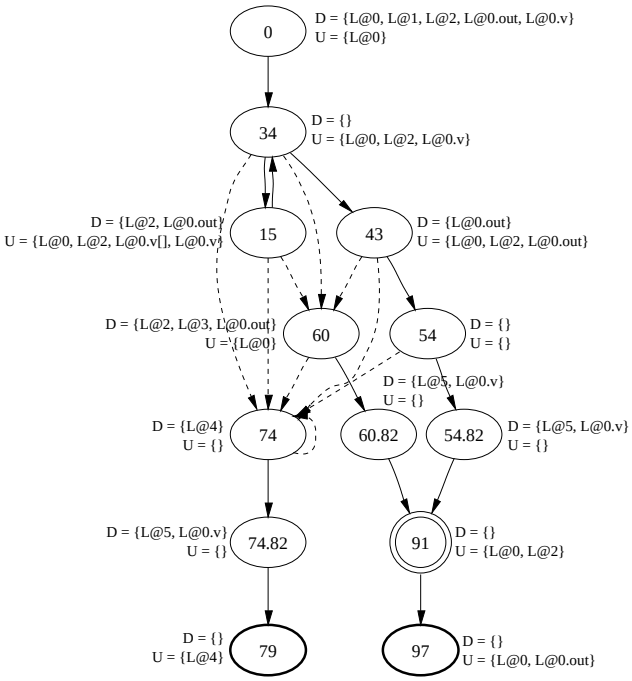


Figure 6: Vet.average's $\mathcal{BG}$.

After the $\mathcal{BG}$ has been constructed, a simple analysis is carried out to eliminate unnecessary nodes, i.e., nodes that contain only a single goto instruction. They can be eliminated by directly connecting its in-coming edges as the in-coming edges of its successor. Figure 6 illustrated the $\mathcal{BG}$ obtained by applying the reduction algorithm to the $\mathcal{IG}$ of Figure 2(e). $\mathcal{BG}$ represents the underlying model used to derive control-flow and data-flow testing requirements. The label of a given block in $\mathcal{BG}$ is the program counter number of its first instruction. The labels of the replicated nodes, i.e., nodes corresponding to a subroutine, are preceded by the label of the node that invoked the subroutine. Observe that since instruction node 68 of $\mathcal{IG}$ now composes the block node 60 in $\mathcal{BG}$, instructions nodes 68.82 of $\mathcal{IG}$

correspond to block node 60.82 in $\mathcal{BG}$. All the other replicated instruction nodes that correspond to the finally block, i.e., instruction nodes 84, 85, 86 and 89 in $\mathcal{IG}$, are part of the block nodes $xx.82$ in $\mathcal{BG}$.

On constructing the $\mathcal{BG}$ we also have two different types of edges to represent primary edges (continuous line) and secondary edges (dashed lines). Moreover, we make a distinction among three different types of nodes in $\mathcal{BG}$: termination nodes represented by bold line circles (as blocks 79 and 97 in Figure 6); call nodes represented by double line circles (as block 91 in Figure 6); and regular nodes represented by single line circles (as all other nodes in Figure 6). The call nodes are being distinguished from the others because we intend to extend our analysis to inter-method level; thus, call nodes are useful for constructing the inter-method control-flow and data-flow graphs. Def-use information is trivially computed for each $\mathcal{BG}$ node by the union of the definition (use) sets of each $\mathcal{IG}$ node included in the $\mathcal{BG}$ node.

Once the $\mathcal{BG}$ has been obtained, different testing criteria can be applied to derive different testing requirements that can be used to assess the quality of a given test set or to generate a given test set. In the next section we describe some of the testing criteria that we are working on and the set of testing requirements derived from each one.

2.3 Intra-method Structural Testing Requirements

Java bytecode can be thought of as an assembly-like language from that control-flow and data-flow information can be collected and represented as a $\mathcal{BG}$, as described above. Once collected, such information for each method, intra-method testing criteria can be defined and applied. Basically, at method level, as mentioned in [7], traditional control-flow and data-flow testing criteria [19] can be applied, since they are based on the same underlying representation, i.e., the $\mathcal{BG}$. Sinha and Harrold [22] describe a set of data-flow based testing criteria considering exceptions. Thus we can adopt coverage criteria for the later [19, 22]. We propose to conduct coverage testing on Java programs, including Java components with respect to six different testing criteria: four are control-flow-based and two are data-flow-based.

2.3.1 Control-Flow Testing Requirements

The $\mathcal{BG}$ is a representation of a given method in a program. Control-flow testing criteria can be derived based on such a program representation to provide a theoretical and systematical mechanism to select and assess the quality of a given test set. We are using two well known control-flow testing criteria to derive testing requirements from the $\mathcal{BG}$: *all-nodes* and *all-edges* [20].

- **all-nodes criterion**: requires that each $\mathcal{BG}$ node has been exercised at least once by a test case in the test set. This criterion ensures that every statement in the method have been executed at least once by a given test case. we decided to subdivide such criterion in two non-overlapping testing criteria such that the tester can concentrate on different aspects of a program at a time:
  - **all-primary-nodes**: requires that each primary node has been exercised at least once by a test case in the test set. This criterion requires that all statements not related with exception-handling mechanism were executed at least once;
  - **all-secondary-nodes**: requires that each secondary node has been exercised at least once by a test case in the test set. This criterion requires that all statements related with exception-handling mechanism were executed at least once;

- **all-edges criterion**: requires that each $\mathcal{BG}$ edge has been exercised at least once by a test case in the test set. This criterion ensures that every possible control transfer in the method has been executed at least once by a given test case. Since in our $\mathcal{BG}$ there are two different types of edges, we decided to subdivide such criterion in two non-overlapping testing criteria:

  - **all-primary-edges**: requires that each primary edge has been exercised at least once by a test case in the test set. This criterion requires that all conditional expressions were evaluated as true and false at least once;
  - **all-secondary-edges**: requires that each secondary edge has been exercised at least once by a test case in the test set. This criterion requires that each exception-handler be executed at least once from each node where an exception might be raised.

To illustrate how such criteria can be applied, Table 3 presents the set of testing requirements required by each one of them, considering the $\mathcal{BG}$ of the method Vet.average (Figure 6).

Table 3: Set of control-flow testing requirements for Vet.average $\mathcal{BG}$.

Criterion		**Testing Requirements**
all-nodes	all-primary-nodes	{0, 15, 34, 43, 54, 54.82, 91, 97}
	all-secondary-nodes	{60, 60.82, 74, 74.82, 79}
all-edges	all-primary-edges	{(0,34), (15,34), (34,15), (34,43), (43,54), (54,54.82), (54.82,91), (60,60.82), (60.82,91), (74,74.82), (74.82,79), (91,97) }
	all-secondary-edges	{(15,60), (15,74), (34,60), (34,74), (43,60), (43,74), (54,74), (60,74), (74,74)}

2.3.2 Complexity Analysis of Control-Flow Testing Criteria

TO BE DONE...

2.3.3 Data-Flow Testing Requirements

With respect to data-flow testing, we are using the well known *all-uses* criterion [19] that is composed of the *all-c-uses* and *all-p-uses* criteria. A precise definition about these criteria can be found in [19]. A *use* represents the use of a variable in a statement. If the value of a variable is used for some computation, it is a *c-use* (Computational Use), whereas if the value is used in a predicate that determines which branch is to be executed, it is a *p-use* (Predicate Use). Let b_i and b_j to be two points in the bytecode where a variable x is defined and used, respectively. This definition and this use are referred to as $d_i(x)$ and $u_j(x)$, respectively. The pair $(d_i(x), u_j(x))$ is a def-use pair if there is a definition clear path with respect to x from b_i to b_j, i.e., x is not defined at any point other than b_i. The pair is also said feasible if there exists a test case t such that the execution of the method on t causes such definition clear path from b_i to b_j to be traversed.

For an example of a c-use, consider the DUG of Figure 6. At node 0, the variable definition set contains the variable L@0.v, which represents the instance variable v in the corresponding source code. At node 15 there is a use of L@0.v to compute the sum of its elements, determining a c-use pair w.r.t. L@0.v from node 0 to node 15 (c-use). On the other hand, at node 15, there is a definition of L@2 that represents the local variable i in the corresponding source code. Such a variable is used in the predicate located at node 34 to evaluate if the end of v has been reached. Thus, there is a p-use pair w.r.t. L@2 from node 15 to node 34. From the bytecode, it is not possible to distinguish p-uses

and c-uses. In our implementation of all-uses criterion we assume that a use in a node with more than one out-going edge is a p-use and associate it with each of those edges. As with the all-edges criterion, we divided the all-uses criterion such that two sets of non-overlapping testing requirements are obtained, to consider the primary and secondary edges. We named such criteria all-primary-uses and all-secondary-uses, respectively. The first takes all the def-use pairs for which there exists a path of primary edges only. The other def-use pairs are required by the second.

To illustrate how such criteria can be applied, Table 4 presents the set of testing requirements required by each one of than, considering the $\mathcal{BG}$ of the method Vet.average (Figure 6).

A test set T may be evaluated against the all-uses criterion (all-primary-uses/all-secondary-uses) by computing the ratio of the number of def-use pairs covered to the total of all-uses (all-primary-uses/all-secondary-uses) requirements. The same applies to all-nodes and all-edges (all-primary-edges/all-secondary-edges) criteria. More details about the testing criteria definition can be found in [26].

Table 4: Set of data-flow testing requirements for Vet.average $\mathcal{BG}$.

Criterion		**Testing Requirements**		
all-uses	all-primary-uses	$\langle L@0, 0, (15, 34)\rangle$	$\langle L@0, 0, (34, 15)\rangle$	$\langle L@0, 0, (34, 43)\rangle$
		$\langle L@0, 0, (43, 54)\rangle$	$\langle L@0, 0, (60, 60.82)\rangle$	$\langle L@0, 0, 54.82\rangle$
		$\langle L@0, 0, 60.82\rangle$	$\langle L@0, 0, 74.82\rangle$	$\langle L@0, 0, 91\rangle$
		$\langle L@0, 0, 97\rangle$	$\langle L@0.out, 0, (43, 54)\rangle$	$\langle L@0.out, 15, (43, 54)\rangle$
		$\langle L@0.out, 43, 97\rangle$	$\langle L@0.out, 60, 97\rangle$	$\langle L@0.v, 0, (15, 34)\rangle$
		$\langle L@0.v, 0, (34, 15)\rangle$	$\langle L@0.v, 0, (34, 43)\rangle$	$\langle L@0.v[], 0, (15, 34)\rangle$
		$\langle L@2, 0, (15, 34)\rangle$	$\langle L@2, 0, (34, 15)\rangle$	$\langle L@2, 0, (34, 43)\rangle$
		$\langle L@2, 0, (43, 54)\rangle$	$\langle L@2, 0, 91\rangle$	$\langle L@2, 15, (15, 34)\rangle$
		$\langle L@2, 15, (34, 15)\rangle$	$\langle L@2, 15, (34, 43)\rangle$	$\langle L@2, 15, (43, 54)\rangle$
		$\langle L@2, 15, 91\rangle$	$\langle L@2, 60, 91\rangle$	$\langle L@4, 74, 79\rangle$
	all-secondary-uses	$\langle L@0, 0, (15, 60)\rangle$	$\langle L@0, 0, (15, 74)\rangle$	$\langle L@0, 0, (34, 60)\rangle$
		$\langle L@0, 0, (34, 74)\rangle$	$\langle L@0, 0, (43, 60)\rangle$	$\langle L@0, 0, (43, 74)\rangle$
		$\langle L@0, 0, (60, 74)\rangle$	$\langle L@0.out, 0, (43, 60)\rangle$	$\langle L@0.out, 0, (43, 74)\rangle$
		$\langle L@0.out, 15, (43, 60)\rangle$	$\langle L@0.out, 15, (43, 74)\rangle$	$\langle L@0.out, 43, (43, 60)\rangle$
		$\langle L@0.out, 43, (43, 74)\rangle$	$\langle L@0.v, 0, (15, 60)\rangle$	$\langle L@0.v, 0, (15, 74)\rangle$
		$\langle L@0.v, 0, (34, 60)\rangle$	$\langle L@0.v, 0, (34, 74)\rangle$	$\langle L@0.v[], 0, (15, 60)\rangle$
		$\langle L@0.v[], 0, (15, 74)\rangle$	$\langle L@2, 0, (15, 60)\rangle$	$\langle L@2, 0, (15, 74)\rangle$
		$\langle L@2, 0, (34, 60)\rangle$	$\langle L@2, 0, (34, 74)\rangle$	$\langle L@2, 0, (43, 60)\rangle$
		$\langle L@2, 0, (43, 74)\rangle$	$\langle L@2, 15, (15, 60)\rangle$	$\langle L@2, 15, (15, 74)\rangle$
		$\langle L@2, 15, (34, 60)\rangle$	$\langle L@2, 15, (34, 74)\rangle$	$\langle L@2, 15, (43, 60)\rangle$
		$\langle L@2, 15, (43, 74)\rangle$		

2.3.4 Complexity Analysis of Data-Flow Testing Criteria

TO BE DONE...

2.4 Dominators and Super-Block Analysis

Studies have shown that it is important to generate a test set with high coverage while testing C programs so that more faults are likely to be detected[16, 31, 32]. The same applies to Java programs without lost of generality. To explain our approach to increase the coverage as soon as possible w.r.t. a given test criterion (all-blocks in our example), consider the $\mathcal{BG}$ presented in Figure 6. The main idea is to assign different weights to each $\mathcal{BG}$ node based on dominator analysis and "super block" [1]. The objective is to generate a test to cover one of the areas with the highest weight, if possible, before other areas with a lower weight are covered so that the maximum coverage can be added in each single execution. In this way, we provide useful hints on how to generate efficient test cases to increase,

as much as possible with as few tests as possible, the control-flow (such as block and decision) and data-flow coverage (such as all-uses) of the programs being tested.

Basically, a super-block is a subset of nodes with the property that if any node in a super block is covered then all nodes in that super block are covered[2]. Pre- and post-dominator relationships among nodes are used to identify the set of super blocks from a given $\mathcal{BG}$. According to [1], a node u pre-dominates a node v denoted as $u \overset{pre}{\rightarrow} v$, if every path from the entry node to v contains u. A node w post-dominates a node v denoted as $u \overset{post}{\rightarrow} v$, if every path from v to the exit node contains w. For example, in Figure 6, nodes 0 and 34 pre-dominate node 74 and nodes 74.82 and 79 post-dominate it. Pre- and post-dominator relationships can be expressed in the form of pre- and post dominator trees, respectively. $u \overset{pre}{\rightarrow} v$ *iff* there is a path from u to v in the predominator tree. Similarly, $w \overset{post}{\rightarrow} v$ *iff* there is a path from w to v in the post-dominator tree. Figures 7(a) and 7(b) show the pre- and post-dominator trees of the $\mathcal{BG}$ in Figure 6.

The dominator relationship amongst $\mathcal{BG}$'s nodes is represented by a "basic block dominator graph" that corresponds to the union of the pre- and post-dominator trees. Figure 7(c) shows the basic block dominator graph of the $\mathcal{BG}$ in Figure 6.

From the basic block dominator graph, strongly connected components (super blocks) are identified and the corresponding super block dominator graph is obtained. A strongly connected component has a property that every node in the component dominates all other nodes in that component. For example, nodes {74, 74.82, 79} compose a strongly connected component.

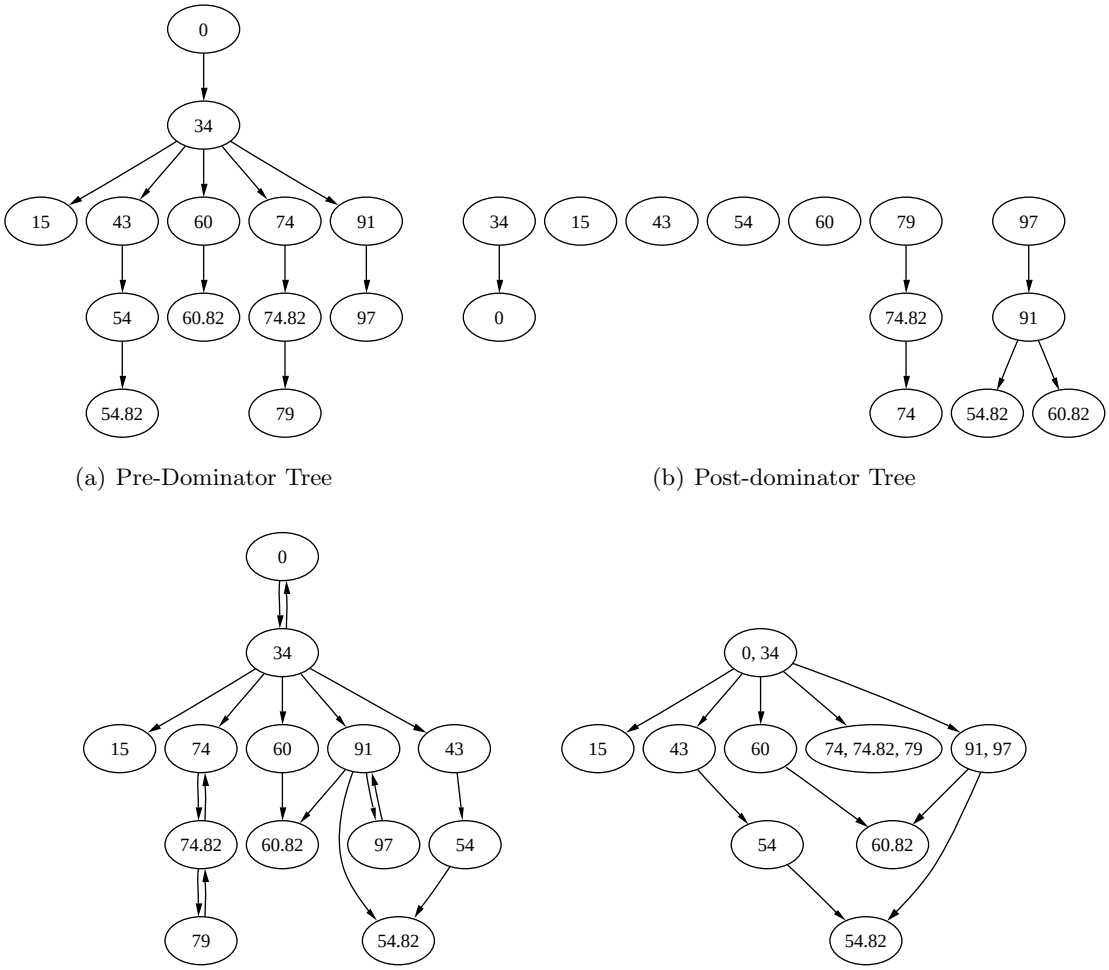
Figure 7(d) represents the super block dominator tree of the $\mathcal{BG}$ in Figure 6. From this representation it is possible to calculate the weight of each $\mathcal{BG}$ node. Basically, the weight of a given node is the number of nodes that have not been covered but will be if that block is covered. In Figure 8(a), the initial weight of each super block is show on the bottom of each node.

For example, to arrive at node 54.82 in Figure 6 requires the execution also to go through nodes 0, 34, 43, and 54. After arriving in node 54.82, nodes 91 and 97 will also be executed. This implies node 54.82 is dominated by nodes 0, 34, 43, 54, 91 and 97. It also means nodes 0, 34, 43, 54, 91 and 97 will be covered (if they haven't been) by a test execution if that execution covers node 54.82. Assuming none of the blocks is covered so far, we say that node 54.82 has a weight of at least 7 because covering it will increase the coverage by at least seven nodes. Using the same approach, node 15 has a weight of 3 since its coverage only guarantees an increase of coverage by at least three nodes. A very important note is that while assigning the weight to a given node, we use a conservative approach by counting only the additional nodes that will definitely be covered because of the coverage of this given node. This is why we use the phrase "at least" in the above statements. Of course, covering a node of a weight 7 (like node 54.82 in our example) may end up covering more than seven blocks (por ex., the execution can go through nodes 0, 34, 15, 34, 43, 54 before it reaches node 54.82 and continues though nodes 91 and 97). Nevertheless, the additional nodes (node 15 in our example) are not guaranteed to be covered.

Since node 54.82 has a higher weight than node 15, we say that node 54.82 has a higher priority to be covered than node 15 (i.e., tests that cover node 54.82 have a higher priority to be executed than tests that only cover node 15)[3] so that the maximum node coverage can be added in each single

[2]Assuming that the underlying hardware does not fail and no exception is raised during the execution of a test

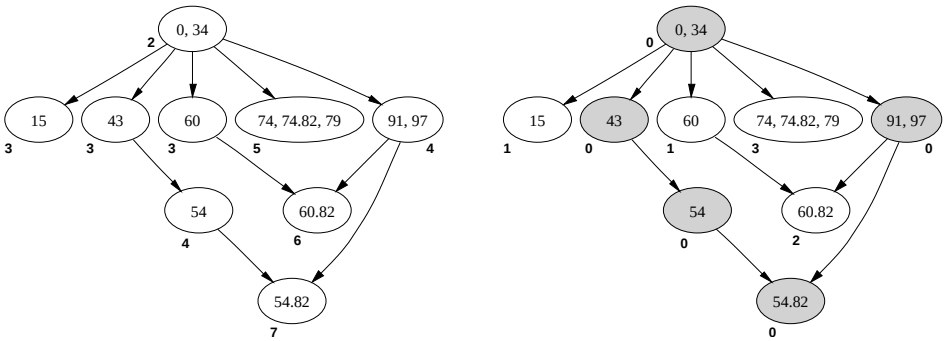
[3]Observe that, we are using the term high priority only considering the coverage that will be obtained. The tester, based on his experience may desire to cover first a node with a lower weight but that has a higher complexity in terms of implementation, i.e., depending on the criticality of a given part of the code, or based on another assumption, the tester can choose to cover a different node first and then, by recomputing the weight, to use the weight information to increase the coverage faster.



(a) Pre-Dominator Tree (b) Post-dominator Tree

(c) Basic Block Dominator Tree (d) Super Block Dominator Tree

Figure 7: Control-Flow Dependence Analysis.



(a) (b)

Figure 8: Super block dominator graph with weights: (a) before any test case execution, and (b) after the execution of one test case.

execution. In this way, the node coverage can be increased as much as possible with as few tests as possible.

After executing certain tests the weights of nodes that are not covered by these tests may change. For example, after the execution of a test (say t_1) that covers node 54.82 (which also guarantees the coverage of node 0, 34, 43, 54, 91 and 97), the execution of another test (say t_2) to cover node 15 will

increase the coverage by only one node (namely, node 15 itself). This is because nodes 0 and 34 have already been covered by test t_1 and the execution of other tests (such as t_2) will not change this fact. Under this scenario, after t_1 has been executed, node 15 will have weight one. This implies that after a test (t_1 in our case) is executed to cover node 54.82, the priority, in terms of increasing the coverage, of executing another test (t_2 in our case) to cover node 15 may be reduced.

This procedure is applied recursively after the execution of each test to recompute the weight of each node that has not been covered by the current tests, as well as the priority of tests to be executed for covering such nodes. The objective is to continue this recursive procedure until all the blocks, if possible, are covered by at least one test (i.e., achieve 100% node coverage) or the execution will stop after a predefined time-out been reached. In the latter case, although tests so executed might not give 100% node coverage, they still provide as high a block coverage as possible. In the reality, as mentioned in [1], the tester only needs to create test cases that covers one node of each leaf node in the super block dominator graph to cover all the other nodes.

2.5 Program Slicing

Computer programmers break apart large programs into smaller coherent pieces. Each of these pieces: functions, subroutines, modules, or abstract datatypes, is usually a contiguous piece of program text. Programmers also routinely break programs into one kind of coherent piece which is not contiguous. When debugging unfamiliar programs programmers use program pieces called slices which are sets of statements related by their flow of control or data. The statements in a slice are not necessarily textually contiguous, but may be scattered through a program [29]. A program slice consists of the parts of a program that (potentially) affect the values computed at some point of interest. Such a point of interest is referred to as a slicing criterion, and is typically specified by a location in the program in combination with a subset of the program's variables and/or statements. The task of computing program slices is called program slicing. The original definition of program slicing was proposed by Weiser in 1979 [28, 30]. Today, a lot of slightly different notions of program slices can be found in the literature, as well as a number of criteria to compute them [23]. An important distinction exists between a static and a dynamic slice. Static slices are computed without making assumptions regarding a program's input, whereas the computation of dynamic slices relies on a the execution trace information of specific test case.

Program slicing is a broadly applicable program analysis technique that can be used to perform different software engineering activities, such as: program understanding, debugging, testing, parallelization, re-engineering, maintenance, and others [6]. In the context of JaBUTi, the three most important activities are program understanding, debugging and testing.

Program understanding uses program slicing to help engineers to understand code. For example, a backward slice from a point in the program identifies all parts of the code that contribute to that point. A forward slice identifies all parts of the code that can be affected by the modification to the code at the slice point.

Testing and Regression Testing also uses slicing. For example, suppose a proposed program modification only changes the value of variable v at program point p. If the forward slice with respect to v and p is disjoint from the coverage of regression test t, then test t does not have to be rerun. Suppose a coverage tool reveals that a use of variable v at program point p has not been tested. What input data is required in order to cover p? The answer lies in the backward slice of v with respect to p.

In Section 7 it is described the characteristics JaBUTi's slicing tool and how to use it to smart debugging and fault localization.

2.6 Complexity Metrics

Complexity metrics are very useful to several software engineering tasks. Their main objective is to provide different kinds of measure of a project/program such that further projects can use the historical database to better estimate time, cost and complexity of new projects. There are different kinds of complexity metrics. For example, Lorenz e Kidd [12] defined a set of design metrics to evaluate static characteristics of an OO software project. The proposed set of metrics is divided into three groups: 1) **Class Size Metrics** to quantify individual classes; 2) **Class Inheritance Metrics** to evaluate the quality of using inheritance; and 3) **Class Internal Metrics** to evaluate general characteristics of a class.

Another well-known set of metrics, proposer by Chidamber and Kemerer [4], is composed by six design metrics six design metrics developed to evaluate the complexity of a given class.

Utsonomia [24] have studied and adapted both sets of design metrics for Java bytecode. JaBUTi implements such adapted metrics to allow a tester to collect static metrics information for the classes under testing.

Another benefit of complexity metrics is that the collected information can be used to establish incremental testing strategies by prioritizing the test of certain classes, reducing the cost and improving the quality of the testing activity. For instance, JaBUTi prioritizes testing requirements based on coverage information. By using complexity metrics, the class's inheritance, size, and complexity can be combined with coverage information, providing additional hints to reduce the cost of test case generation.

In Section 8 it is described how to use JaBUTi to collect static information about the classes under testing, considering the set of complexity metrics adapted from Lorenz e Kidd [12] and Chidamber and Kemerer [4] works.

3 The Vending Machine Example

To illustrate the JaBUTi's functionalities we will use a simple example, adapted from [15], consisting of a component and an application that uses it. Figure 9 shows the Java source code of the VendingMachine application and of the Dispenser component. Although JaBUTi does not require the source code available to perform its operations, we show it here to ease the understanding of the vending machine application.

This source code implements a typical vending machine that is able to dispense specific items to a customer under certain conditions. The basic operations that a given customer may perform are: (1) to insert a coin of 25 cents into the machine (VendingMachine.inservCoin()); (2) to ask the machine to return the inserted and not consumed coins (VendingMachine.returnCoin()); and (3) to ask the machine to vend a specific item (VendingMachine.vendItem()). The Dispenser component keeps information about the price of each item and which items are valid and available. The basic steps performed by the Dispenser component are:

1. Checks if at least one coin have been inserted;

2. Checks if a valid item have been selected;

3. Checks if the valid item selected is available;

4. Checks if the credit is enough to buy the valid available selected item.

Different error messages are generated by the Dispenser component in case the pre-requirements to delivered a given item are not satisfied. Dispenser's source code lines 16, 18, 20 and 24 illustrates these messages.

In case all pre-requirements are satisfied, the message at source line 26 is displayed indicating that the operation was performed successfully. Observe that the vector of integers availSelectionVals (Dispeser's source line 08) defines the current set of valid and available items. For example, according to availSelectionVals, items 5, 18 and 20 are unavailable. Such a vector can be updated by calling the Dispeser.setValidSelection() method (Dispeser's source line 42).

```
/*01*/ package vending;
/*02*/
/*03*/ public class VendingMachine {
/*04*/
/*05*/    final private int COIN = 25;
/*06*/    final private int VALUE = 50;
/*07*/    private int totValue;
/*08*/    private int currValue;
/*09*/    private Dispenser d;
/*10*/
/*11*/    public VendingMachine() {
/*12*/        totValue = 0;
/*13*/        currValue = 0;
/*14*/        d = new Dispenser();
/*15*/    }
/*16*/
/*17*/    public void insertCoin() {
/*18*/        currValue += COIN;
/*19*/        System.out.println("Current value = " + currValue);
/*20*/    }
/*21*/
/*22*/    public void returnCoin() {
/*23*/        if (currValue == 0)
/*24*/            System.err.println("No coins to return");
/*25*/        else {
/*26*/            System.out.println("Take your coins");
/*27*/            currValue = 0;
/*28*/        }
/*29*/    }
/*30*/
/*31*/    public void vendItem(int selection) {
/*32*/        int expense;
/*33*/
/*34*/        expense = d.dispense(currValue, selection);
/*35*/        totValue += expense;
/*36*/        currValue −= expense;
/*37*/        System.out.println("Current value = " + currValue);
/*38*/    }
/*39*/ } // class VendingMachine
```

```
/*01*/ package vending;
/*02*/
/*03*/ public class Dispenser {
/*04*/    final private int MINSEL = 1;
/*05*/    final private int MAXSEL = 20;
/*06*/    final private int VAL = 50;
/*07*/
/*08*/    private int[] availSelectionVals =
/*09*/            { 1, 2, 3, 4, 6, 7, 8, 9, 10,
/*10*/                11, 12, 13, 14, 15, 16, 17, 19};
/*11*/
/*12*/    public int dispense(int credit, int sel) {
/*13*/        int val = 0;
/*14*/
/*15*/        if (credit == 0)
/*16*/            System.err.println("No coins inserted");
/*17*/        else if ((sel < MINSEL) || (sel > MAXSEL))
/*18*/            System.err.println("Wrong selection " + sel);
/*19*/        else if (!available(sel))
/*20*/            System.err.println("Selection " + sel + " unavailable");
/*21*/        else {
/*22*/            val = VAL;
/*23*/            if (credit < val) {
/*24*/                System.err.println("Enter " + (val − credit) + " coins");
/*25*/            } else
/*26*/                System.out.println("Take selection");
/*27*/        }
/*28*/        return val;
/*29*/    }
/*30*/
/*31*/    private boolean available(int sel) {
/*32*/        try {
/*33*/            for (int i = 0; i < availSelectionVals.length; i++)
/*34*/                if (availSelectionVals[i] == sel)
/*35*/                    return true;
/*36*/        } catch (NullPointerException npe) {
/*37*/            return false;
/*38*/        }
/*39*/        return false;
/*40*/    }
/*41*/
/*42*/    public void setValidSelection(int[] v) {
/*43*/        availSelectionVals = v;
/*44*/    }
/*45*/ } // class Dispenser
```

Figure 9: Example adapted from [15] of a Java application (VendingMachine) and one component (Dispenser).

Since neither VendingMachine nor Dispenser classes have a main method, to allow the invocation of each method of the VendingMachine class, we developed a test driver class (TestDriver) that accepts as

input a text file containing a set of methods' names that have to be executed in the VendingMachine class, creates an instance of VendingMachine, and perform the execution of the required methods. Figure 10 shows the source code of the test driver.

```
/*01*/ package vending;
/*02*/
/*03*/ import java.io.*; import java.util.StringTokenizer;
/*04*/
/*05*/ public class TestDriver {
/*06*/
/*07*/    static public void main(String args[ ]) throws Exception {
/*08*/
/*09*/       BufferedReader drvInput;
/*10*/       String tcLine = new String();
/*11*/
/*12*/       String methodName = new String();
/*13*/
/*14*/       VendingMachine machine = new VendingMachine();
/*15*/
/*16*/       if (args.length < 1)
/*17*/          drvInput = new BufferedReader(new InputStreamReader(System.in));
/*18*/       else
/*19*/          drvInput = new BufferedReader(new FileReader(args[0]));
/*20*/
/*21*/       System.out.println("VendingMachine ON");
/*22*/       // Machine is ready. Reading input...
/*23*/       while ((tcLine = drvInput.readLine()) != null) {
/*24*/          StringTokenizer tcTokens = new StringTokenizer(tcLine);
/*25*/
/*26*/          if (tcTokens.hasMoreTokens())
/*27*/             methodName = tcTokens.nextToken();
/*28*/
/*29*/          if (methodName.equals("insertCoin"))
/*30*/             machine.insertCoin();
/*31*/          else if (methodName.equals("returnCoin"))
/*32*/             machine.returnCoin();
/*33*/          else if (methodName.equals("vendItem")) {
/*34*/             Integer selection = new Integer(tcTokens.nextToken());
/*35*/
/*36*/             machine.vendItem(selection.intValue());
/*37*/          }
/*38*/       }
/*39*/       System.out.println("VendingMachine OFF");
/*40*/    }
/*41*/ }
```

Figure 10: Example of a test driver for `VendingMachine` and `Dispenser` classes.

For example, considering a typical execution of the vending machine, a customer insert a certain number of coins, ask to the vending machine to deliver a given item, and the vending machine dispenses the required item if it is valid and available. This steps can be represented by a text file input1 (Figure 11).

```
insertCoin
insertCoin
vendItem 3
```

Figure 11: A simple test case file: input1.

By executing the command illustrated in Figure 12, input1 is read line by line. The first two lines cause the execution of the method VendingMachine.insertCoin twice, indicating that the customer deposited 50 cents into the vending machine. The last line corresponds to the choice to buy the item number three, a valid item that will be delivered to the customer. Using this approach, valid and invalid test cases can be specified to check whether the VendingMachine application and the Dispenser component behave correctly w.r.t. their specifications.

```
java vending.TestDriver input1
```

Figure 12: How to execute the implemented test driver.

Orso *et al.* [15] comment that the source code presented in Figure 9 contains a fault in method Dispenser.dispense(): when a available item is selected and the credit is insufficient, but greater than zero, the variable val (set to VAL at line 22 of Dispenser class) is not set to zero; consequently, when control returns from Dispenser.dispense() to VendingMachine.vendItem(), currValue is erroneously decremented. To fix this error, the statement val = 0 should be included after the statement located at Dispenser.dispense()'s source line 24. Observe that we will use the faulty version of the Dispenser component to show how the slicing tool (described in Section 7) can be used to help the localization of such a fault.

4 JaBUTi Functionality and Graphical Interface

JaBUTi implements a subset of the functionalities provided by *xSuds*, a complete tool suite for C and C++ programs [2]. This section describes the operations that can be performed by JaBUTi. The graphical interface allows the beginner to explore and learn the concepts of control-flow and data-flow testing. Moreover, it provides a better way to visualize which part of the classes under testing are already covered and which are not. A general view of the JaBUTi graphical interface, including its menus, is presented in Figure 13. A brief description of each option on each menu is presented below.

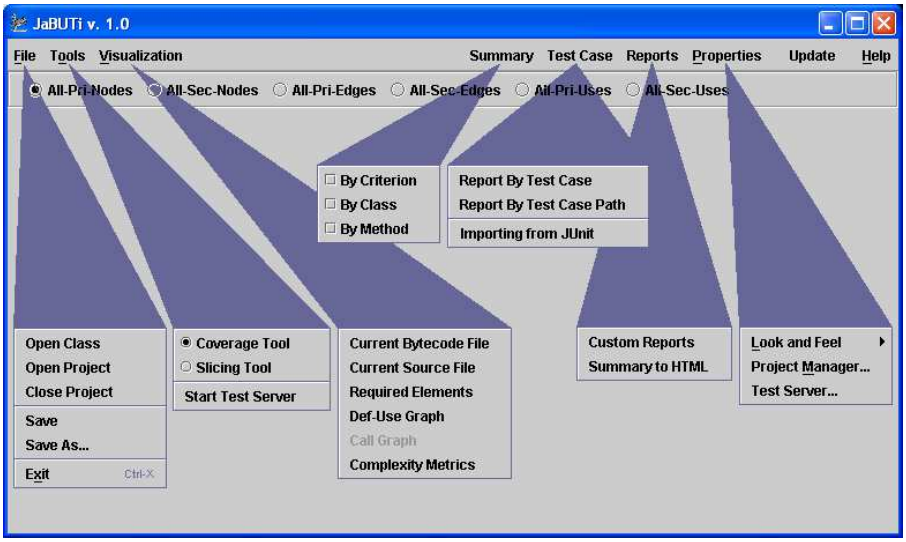


Figure 13: Operations available in the graphical interface.

- **File Menu** - provides options to create and manipulate a JaBUTi project.
  - **Open Class** - allows to select the base class file from where the classes to be tested are identified.
  - **Open Project** - opens a previously created project.
  - **Close Project** - closes the current project.
  - **Save** - saves the current project.

  - **Save As** - saves the current project with a different name.
  - **Exit** - exits of the tool.

- **Tools** - provides the set of tools available in JaBUTi.
  - **Coverage Tool** - enables the JaBUTi coverage tool.
  - **Slicing Tool** - enables the JaBUTi slicing tool.

- **Visualization** - provides different forms of visualization of the classes and methods under testing.
  - **Current Bytecode File** - shows the highlighted bytecode of the current selected class file.
  - **Current Source File** - shows the highlighted source code of the current selected class file. Observe that this option requires that the source code is available to be performed.
  - **Required Elements** - shows the set of required elements for a given method of a given class, considering the current selected criterion (shown below the main menu). The presented screen also allows to mark a testing requirement as active/deactive or feasible/infeasible.
  - **Def-Use Graph** - shows the DUG of a given method of the current class.
  - **Complexity Metrics** - shows the resultant value of the set of complexity metrics implemented in JaBUTi for the complete set of user classes obtained from the base class. This set of classes includes the classes under testing.

- **Summary** - provides personalized coverage information in different levels of abstractions.
  - **By Criterion** - shows the cumulative coverage information for each testing criterion, considering all classes under testing.
  - **By Class** - shows the coverage information with respect to the current selected criterion, for each individual class under testing.
  - **By Method** - shows the coverage information with respect to the current selected criterion, for each individual method of each class under testing.

- **Test Case** - provides options for test set manipulation and report generation.
  - **Report By Test Case** - shows the coverage information with respect to the current selected criterion, for each individual test case, considering all class under testing. The presented screen also allows to enable/disable and delete/undelete test cases.
  - **Report By Test Case Path** - shows the coverage information with respect to the current selected criterion, for each individual test case path, considering all class under testing.
  - **Importing from JUnit** - allows to import a test set generated according to the JUnit framework.

- **Reports** - provides options to save JaBUTi's reports in HTML format.
  - **Custom Reports** - allows to generate a custom HTML report from the current testing project considering different levels of granularity.
  - **Summary to HTML** - allows to generate a HTML from any tabled style report provided by the JaBUTi graphical interface.

- **Properties** - provides general configuration options.
  - **Look and Feel** - allows to change the look and feel style considering three different options: Metal (default), Motif, and Windows.
  - **Project Manager...** - allows to verify and change the current set of classes under testing in the current project.
- **Update** - provides a visual information every time an event that affect the coverage occurs. For example, such a button becomes red in case additional test cases are imported or appended in the end of the trace file to indicate that a new event that affects the coverage information occurs. As soon as it is clicked, its background color changes to grey.
- **Help** - provides only one option to show information about the authors/developers of JaBUTi.

JaBUTi requires the creation of a testing project, such that the tester can specify only once the set of classes to be instrumented and tested. Section 5 describes how to create a JaBUTi's testing project. After having created the project, JaBUTi provides to the tester a coverage analysis tool, a slicing tool and a static metric measure tool. The coverage analysis tool is described in Section 6. Section 7 describes the slicing tool, and Section 8 describes the measure tool.

5 How to Create a Testing Project

In JaBUTi the testing activity requires the creation of a testing project. A testing project is characterized by a file storing the necessary information about (i) the base class file, (ii) the complete set of classes required by the base class, (iii) the set of classes to be instrumented (tested), and (iv) the set of classes that are not under testing. Additional information, such as the CLASSPATH environment variable necessary to run the base class is also stored in the project file, whose extension is .jbt. During the execution of any .class file that belongs to the set of classes under testing of a given project, dynamic control-flow information (execution trace) is collected and saved in a separate file that has the same name of the project file but with a different extension (.trc).

For example, considering the vending machine example, described in Section 3, the vending package is composed by three .java files: VendingMachine.java, Dispenser.java and TestDriver.java. Suppose that these files are saved in a directory named `~\example`. The directory structure is like:

```
auri@AURIMRV ~
$ ls -l example/*
-rw-r--r--    1 auri         1313 Aug  6 09:07 Dispenser.java
-rw-r--r--    1 auri         1340 Aug  6 09:07 TestDriver.java
-rw-r--r--    1 auri          923 Aug  6 09:07 VendingMachine.java
```

To compile such an application one of the following command can be used:

```
auri@AURIMRV ~
$ javac -d example example/*.java
```

or

```
auri@AURIMRV ~
$ javac -g -d example example/*.java
```

Observe that in the later command, the debug option is activated, thus, the generated .class files contains more information, such as the real variable names. In this report we are using class files compiled with the debug option.

After the Java source files have been compiled, the `~\example` directory contains the following structure:

```
auri@AURIMRV ~
$ ls -l example/*
-rw-r--r--    1 auri         1313 Aug  6 09:07 Dispenser.java
-rw-r--r--    1 auri         1340 Aug  6 09:07 TestDriver.java
-rw-r--r--    1 auri          923 Aug  6 09:07 VendingMachine.java
example/vending:
vending:
total 6
-rw-r--r--    1 auri         1478 Aug  6 09:49 Dispenser.class
-rw-r--r--    1 auri         1340 Aug  6 09:49 TestDriver.class
-rw-r--r--    1 auri         1253 Aug  6 09:49 VendingMachine.class
```

Now, from the generated .class files, the user can create a project using JaBUTi. To do this, the first step is to invoke JaBUTi's graphical interface. Supposing that JaBUTi is installed on `~\Tools\jabuti`, the command below causes the invocation of its graphical interface.

```
auri@AURIMRV ~/example
$ java -cp ".;..\Tools\jabuti;\
>..\Tools\jabuti\lib\BCEL.jar;\
>..\Tools\jabuti\lib\jviewsall.jar;\
>..\Tools\jabuti\lib\crimson.jar;\
>..\Tools\jabuti\lib\junit.jar" gui.JabutiGUI
```

Observe that the tool requires that some third-party libraries (BCEL [5] to manipulate the Java bytecode files, ILOG JViews [10] to visualize the DUG, Crimson to manipulate XML files[4], and JUnit [3] to import test sets.) to be included in the CLASSPATH to allow its execution. The current directory, (“.” in our example), and the base directory of the tool (`..\Tools\jabuti`) are also included to allow the correct execution of our example and the tool itself. If desired, the user can set the CLASSPATH environment variable as a system variable that is initialized during the boot process. In this case, to call JaBUTi's GUI, the parameter -cp can be omitted. Figure 14 illustrates the JaBUTi's initial window.

To create a new project, the first step is to select a base .class file from File → Open Class menu. A dialog window, as illustrated in Figure 15(a) appears. From this dialog window, the tester selects the directory where the base class file is located and then select the base class file itself (Figure 15(b)). Once the base class file is selected the tool automatically identifies the package that it belongs (if any) and fills out the Package field with the package's name. The Classpath should contains only the path necessary to run the selected base class. In our example, since the tool is being called inside the

[4]Such a package is required when a java compiler under version 1.4.1 is used (considering the Sun compiler)).

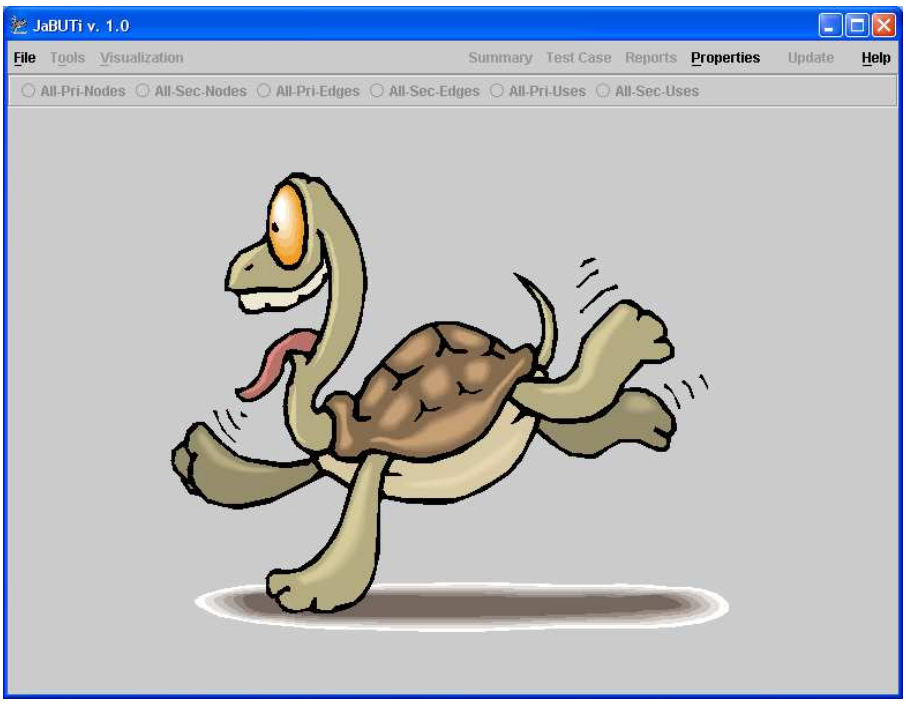
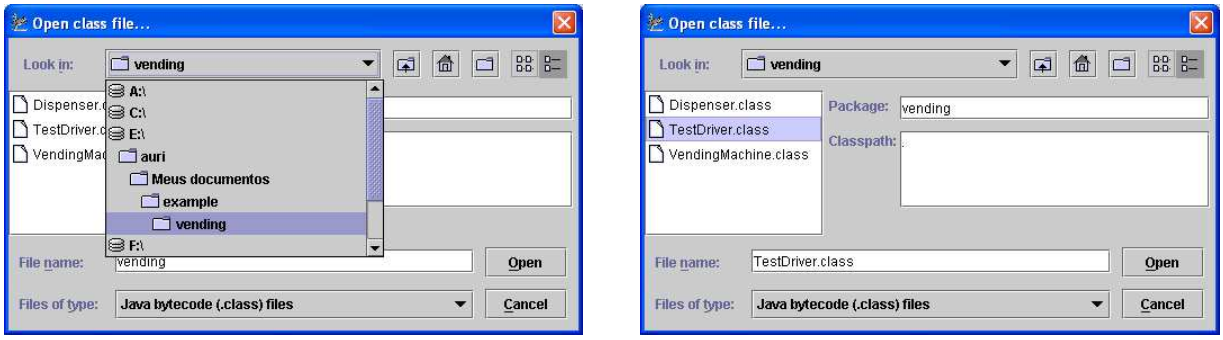


Figure 14: JaBUTi main window.

~\example directory, to run vending.TestDriver it is necessary that the Classpath field contains only the current directory, as shown in Figure 15(b).



(a) (b)

Figure 15: Open Class: (a) Selecting the directory and (b) Selecting the main class file.

By clicking the Open button (Figure 15(b)), the Project Manager window, as illustrated in Figure 16, will be displayed. From the selected base class file (TestDriver in our example) the tool identifies the complete set of system and non-system class files necessary to execute TestDriver. Currently, JaBUTi does not allows the instrumentation of system class files. Therefore, the complete set of non-system class files (user's classes) relate to TestDriver can be instrumented. From the Project Manager window (left side) the user can select the class files that will be tested. At least one class file must be selected. In our example, we select VendingMachine and Dispenser to be instrumented. TestDriver was not selected since it is only the driver that allows the tester to observe whether the behavior of VendingMachine and Dispenser are correct with respect to their specification.

Moreover, the tester must give a name to the project being created (vending.jbt in our example) by clicking on the Select button. By clicking on the Ok button, JaBUTi creates a new project (vending.jbt

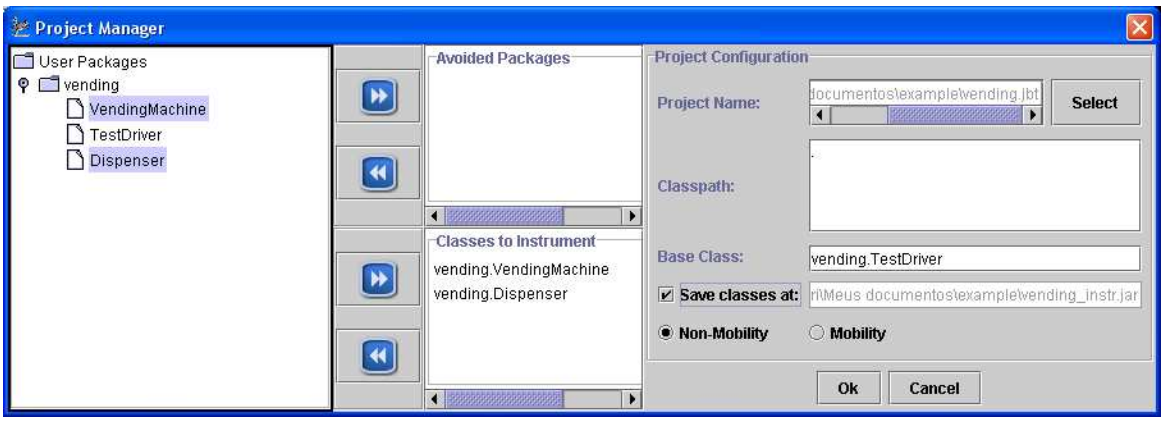


Figure 16: Selecting the class files to be tested.

in our example), constructs the DUG for each method of each class under testing, derives the complete set of testing requirements for each criterion, calculates the weight of each testing requirement, and presents the bytecode of a given class under testing. By creating a project, the tester does not need to go through this entire process again if he/she intends to test the same set of class files. Next time, he/she can just go to File → Open Project menu option and reload a previously saved project.

Once the project is created, the tester just need to open it and the tool automatically detects the classes that compose it. JaBUTi can be used for analyzing the coverage of a given class file, for debugging the class file using the slice tool and for collecting static metrics information. JaBUTi also allows the visualization of the Def-Use Graph (DUG) of each method in a given class file as well as the visualization of the source code, when available. Different kinds of testing reports can also be generated considering different levels of abstraction. The following sections describe these features in detail.

6 How to use JaBUTi as a Coverage Analysis Tool

By default, the tool displays the bytecode instead of the Java source code, since the source code may not be available. The user can use the Visualization menu to change the display to show the bytecode or source code, as well as the DUG of each method in the current class. As can be observed in Figure 17, JaBUTi uses different colors to provide hints to the tester to ease the test generation. The different colors represent requirements with different weights, and the weights are calculated based on dominator and super-block analysis [1]. Informally, the weight of a testing requirement corresponds to the number of testing requirements that will be covered if this particular requirement is covered. Therefore, covering the requirement with the highest weight will increase the coverage faster[5]. The weight schema is used in all views of a given class/method: bytecode, source code and DUG. Figure 17 shows part of the colored bytecode of the Dispenser.dispense() method before the execution of any test case and Figure 18 part of the DUG of the same method. The different colors correspond to the weight of each node, considering the All-Pri-Nodes criterion. Observe that the color bar (below the main menu) goes from white (weight 0) to red (weight 13).

[5]Observe that the weight is calculated considering only the coverage information and should be seen as hints. It does not take into account, for instance, the complexity or the criticality of a given part of the program. The tester, based on his/her experience may desire to cover first a requirement with a lower weight but that has a higher complexity or criticality and then, after recomputing the weights, uses the hints provided by JaBUTi to increase the coverage faster.

In our example, observe that the node 105 in Figure 18, composed by bytecote instructions from 105 to 112 (Figure 17), is one of the highest weight. In this way, a test case that exercises node 105 increases the coverage in at least 13. A requirement with weight zero is a covered requirement and it is painted in white.

Although the source code is not required by JaBUTi, when it is available, the corresponding source code of the current class can also be displayed in colors, mapped back from the bytecode, facilitating the identification of which part of the code should be covered first. For example, Figure 19 shows that the statement on line 24 has the highest priority w.r.t. the All-Pri-Nodes criterion. By covering this particular node, at least 13 other nodes will be covered.

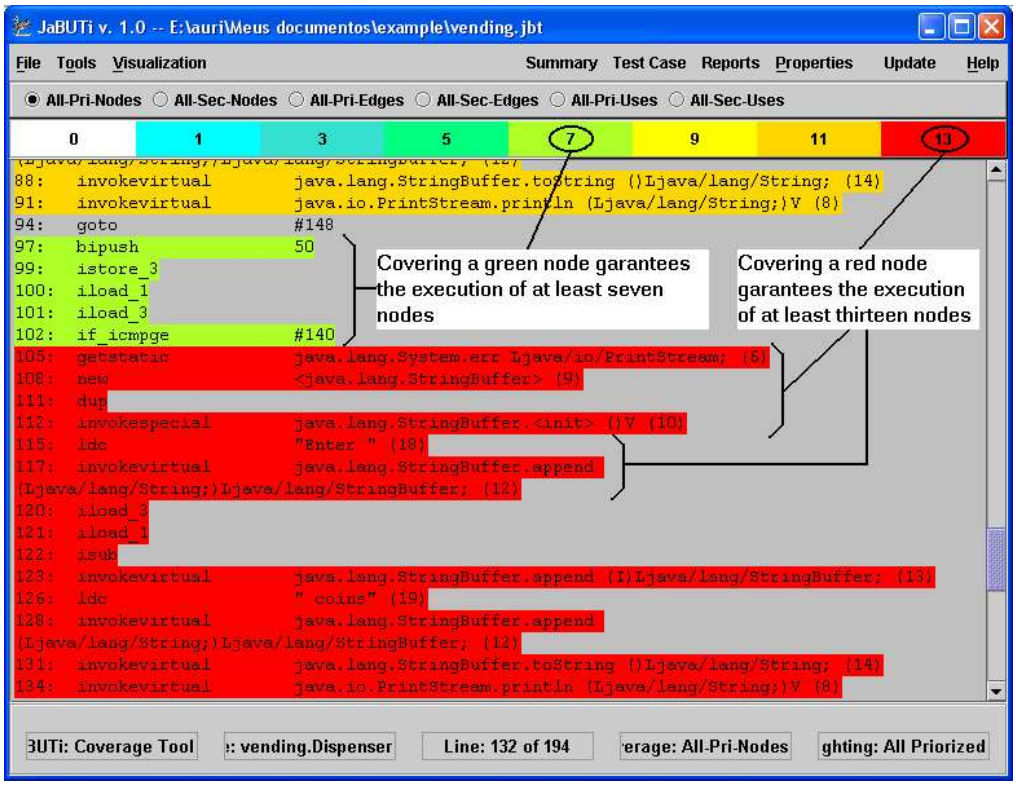


Figure 17: Dispenser.dispenser method: bytecode prioritized w.r.t. All-Pri-Nodes criterion.

Considering the DUG presented in Figure 18, it can be observed that there are two different types of nodes, represented by single and double line circles. As described in Section 2.2, double circles represent call nodes, i.e., nodes where exists a method call to another method. This nodes are identified since we intend to extend our tool to deal, not only with intra-method testing criteria, but also with inter-method testing criteria that requires the identification of the relationship among methods. Bold circles, not visible in Figure 18, represent exit nodes. Observe that methods in Java can have more that one exit node due to the exception-handling mechanism. All the other nodes are represented as single line circles. We also have two different types of edges to represent the "normal" control-flow (continuous line – Primary Edges) and exception control-flow (dashed lines – Secondary Edges). Figure 18 does not contain exception edges. Primary and secondary edges can be hidden by deselecting the Show Primary and Show Secondary Edges check box, respectively. The node information shown when the cursor is moved onto the node, as illustrated in Figure 18, can also be disabled by deselecting the Show Node Info check box.

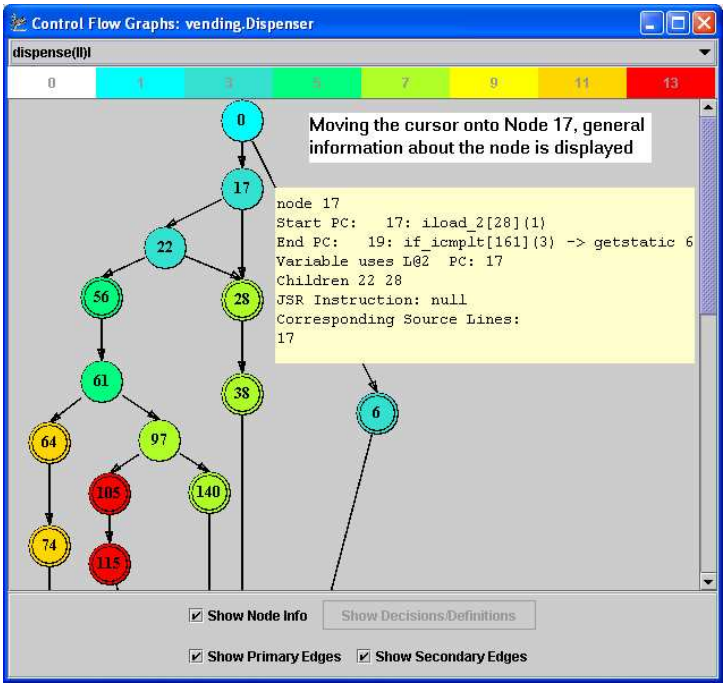


Figure 18: Dispenser.dispenser method: DUG prioritized w.r.t. All-Pri-Nodes criterion.

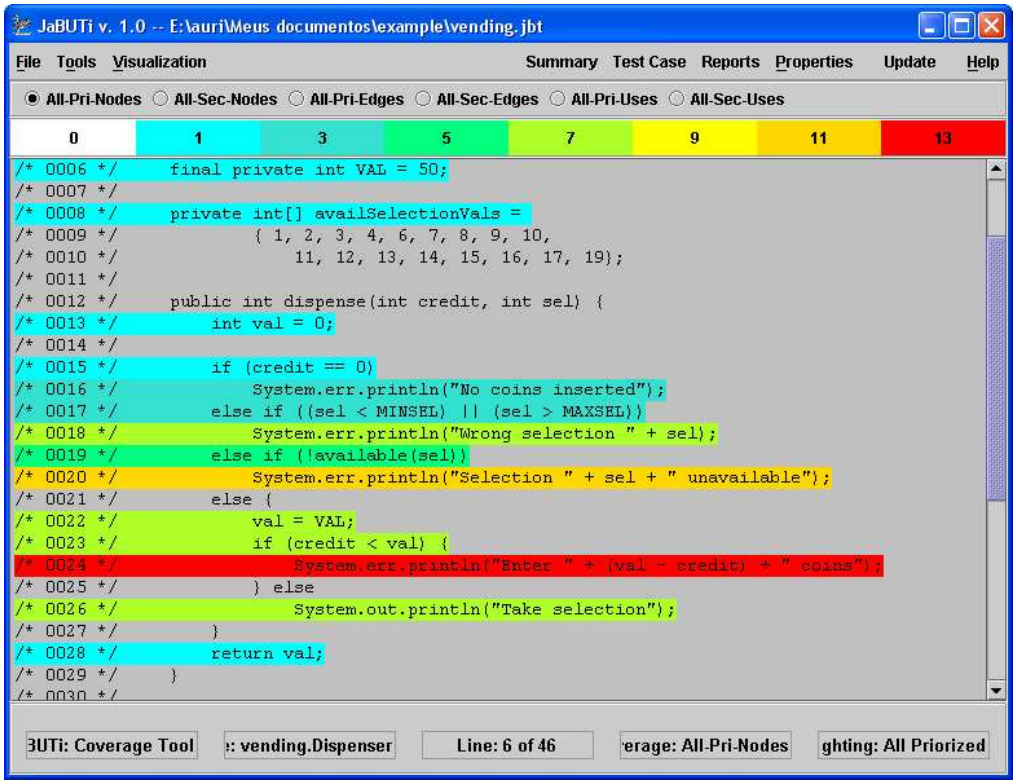


Figure 19: Dispenser.dispenser method: source code prioritized w.r.t. All-Pri-Nodes criterion.

6.1 How the testing requirements are highlighted

As can be observed above the main menu in Figure 17, JaBUTi supports the application of six structural testing criteria, as described in Section 2.3: All-Pri-Nodes, All-Sec-Nodes, All-Pri-Edges, All-Sec-Edges, All-Pri-Uses, and All-Sec-Uses. Depending on which criterion is active, the bytecode,

source code or DUG is colored in a different way. Figures 17, 18, and 19 show the color schema considering the All-Pri-Nodes criterion, which is the same as the All-Sec-Nodes, i.e., for these criteria, each requirement is a node, therefore, since each node has its own weight, the complete bytecode, source code or DUG appears highlighted according to the weight of each node.

Considering the All-Pri-Edges and All-Sec-Edges criteria, their requirements (DUG edges) are colored using a 2-layer approach. For All-Pri-Edges criterion, only the nodes with more than one out-going edge (decision nodes) are painted in the first layer. For example, Figure 20 shows part of the decision nodes of method Dispenser.dispense() and how they are painted in the first layer. For each decision node, its weight is the maximum weight of its branches. Suppose a decision node has two branches: one has a weight of 2 and the other has a weight of 7. The weight of this decision node is 7. This is the case of DUG node 61, in our example. A decision node has a zero weight if and only if all its branches are covered. Such decisions are highlighted in white. Observe that, in the bytecode view, only the last bytecode instruction of a decision node is highlighted, not the entire node as the All-Pri-Nodes and the All-Sec-Nodes criteria. For example, DUG decision node 22 goes from offset 22 to 25, although, in the bytecode view, only bytecode instruction at offset 25 is highlighted.

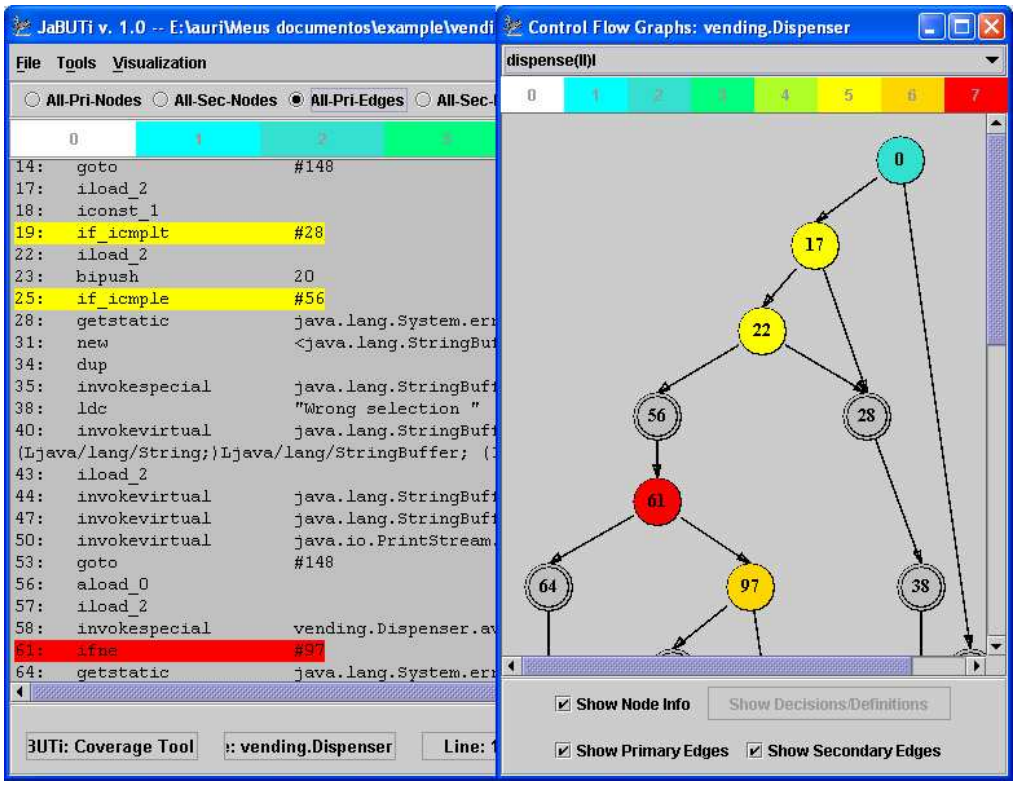


Figure 20: Color schema for All-Pri-Edges criterion: first layer.

By clicking either in a colored bytecode instruction or in a DUG node, all destination nodes of the branches associated with the selected decision node are highlighted and the decision node itself changes to a different color. For example, by clicking on the decision node with the highest weight (node 61 in the example), its children (nodes 64 and 97) are highlighted in different colors, considering their individual weights: node 64 has a weight of 7 (red) and node 97 has a weight of 2 (dark cyan), as illustrated in Figure 21. Therefore, to improve the coverage with respect to the All-Pri-Edges criterion, the tester should exercises first the edge $(61, 64)$, since it has the highest weight.

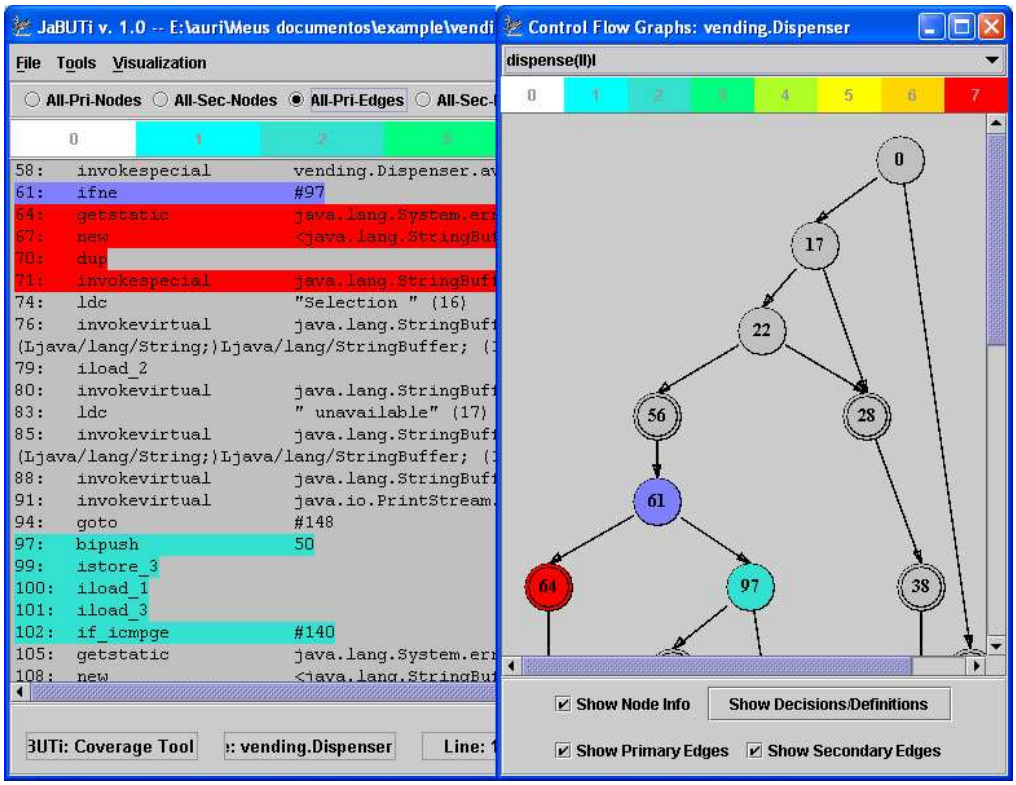
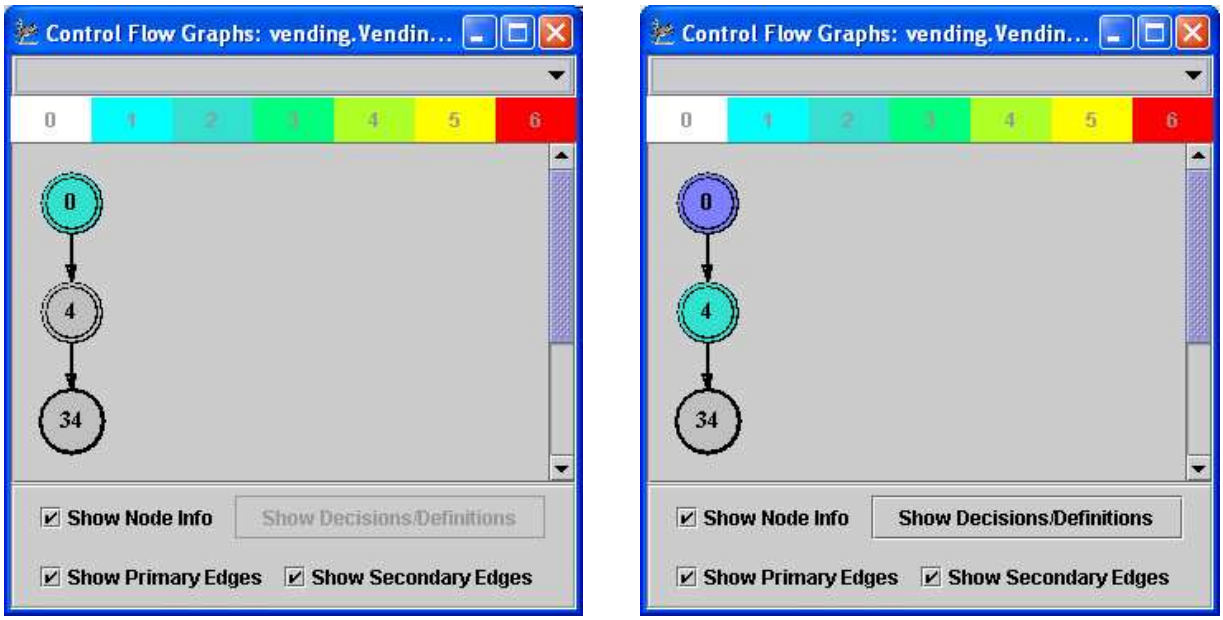


Figure 21: Color schema for All-Pri-Edges criterion: second layer.

Observe that, in case a given method has no decision node, only the entry node is painted in the first layer and its child in the second layer. In this case, edges criterion is equivalent to nodes criterion, since, in a normal execution, once the entry node is exercised, all the other nodes and edges are. Figure 22 illustrates how the DUG of the default constructor of the class VendingMachine (VendingMachine.init()) is highlighted before (Figure 22(a)) and after (Figure 22(b)) the node selection.



(a) (b)

Figure 22: Special case when no decision node is found.

For the All-Sec-Edges criterion, the same approach is used. In the first layer, all nodes with at least one secondary out-going edge, instead of decision nodes, are highlighted. For each such a node, its weight is the maximum weight of its branches and a node with more that one secondary out-going edge is considered covered (zero weight) if and only if all exception-handler associated with such a node is covered.

Figure 23 and 24 shows the first and the second layer of Dispenser.available() method, considering the All-Sec-Edges criterion, respectively. In this example, in the first layer, all highlighted nodes has the same weigh (one) since it has only one valid exception-handler for the entire method. In the bytecode view, only the last bytecode instruction of each node is highlighted. For example, node 20 goes from offset 20 to 26, therefore, bytecode instruction at offset 26 is highlighted. By clicking on such an instruction or on the DUG node 20, Figure 24 shows the resultant color schema of the second layer.

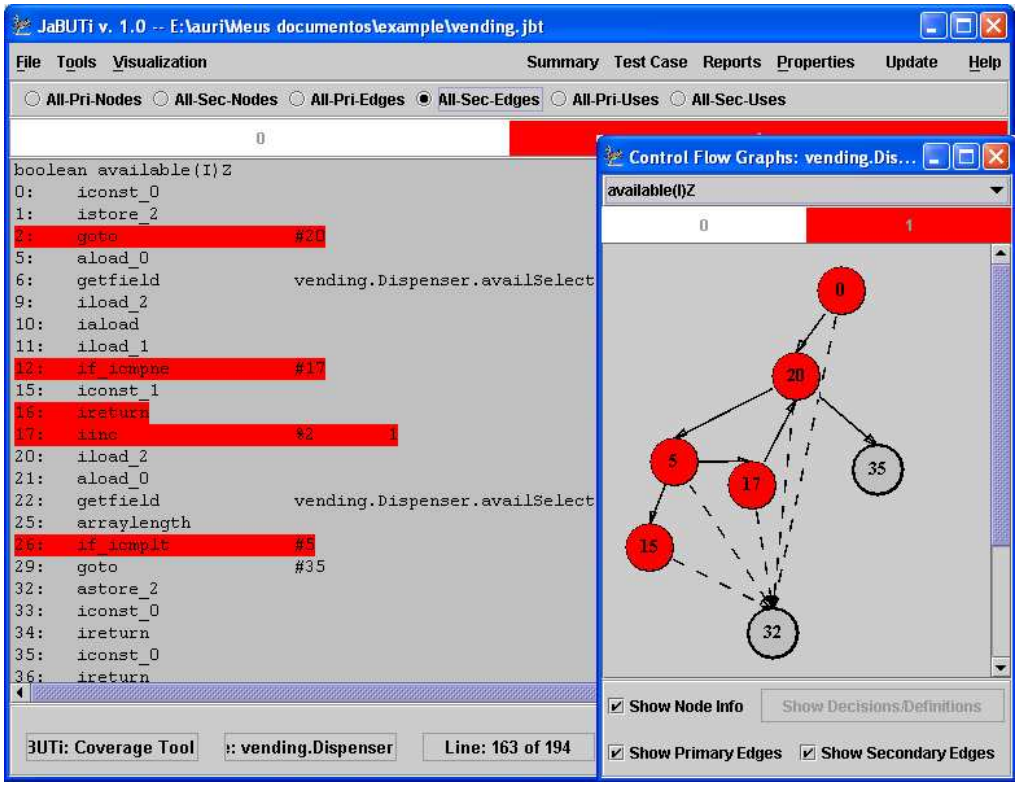


Figure 23: Color schema for All-Sec-Edges criterion: first layer.

Similar to a decision and its branches are displayed, a 2-layer representation is also used to display def-use associations for the All-Pri-Uses and All-Sec-Uses criteria. The first layer shows all the definitions which have at least one c-use or p-use association. Clicking on a definition goes to the second layer displaying all c-use and p-use associated with the selected definition. For each definition, its weight is the maximum weight of its c-uses or p-uses. For example, suppose a definition has three def-use associations, one c-use and two p-uses, and the weights of these associations are 5, 3 and 7, respectively. The weight of this definition is 7. A definition has a zero weight if and only if all its c-uses and p-uses are covered. Such definitions are displayed with a white background.

Since even in the bytecode, more than one variable may be defined in the same offset, if desired, by clicking with the right mouse button over a definition point (bytecode offset, source code line or DUG node), a pop-up menu is opened showing all the variables defined in that point such that it is

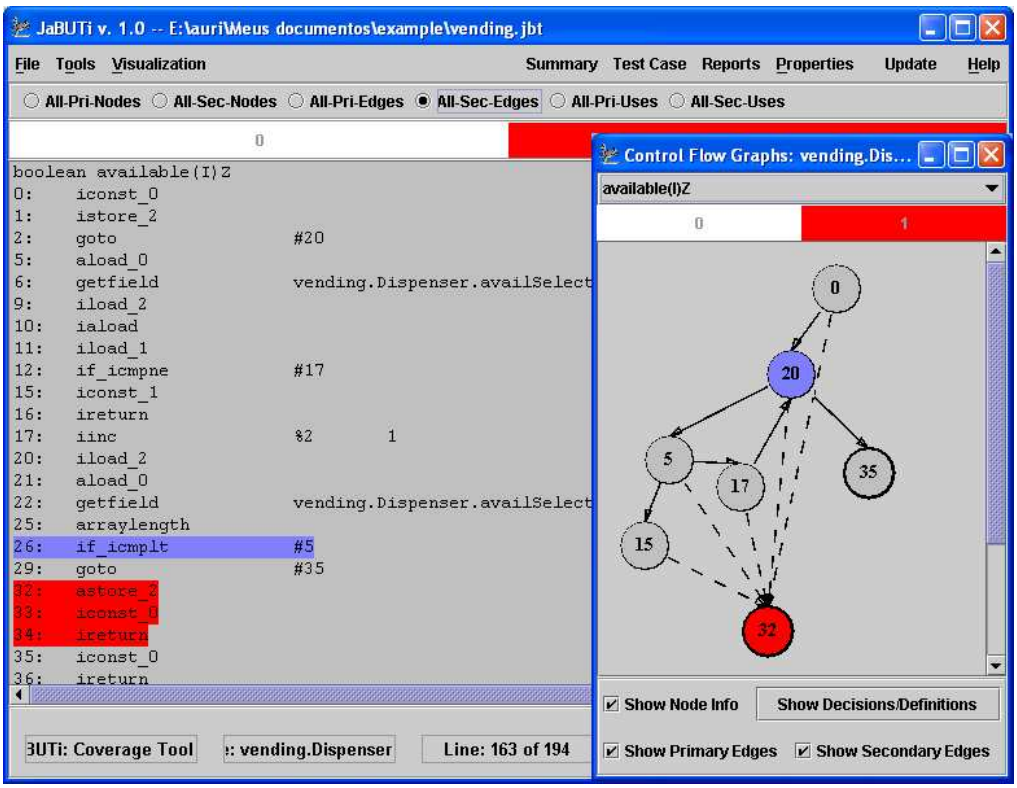


Figure 24: Color schema for All-Sec-Edges criterion: second layer.

possible to choose which variable definition to select. For example, Figure 25 shows the set of defined variables at bytecode offset 0 that is part of the DUG node 0. Observe that in the DUG node 0 there is one additional variable definition because L@3 (val) is defined at bytecode offset 1 that also belongs to DUG node 0. When a definition point is clicked with the left mouse button the definition with the highest weight is considered selected. If all of then have the same weight, the first is selected. In our example, supposing that L@1 (credit) is selected (the definition with the highest weight), Figure 26 shows some of its uses (p-uses in this case) with the corresponding weight.

It is important to observe that the weights provided by the tool may be seen as hints for the tester to facilitate the generation of test cases, such that a higher coverage can be obtained with fewer test cases. Since the prioritization does not consider the criticality of a given part of the code, if desired, the tester may choose a different part of the code to be tested first based on his/her knowledge about the application, even if such a part has a lower weight than other parts of the code. After the critical parts have to be tested, additional test cases can be developed considering the hints.

6.2 How to generate testing reports

To evaluate the coverage obtained, the tool provides personalized tabled style testing reports that can be accessed from the Summary and Test Case menus. Any tabled style report can be saved as a HTML file by accessing Reports → Summary to HTML menu option. The tool provides reports w.r.t. each testing criterion (Summary → By Criterion), w.r.t. each class file (Summary → By Class) and w.r.t. each method (Summary → By Method). Figures 27, 28, and 29 show each one of these reports, respectively, considering that no test case have been executed.

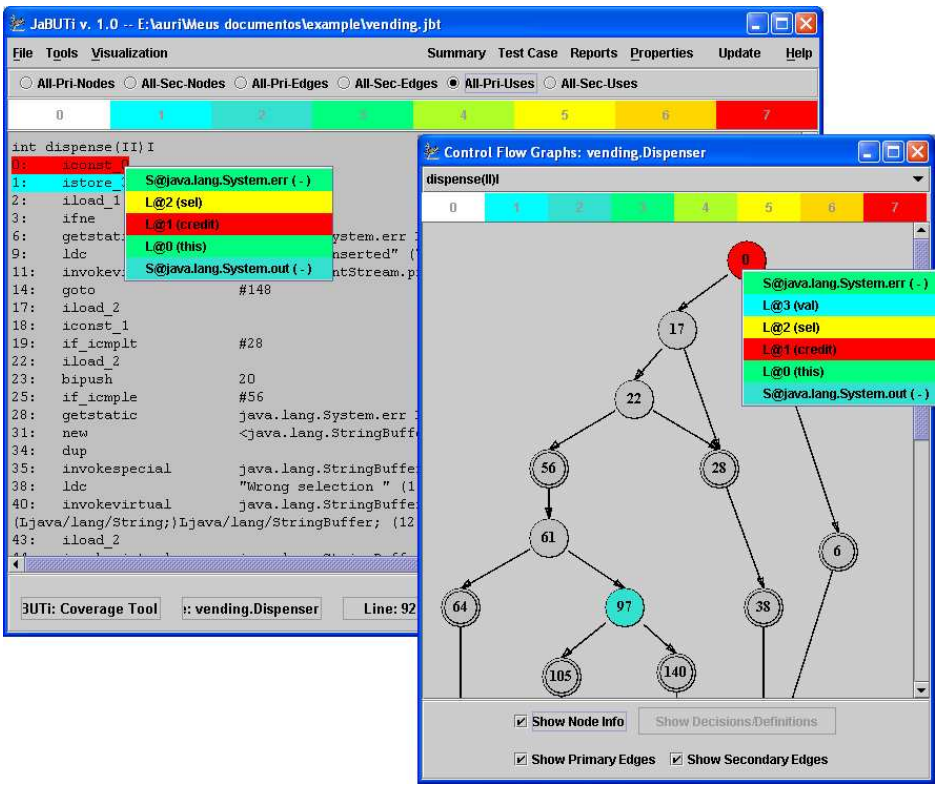


Figure 25: Color schema for All-Pri-Uses criterion: first layer.

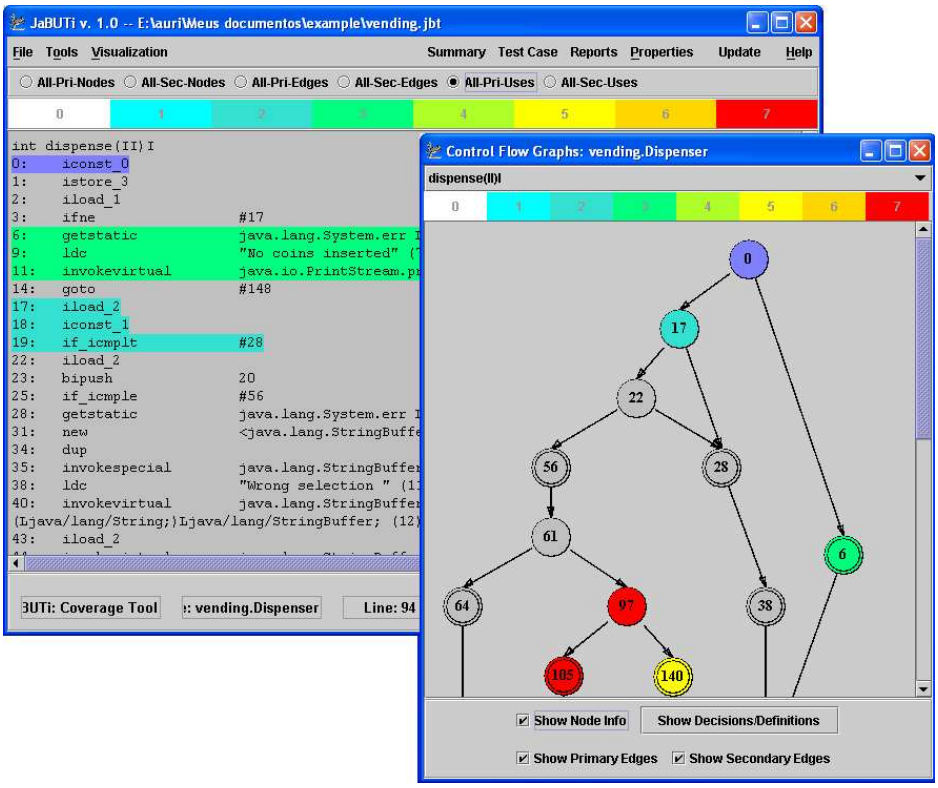


Figure 26: Color schema for All-Pri-Uses criterion: second layer.

For example, in Figures 27 it is possible to evaluate the number of required elements by criterion that were generated for the entire project, i.e., classes VendingMachine and Dispenser. The individual information per class file can be obtained by generating the summary report by class (Figures 28).

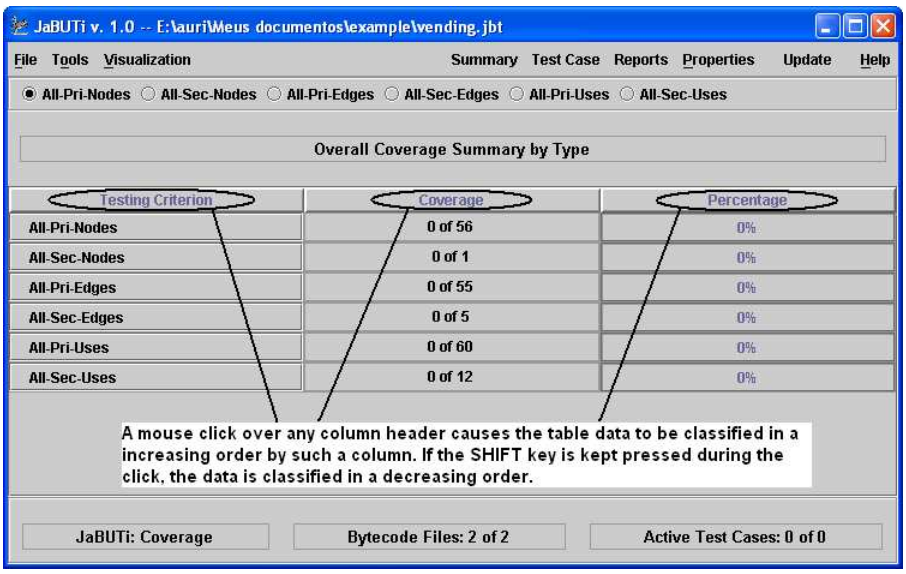
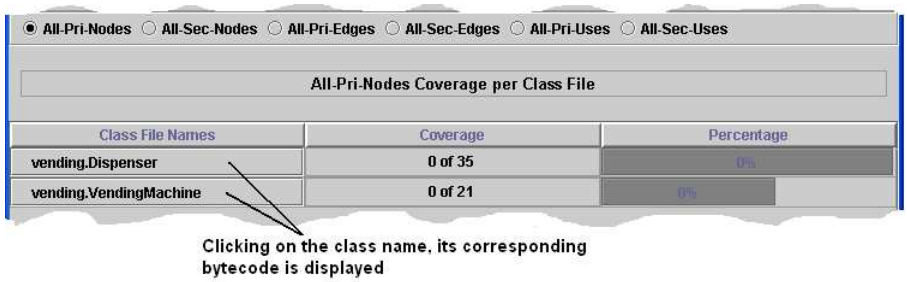


Figure 27: Initial summary information per testing criterion.

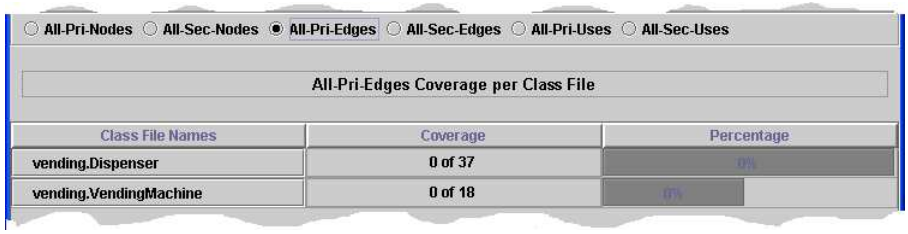
When showing the summary by class or by method, the tester can choose, among the available testing criteria, which one he/she wants to evaluate. Figures 28(a), 28(b), and 28(c) illustrate the summary per individual class w.r.t. the All-Pri-Nodes, All-Pri-Edges, and All-Pri-Uses criteria, respectively. Considering the summary by class and by method, by clicking on the class file name or in the method name, the corresponding bytecode is highlighted and displayed considering the weight w.r.t. the selected criterion.

As commented in Figures 27, double-clicking on the desired column header, any tabled report generated by JaBUTi is classified in an increasing order, considering the clicked column header. A double-click with the SHIFT key pressed causes the table data to be sorted in a decreasing order.

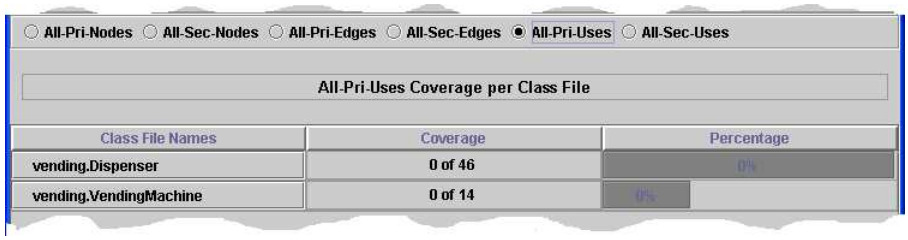
Using these summary reports the tester can evaluate the current coverage of each class under testing with different granularity and decides whether a given class requires additional testing w.r.t. six different intra-method testing criteria. Section 6.4 illustrates how to include test cases and how to generate testing reports by test case and by test case paths.



(a)



(b)



(c)

Figure 28: Initial summary per class file: (a) All-Pri-Nodes criterion, (b) All-Pri-Edges criterion, and (c) All-Pri-Uses criterion.

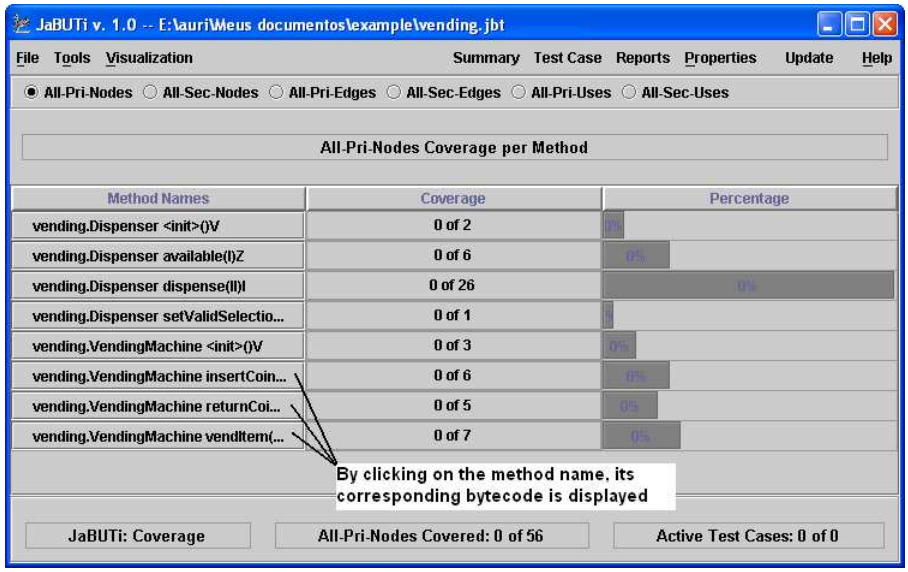
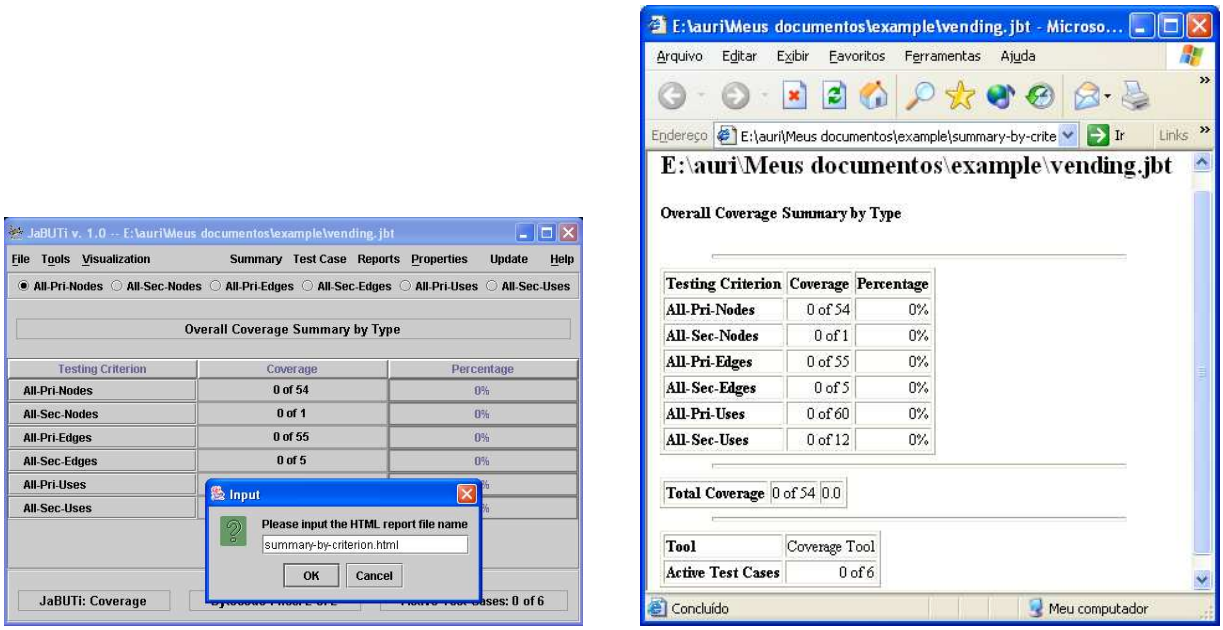


Figure 29: Initial summary information per method: All-Pri-Nodes criterion.

6.3 How to generate an HTML version of a JaBUTi report

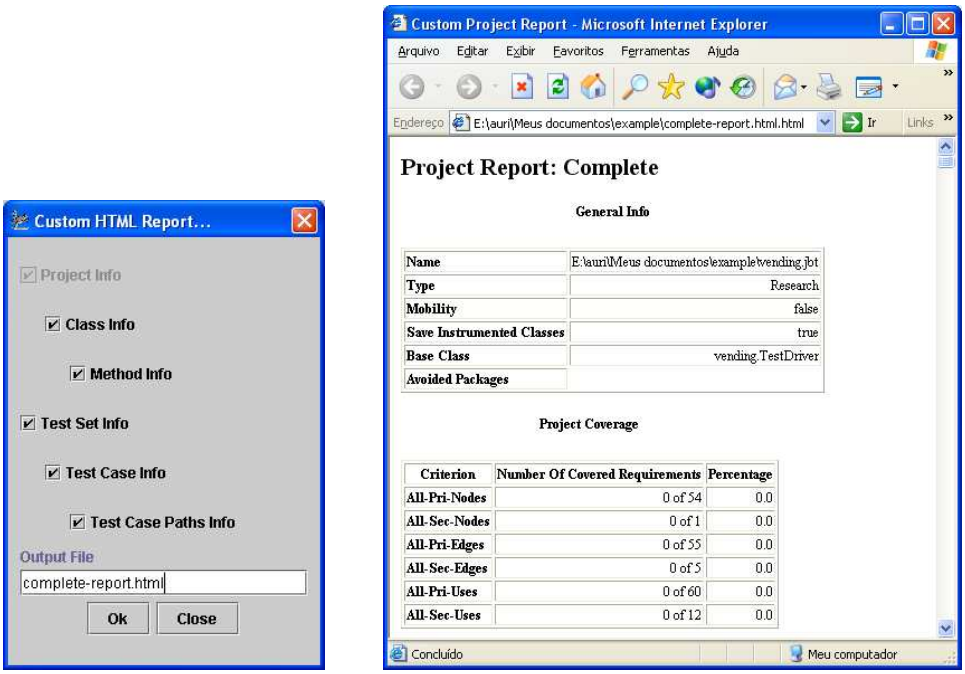
As mentioned above, any kind of tabled report presented in JaBUTi's graphical interface can be saved as an HTML file through the Reports → Summary to HTML menu option. For example, Figure 30(a) shows how to create a summary-by-criterion.html file, corresponding to the current JaBUTi screen. Figure 30(b) illustrates the generated HTML file in a browser window. In this way the tester can collect and save different testing report showing the evolution of the testing activity.



(a) (b)

Figure 30: Example of an HTML report generated by JaBUTi.

A different kind of report can be generated through the Reports → Custom Report menu option. By selecting this option, a dialog windows, as illustrated in Figure 31(a), appears and the tester can choose the level of information that will be saved in a HTML file. Observe that to save information at method level it is also required to save information about the class and project level, since the information is saved hierarchically. Part of a complete report for the entire project is presented in Figure 31(b).



(a) (b)

Figure 31: Example of custom HTML report generated by JaBUTi for the entire project.

6.4 How to include a test case

JaBUTi is designed to support test case set adequacy evaluation and to provide guidance in test case selection. If there is a previously developed test set, e.g. a functional test set, such a test set can be evaluated against the structural testing criteria implemented by JaBUTi. This allows the tester to check, for example, whether all instructions/statements are executed by a particular test set. If they are not yet executed, additional test cases can be developed to improve the quality of the previous test set.

On the other hand, if there is no previous test set available, the tester can use the hints provided by the tool to create test cases aiming at to cover the different testing requirements generated by JaBUTi based on its structural criteria. Once the test criteria can be applied incrementally, the tester can start by developing an adequate test set w.r.t. the All-Pri-Nodes criterion, then, if necessary, to develop additional test cases to evolve the All-Pri-Nodes-adequate test set to a All-Pri-Edges-adequate test set, and later, if necessary, to develop additional test cases to evolve it to an All-Pri-Uses-adequate test set. All these criteria, prefixed by All-Pri-, are related with the normal program execution. If desired, the tester can check the coverage of the exception-handling mechanism, by using the All-Sec-Nodes, All-Sec-Edges and All-Sec-Uses criteria. The idea is to use these criteria incrementally to reduce their complexity and also to allow the tester to deal with the cost and time constraints.

JaBUTi allows to include test cases in two different ways: 1) using the JaBUTi's class loader; or 2) importing from a JUnit test set. The first is done by a command line application (probe.ProberLoader, the JaBUTi's class loader). This command line application extends the default Java class loader [11] such that, from a given testing project, it identifies which classes should be instrumented before to be loaded and executed. By detecting that a given class belongs to the set of classes under testing, JaBUTi's class loader inserts the probes to collect the execution trace and then loads the instrumented class file to be executed. The trace information w.r.t. the current execution is appended in a trace file with the same name of the testing project but with the extension .trc instead of .jbt.

For example, the test case file input1, presented in Figure 32, touches the testing requirement (considering the All-Pri-Nodes criterion) with the highest weight illustrated in Figure 19 and also reveals a fault contained in the Dispenser component. Such a test case will be used in the next section to show how to use JaBUTi to ease the fault localization.

```
auri@AURIMRV ~/example
$ cat input1
insertCoin
vendItem 3
```

Figure 32: Example of test case file.

The command line in Figure 33(a) shows the output of the vending.TestDriver when executed by the default class loader. Figure 33(b) shows the resultant output when vending.TestDriver is executed using the JaBUTi's class loader. The execution of the command as shown in Figure 33(b) causes the vending.trc to be generated/updated with the execution path of test case file input1.

Considering Figure 33(b), observe that the CLASSPATH variable is set containing all the paths necessary to run the JaBUTi's class loader and also the vending machine example. The next parameter, probe.ProberLoader, is the name of the JaBUTi's class loader. It demands two parameters to execute: the name of the project (-P vending.jbt), and the name of the base class to be executed (vending.TestDriver). In our example, since vending.TestDriver requires one parameter to be executed,

```
auri@AURIMRV ~/example
$ java -cp "." vending.TestDriver input1
VendingMachine ON
Current value = 25
Enter 25 coins
Current value = -25
VendingMachine OFF
```

(a)

```
auri@AURIMRV ~/example
$ java -cp ".;..\Tools\jabuti;\
>..\Tools\jabuti\lib\BCEL.jar;\
>..\Tools\jabuti\lib\crimson.jar;\
> probe.ProberLoader -P vending.jbt \
> vending.TestDriver input1
Project Name: vending.jbt
Trace File Name: vending.trc
Processing File vending.jbt
VendingMachine ON
Current value = 25
Enter 25 coins
Current value = -25
VendingMachine OFF
```

(b)

Figure 33: vending.TestDriver output: (a) default class loader, and (b) JaBUTi class loader.

this parameter is also provided (input1). During the execution of vending.TestDriver, VendingMachine and Dispenser classes are required to be loaded. From the project file (vending.jbt) the JaBUTi's class loader detects that these class files have to be instrumented before to be executed. The instrumentation is performed on-the-fly every time the probe.ProberLoader is invoked.

The resultant execution trace information, corresponding to the execution of the test case input1, is appended in the end of the trace file vending.trc . Every time the size of the trace file increase, the Update button in the JaBUTi's graphical interface becomes red, indicating that the coverage information can be updated considering the new test case(s). Figure 34 illustrates this event.

Figure 34: Update button with a different background color: new test case(s) available.

By clicking on the Update button, JaBUTi imports the new test case(s), empties the trace file vending.trc and updates the coverage information and the weights for each testing criterion. For example, after the importation of test case input1, the weight of the Java source code w.r.t. the All-Pri-Nodes criterion changed as illustrated in Figure 35.

Comparing the updated source of Figure 35 (front) with the one presented in Figure 35 (back) it can be observed that the requirement with the highest changed from source line 24 (now covered – painted in white) to source line 20. Considering the entire project, Figure 36(b) shows the updated coverage for each method in the Dispenser and VendingMachine classes w.r.t. the All-Pri-Nodes criterion. Observe that input1 covered 13 primary nodes (50%) of Dispenser.dispense method and 36 of 56 primary nodes (64%) considering the entire project. By accessing the Test Case → Report by Test Case menu option, the tester can visualize the coverage of the entire project by test case, as illustrated in Figure 36(a).

If desired, the tester can develop additional test cases to improve the coverage w.r.t. All-Pri-Nodes criterion. For example, besides input1, Table 5 shows four additional test cases developed to improve the coverage of such a criterion.

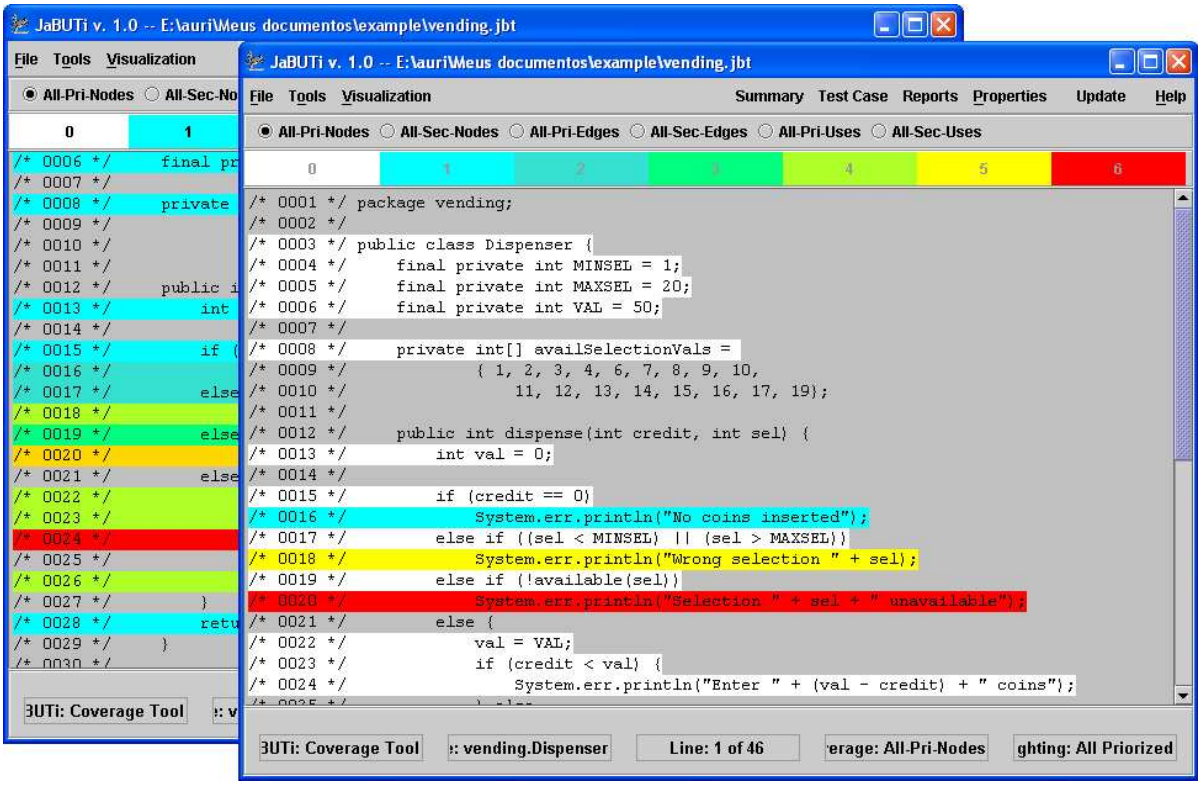


Figure 35: Dispenser.dispenser() method before and after the weight's updating w.r.t. All-Pri-Nodes criterion.

(a) Report by test case

(b) Summary by Method

Figure 36: Updated coverage after test case input1.

JaBUTi also allows to visualize the coverage of a given test case by each execution path (Test Case → Report by Test Case Path), i.e., during the execution of a single test case, several methods can be executed, and each one can be executed several times. Each method execution is considered as a different execution path. Therefore, a test case is composed by zero or more test paths, one for each individual method execution. Figure 37 shows this kind of report. For instance, test case 0001 is composed by six paths numbered from 0001-0 to 0001-5. Besides the coverage by path, the report also shows additional information about each path, collected during the execution.

Table 5: Adequate test set to the Dispenser component.

Name	Content	Correct output
input1	insertCoin vendItem 3	no
input2	insertCoin vendItem 18	yes
input3	insertCoin insertCoin vendItem 25	yes
input4	vendItem 3	yes
input5	insertCoin insertCoin vendItem 3	yes

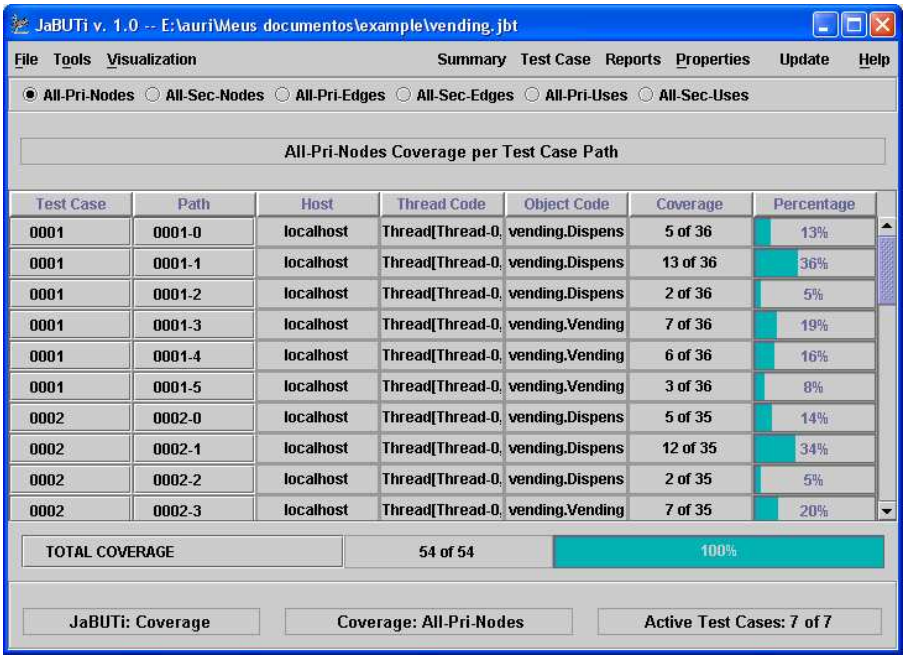


Figure 37: Testing report by execution path w.r.t. the All-Pri-Nodes criterion.

6.5 How to import test cases from JUnit framework

Observe that after five test cases, the coverage of almost all methods, w.r.t. the All-Pri-Nodes criterion, is 100%. The only two methods uncovered are Dispenser.setValidSelection() and VendingMachine.returnCoin(). To obtain a adequate test set w.r.t. the All-Pri-Nodes, additional test cases are required. Figure 38 shows one additional test case, specified according to the JUnit framework, to cover 100% of required elements of the All-Pri-Nodes for the Dispenser class. More information about how to develop test set using the JUnit framework can be found elsewhere [3, 18].

```
/*01*/ package vending;
/*02*/
/*03*/ import junit.framework.*;
/*04*/ import probe.DefaultProber;
/*05*/
/*06*/ /**
/*07*/  * A sample test set for vending machine.
/*08*/  */
/*09*/ public class DispenserTestCase extends TestCase {
/*10*/     protected Dispenser d;
/*11*/
/*12*/     protected void setUp() {
/*13*/         d = new Dispenser();
/*14*/     }
/*15*/
/*16*/     // Testing Dispenser.setValidSelection() method
/*17*/     public void testDispenserException() {
/*18*/         int val;
/*19*/
/*20*/         d.setValidSelection( null );
/*21*/         val = d.dispense( 50, 10 );
/*22*/         assertEquals( 0, val );
/*23*/     }
/*24*/
/*25*/     protected void tearDown() {
/*26*/         DefaultProber.dump();
/*27*/     }
/*28*/
/*29*/     public static Test suite() {
/*30*/         return new TestSuite(DispenserTestCase.class);
/*31*/     }
/*32*/
/*33*/     public static void main(String[] args) {
/*34*/         junit.textui.TestRunner.run(suite());
/*35*/     }
/*36*/ }
```

Figure 38: Example of a test set using the JUnit framework.

As can be observed in Figure 38, line 26, JaBUTi requires that a static method (DefaultProber.dump()) to be called at the end of each test case[6]. Such a method is responsible to write the execution trace in the trace file. Observe that to call such a static method it is also necessary to include the import statement as shown in line 04. Once compiled, such a JUnit test case can be imported by JaBUTi from the Test Case → Import from JUnit menu option. Figure 39 shows the sequence of screens to import a JUnit's test case.

1. Click on the Browser button (Figure 39(a));
2. Select the directory where the JUnit test case class file is located (Figure 39(b));
3. Select the JUnit test case class file (DispenserTestCase.class – Figure 39(c));
4. Select the test cases to be imported and click on the Import Selected button (Figure 39(d)).

[6]JUnit has two special methods TestCase.setUp() and TestCase.tearDown(). The former is executed before any test case execution and the later after a test case execution. Therefore, since we want to execute the method DefaultProber.dump() after the execution of each test case, a call to such a method is placed inside the method TestCase.tearDown().

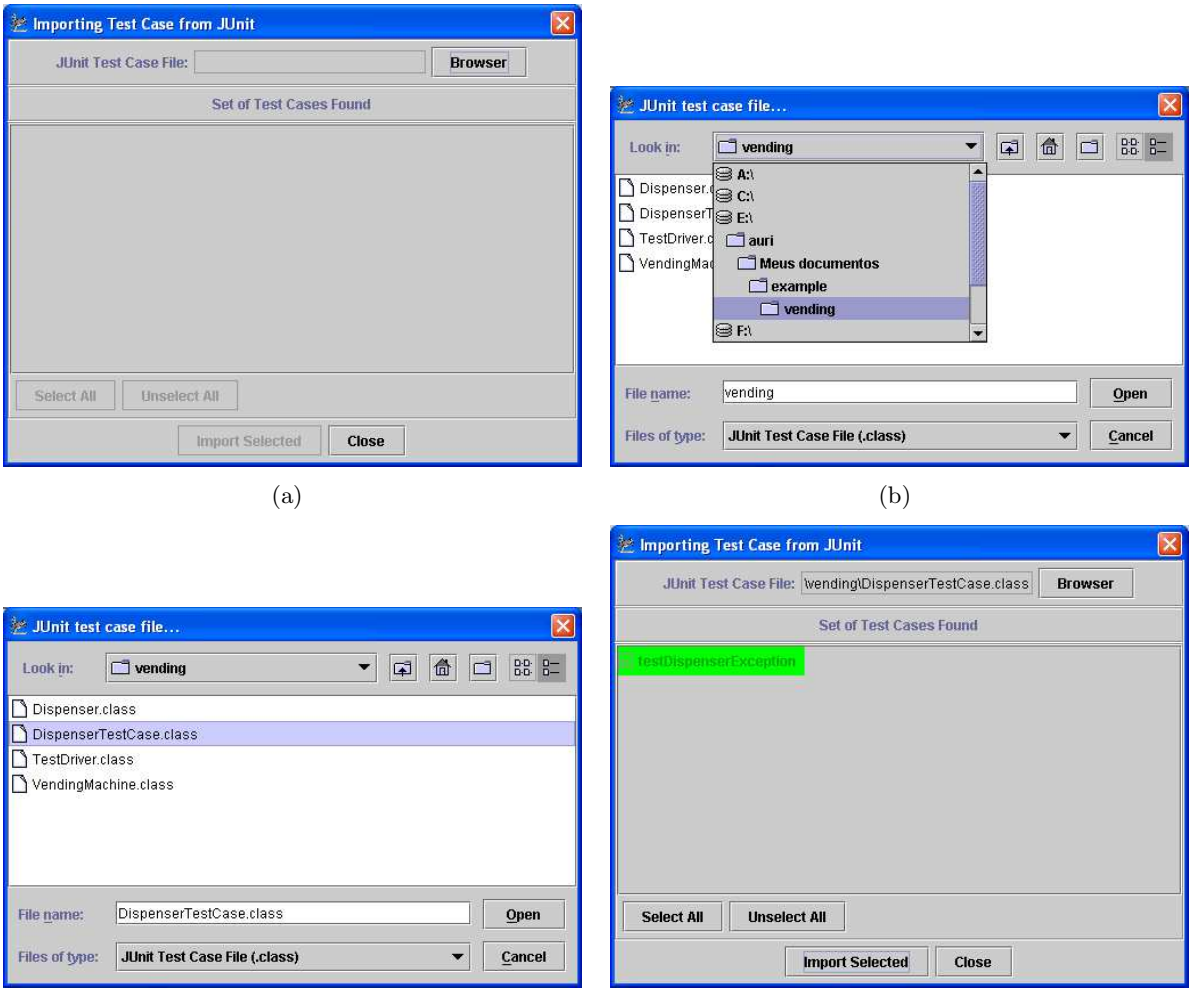


Figure 39: Sequence of Steps to Import a JUnit Test Cases.

In our example (Figure 39(d)), there is only one test case to be imported. Observe that the name of such a test case testDispenserException is highlighted in green. This is because JUnit framework provides several assertions statements, like the one at line 22 of Figure 38, that allows to verify if the test case's output is according to its specification or not. We use a green background color to represent test cases that behave accordantly to their specifications and a red background color to represent the ones that do not.

As soon as JaBUTi detects a new test case execution trace is appended in the end of the trace file, the Update button becomes red indicating that the coverage needs to be updated. Updated the coverage information, Figure 40 shows the summary report by methods and the corresponding coverage w.r.t. the All-Pri-Nodes criterion. The summary report by criterion can be seen in Figure 41

After the execution of these six test cases, all methods of the Dispenser component are 100% covered w.r.t. the All-Pri-Nodes criterion, but this test set is adequate to the VendingMachine class. More specifically, the VendingMachine.returnCoin method is not covered yet. So, after six test cases, the coverage of the entire project w.r.t. All-Pri-Nodes and All-Sec-Nodes are 91% and 100%, respectively. The coverage for the All-Pri-Edges and the All-Sec-Edges are 89% and 20%, respectively, and the coverage for the All-Pri-Uses and All-Sec-Uses are 81% and 25%, respectively.

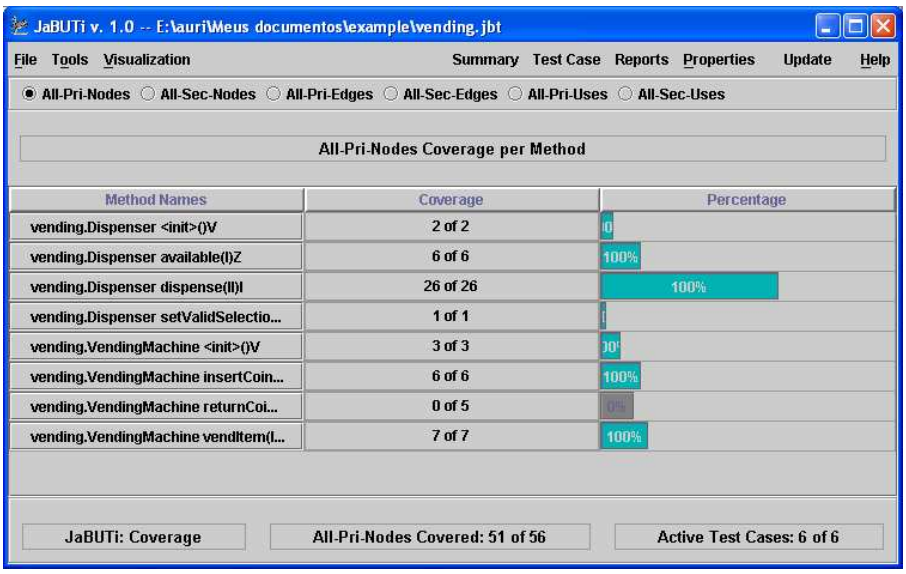


Figure 40: Updated coverage after six test cases w.r.t. the All-Pri-Nodes criterion.

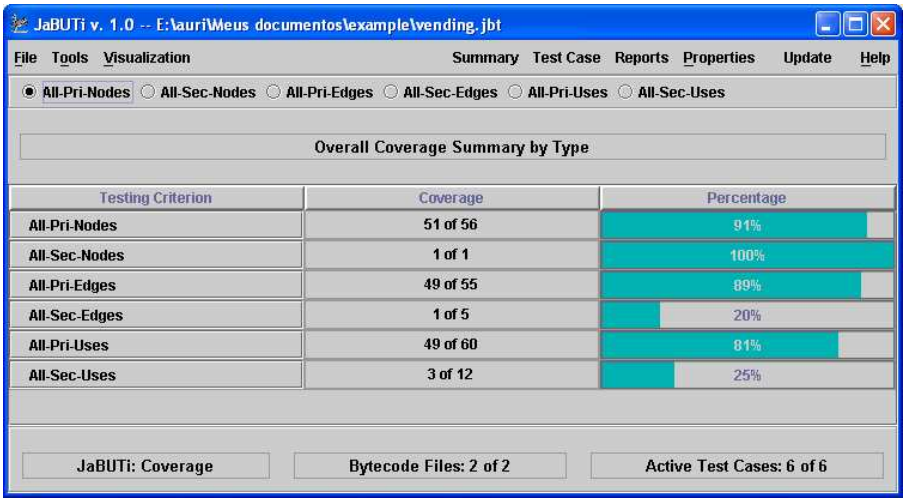


Figure 41: Updated coverage after six test cases w.r.t. all criteria.

Independently of the number of test cases available, if desired, the tester can enable/disable any combination of test cases by accessing the Test Case → Report By Test Case menu option and choosing which test case should be enabled/disabled. Once a different subset of test cases are enabled/disabled all the coverage information should be updated by clicking on the Update button. Figure 42(a) shows the complete test set with all test cases enabled. Figure 42(b) shows the updated coverage considering only the test cases number 2 and 5.

Using the resource of activate/deactivate test cases, the tester can evaluate how the coverage changes, considering different combinations of test case. Moreover, besides activate/deactivate test cases, the tester can also mark a test case to be deleted. Once a test case is marked to be deleted it is only logically deleted. Such a test case is physically deleted when the project is saved and closed. While the project is not closed, a test case marked as deleted can be undeleted.

(a) (b)

Figure 42: Summary by test case: (a) all enabled, and (b) 2 and 5 enabled.

6.6 How to mark a testing requirement as infeasible

When applying structural testing criteria, one problem is to identify infeasible testing requirements since, in general, it is an undecidable problem. Vergilio [25] developed some heuristics to automatically determine infeasible testing requirements but such heuristics are not yet implemented in JaBUTi. Therefore, it is a responsibility of the tester to identify such infeasible testing requirements.

By accessing the Visualization → Required Elements menu option, JaBUTi allows the tester to visualize and mark testing requirements as infeasible, as well as activate/deactivate testing requirements. Once a testing requirement is marked as infeasible or deactivated, the Update button becomes red indicating that the coverage information should be updated to reflect such a change. For example, Figure 43 shows part of the testing requirements for the method Vending.returnCoin() method, considering the All-Pri-Nodes criterion.

Figure 43: Dispenser.dispense() required elements for the All-Pri-Nodes criterion.

Considering Figure 43, two uncovered requirements were marked as infeasible, primary nodes 7 and 26. Since the tester can mark erroneously a testing requirement as infeasible, in case such a testing requirement is covered in the future by an additional test case, the tool indicates such a inconsistency, highlighting the infeasible check box of a covered testing requirement in red, as illustrated in Figure 44. In this case, primary node 26 is covered by the new test case added to exercise the Vending.returnCoin() method, so node 26 is feasible.

During the importation of a given test case, the tester has to check whether the obtained output is correct w.r.t. the specification. As can be observed in Table 5, only test case number 1 does not behave according to the specification. Once any discrepancy is detected, the fault should be localized and corrected. One alternative for fault localization is slicing. In the next section we describe how to use the slicing tool implemented in JaBUTi to help the fault localization and smart debugging.

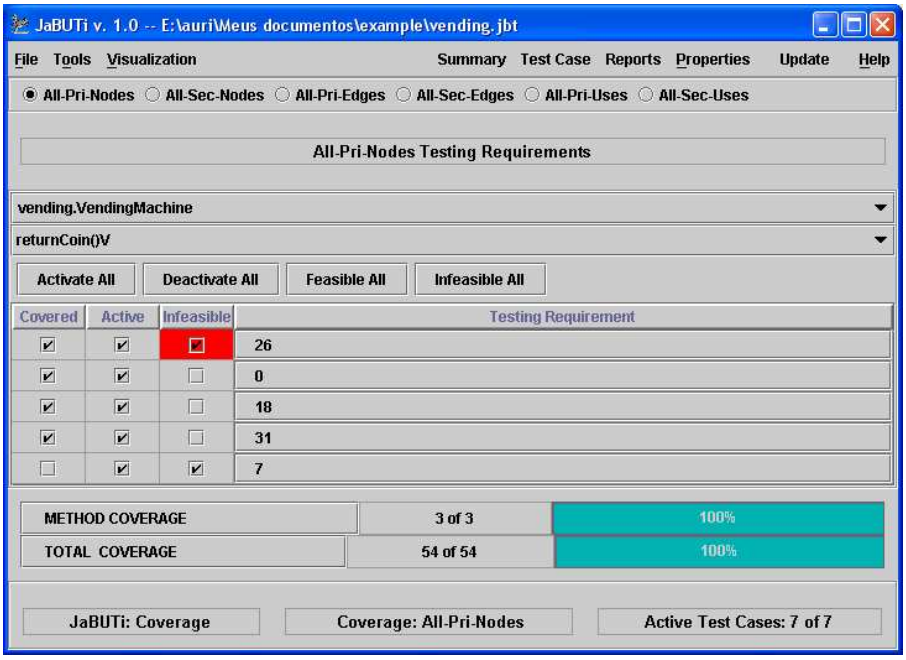


Figure 44: Dispenser.dispense() infeasible requirements erroneously identified.

7 How to use JaBUTi as a Slicing Tool

The JaBUTi slicing tool is available through the Tools → Slicing Tool menu option. The slicing tool implements only a simple heuristic based on control-flow information. As a future work, additional heuristics will be implemented considering not only control-flow but also data-flow information.

By changing to the slicing tool, the tester has to choose, among the test cases, the ones that cause the fault and the ones that do not reveal the fault. Based on the execution path of the failed and succeed test cases, the tool highlights the part of the code more probable to contain the fault.

JaBUTi uses a simple dynamic slice criterion, based on control-flow information, to identify a subset of statements more probable to contain the fault. The idea is (1) to compute the failed set F_S of $\mathcal{BG}$ nodes (the execution path) of a failed test case, which includes all statements executed by the failed test case, (2) to compute the succeed set S_S of $\mathcal{BG}$ nodes considering succeed test case(es), and (3) to calculate the difference and the intersection of these sets to prioritize the statements executed by the failed test case.

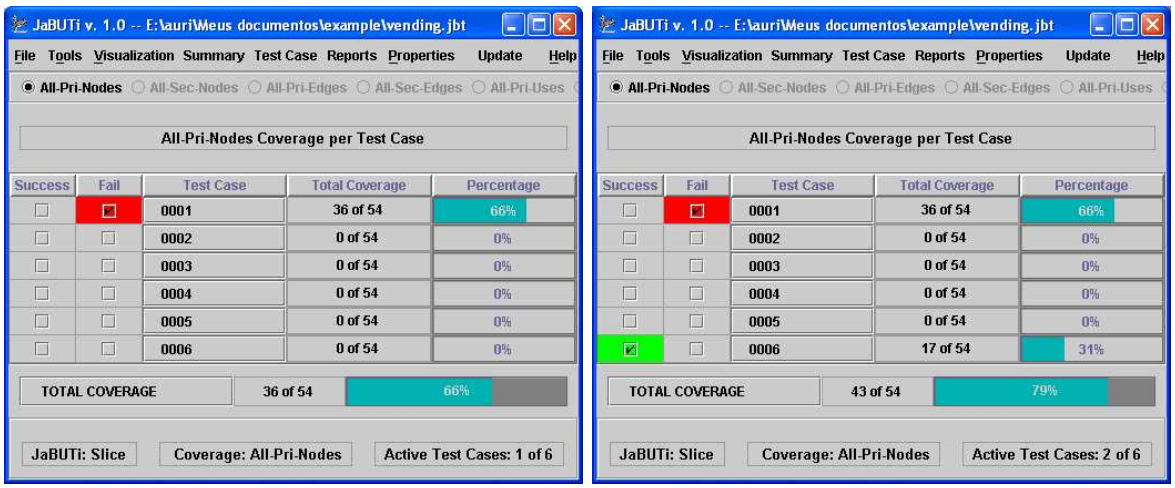
Using such an approach, instead of the complete set of $\mathcal{BG}$ nodes N (which represents all statements of a method), the tester has only to consider the subset of $\mathcal{BG}$ nodes present in F_S, since the other $\mathcal{BG}$ nodes contains the statements not executed by the failed test case and cannot contain the fault. Moreover, considering the subset of nodes executed by the succeed test cases, the most probably location of the fault is in the statements executed by the failed test case but not executed by the succeed test cases, i.e., the subset $F_S \setminus S_S$. Thus, such a subset of statements has a highest priority and should be analyzed first. If the fault is not located on this subset, due to data dependence that can lead to a data-flow dependent fault, the tester has to analyze the other statements executed by both the failed and by the succeed test cases, i.e., the subset $F_S \cap S_S$. In this way, we can provide an incremental search for the fault, trying to reduce the time and the cost to locate the fault in a program.

For example, consider the $\mathcal{BG}$ presented in Figure 6. N is the complete set of $\mathcal{BG}$ nodes ($N = \{0, 15, 34, 43, 54, 54.82, 60, 60.82, 74, 74.82, 79, 91, 97\}$). Suppose a failed test case that goes though $\mathcal{BG}$ nodes $F_S = \{0, 34, 15, 34, 43, 54, 54.82, 91, 97\}$ and a successful test case that goes trough $\mathcal{BG}$ nodes $S_S = \{0, 34, 43, 60, 60.82, 91, 97\}$. The most probably locations for the fault are in the statements in nodes 15, 54 or 54.82, since they are only executed by the failure test case ($F_S \setminus S_S$). If the fault is not located on such statements, it will be found in the other statements that compose the $\mathcal{BG}$ nodes 0, 34, 43, 91 and 97 ($F_S \cap S_S$). All the other $\mathcal{BG}$ nodes have not to be analyzed.

The approach described above is based only on control-flow information. The success of such an approach depends on which test cases are selected as the successful test cases. It is important to select successful test cases that execute the related functionalities of the program as the ones executed by the failure test case. In this way, the difference between the two sets F_S and S_S will result in subset with a few $\mathcal{BG}$ nodes, reducing the number of statements that have to be analyzed first.

In our Vending Machine example, test case 0001 reveals the fault and test case 0006 does not. The tester can first select only the failed test case, as illustrated in Figure 45(a), and checks the execution path of this test case as illustrated in Figure 46(a). The red lines indicate the statements that are executed by the failed test case and the white lines indicates the statements not executed. Since there is a fault, it must be located among these red statements.

After having observed the failed test case execution path, the tester can enable one or more additional succeed test cases (Figure 45(b)), such that the tool can identify, among the statements



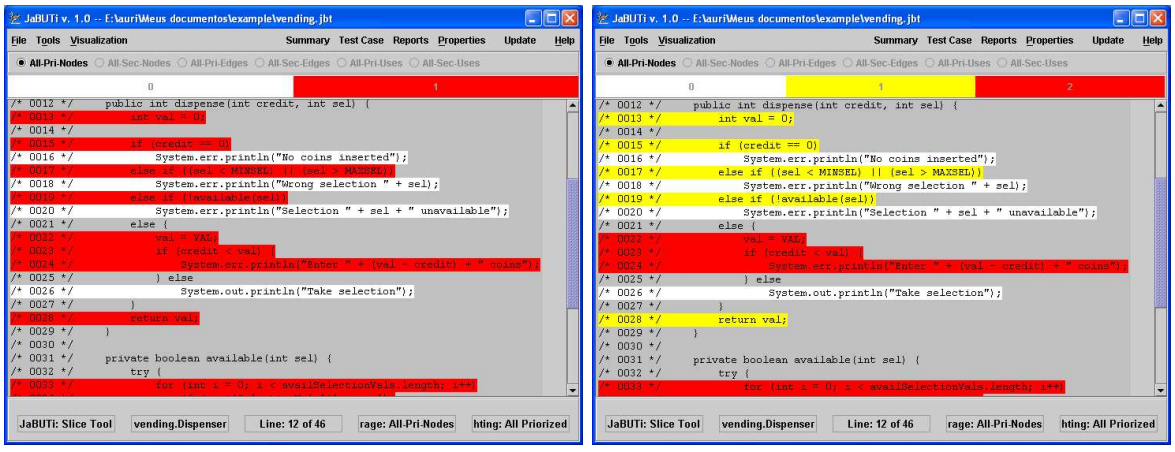
(a) (b)

Figure 45: Slicing tool test case selection: (a) only the failed test case, and (b) a failed and a succeed test cases.

executed ny the failed test case, the dice more probable to contain the fault (statements only executed by the failed test case) and the ones less probable (the ones executed for both the failed and the succeed test cases.) Figure 46(b) shows in yellow (weight 1) the statements touched by test cases number 0001 and 0006 and in red (weight 2) the statements only executed by test case number 0001.

The rationale of such an approach is that, in theory, the fault is more probable to be located at the statements executed only by the failed test case. Although, it can happen that the fault is localized in other than the red statements, but the red points can be used at least as a good starting point, trying to reduce the search space for fault localization.

Once the fault is located and corrected, the testing activity is restarted by creating a new project to revalidate the corrected program. In this case, previous test sets can be used to revalidate the behavior of the new program and also to check if new faults were not introduced by the changes.



(a) (b)

Figure 46: Highlighted execution path: (a) fail test case execution path, and (b) fail test case execution path intersected by the success test case execution path.

8 How to use the JaBUTi's Static Metrics Tool

Adicionalmente, na Seção 8.3, a métrica que avalia a complexidade ciclomática de McCabe [17] de cada método também foi implementada para identificar os métodos de "maior" complexidade dentro de uma dada classe.

8.1 LK's Metrics Applied to Classes

8.1.1 NPIM – Number of public instance methods in a class

Métrica calculada através da contagem do número de métodos de instância públicas na classe.

8.1.2 NIV – Number of instance variables in a class

Métrica calculada através da contagem do número de variáveis de instância na classe, o que inclui as variáveis *public*, *private* e *protected* disponíveis para as instâncias.

8.1.3 NCM – Number of class methods in a class

Métrica calculada através da contagem do número de métodos *static* na classe.

8.1.4 NCV – Number of class variables in a class

Métrica calculada através da contagem do número de variáveis *static* na classe.

8.1.5 ANPM – Average number of parameters per method

Métrica calculada através da divisão entre o somatório do número de parâmetros de cada método da classe pelo número total de métodos da classe.

Variação: número máximo de parâmetros em um método da classe.

8.1.6 AMZ – Average method size

Métrica calculada através da divisão entre a soma do número de linhas de código dos métodos da classe pelo número de métodos na classe (soma dos métodos instância e classe).

Variações: média do número de instruções do bytecode e tamanho do bytecode.

8.1.7 UMI – Use of multiple inheritance

Como a herança múltipla não se aplica à linguagem JAVA será definida uma variação à esta métrica.

Variação: número de interfaces implementadas pela classe (*Number of interfaces implemented* - NINI).

8.1.8 NMOS – Number of methods overridden by a subclass

Métrica calculada através da contagem do número de métodos definidos na subclasse com o mesmo nome de métodos de sua superclasse.

8.1.9 NMIS – Number of methods inherited by a subclass

Métrica calculada através da contagem do número de métodos herdados pela subclasse de suas superclasses.

8.1.10 NMAS – Number of methods added by a subclass

Métrica calculada através da contagem do número de novos métodos adicionados pelas subclasses.

8.1.11 SI – Specialization index

Métrica calculada através da divisão entre o resultado da multiplicação de NMOS e DIT (métrica de CK) pelo número total de métodos.

8.2 CK's Metrics Applied to Classes

8.2.1 NOC – Number of Children

Métrica calculada através da contagem do número de subclasses imediatas subordinadas à classe na árvore de hierarquia.

8.2.2 DIT – Depth of Inheritance Tree

É o maior caminho da classe à raiz na árvore de hierarquia de herança. Interfaces também são consideradas, ou seja, o caminho através de uma hierarquia de interfaces também pode ser o que dá a profundidade de uma classe.

Variação: como a representação de programa utilizada não inclui todas as classes até a raiz da árvore de hierarquia, será utilizado o caminho da classe até a primeira classe que não pertence à estrutura do programa.

8.2.3 WMC – Weighted Methods per Class

Métrica calculada através da soma da complexidade de cada método. Não se define qual tipo de complexidade pode ser utilizada, assim serão aplicadas as seguintes variações:

- Utiliza-se o valor 1 como complexidade de cada método; assim WMC_1 é o numero de métodos na classe;
- Utiliza-se a métrica CC para a complexidade de cada método; esta métrica será chamada WMC_CC;
- Utiliza-se a métrica LOCM para a complexidade de cada método; esta métrica será chamada WMC_LOCM;
- Utiliza-se o tamanho do método (número de instruções) para a complexidade de cada método; esta métrica será chamada WMC_SIZE;

8.2.4 LCOM – Lack of Cohesion in Methods

Métrica calculada através da contagem do número de pares de métodos na classe que não compartilham variáveis de instância menos o número de pares de métodos que compartilham variáveis de instância. Quando o resultado é negativo, a métrica recebe o valor zero. Os métodos estáticos não são considerados na contagem, uma vez que só as variáveis de instância são tomadas.

Variações:

- Considerar só a coesão entre métodos estáticos; esta métrica será chamada LCOM_2;
- Considerar a coesão de métodos estáticos ou de instância; esta métrica, chamada LCOM_3 pode ser calculada como $LCOM\_ - LCOM\_2$;

8.2.5 RFC – Response for a Class

Métrica calculada através da soma do número de métodos da classe mais os métodos que são invocados diretamente por eles. É o número de métodos que podem ser potencialmente executados em resposta a uma mensagem recebida por um objeto de uma classe ou por algum método da classe. Quando um método polimórfico é chamado para diferentes classes, cada diferente chamada é contada uma vez.

8.2.6 CBO – Coupling Between Object

Há acoplamento entre duas classes quando uma classe usa métodos e/ou variáveis de instância de outra classe. Métrica calculada através da contagem do número de classes às quais uma classe está acoplada de alguma forma, o que exclui o acoplamento baseado em herança. Assim, o valor CBO de uma classe A é o número de classes das quais a classe A utiliza algum método e/ou variável de instância.

8.3 Another Metrics Applied to Methods

8.3.1 CC – Cyclomatic Complexity Metric

Métrica que calcula a complexidade do método, através dos grafos de fluxo de controle que descreve a estrutura lógica do método.

Os grafos de fluxo consistem de nós e ramos, onde os nós representam comandos ou expressões e os ramos representam a transferência de controle entre estes nós.

A métrica pode ser calculada das seguintes formas:

- O número de regiões do grafo de fluxo corresponde à Complexidade Ciclomática;
- A Complexidade Ciclomática, V(G), para o grafo de fluxo G é definida como:

$$V(G) = E - N + 2$$

  onde, V(G) mede os caminhos linearmente independentes encontrados no grafo, E é o número de ramos do grafo de fluxo e N o número de nós.

- A Complexidade Ciclomática, V(G), para o grafo de fluxo G é definida como:

$$V(G) = P(G)+1$$

onde, P(G) é o número de nós predicativos contidos no grafo de fluxo G. Os nós predicativos são comandos condicionais (*if*, *while*, ...) com um ou mais operadores booleanos (*or*, *and*, *nand*, *nor*). Um nó é criado para cada nó 'a' ou 'b' de um comando `IF a OR b`.

Outras formas de se calcular a Complexidade Ciclomática são:

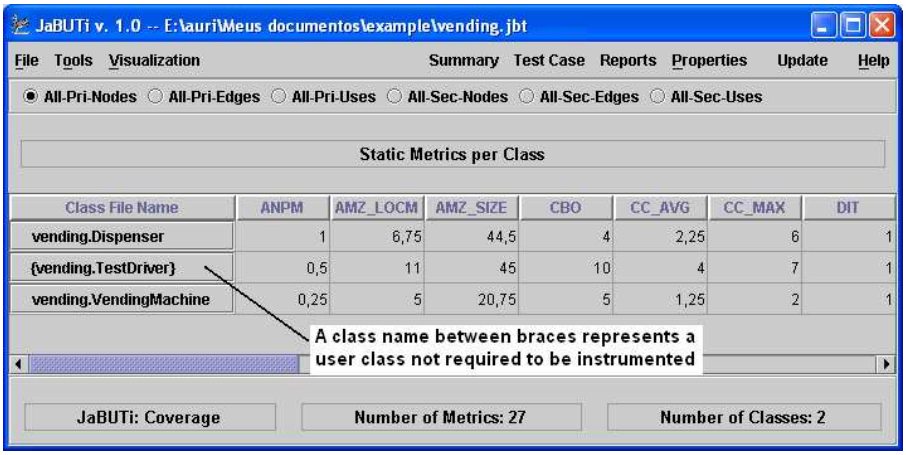
- V(G) = número de regiões de G;
- V(G) = número de ramos - número de nós + 2;
- V(G) = número de nós predicativos + 1.

Variações: a métrica é aplicada a métodos mas pode ser aplica à classe através da soma (ver WMC_CC), da média (que será chamada CC_AVG) e do máximo (CC_MAX) entre os métodos.

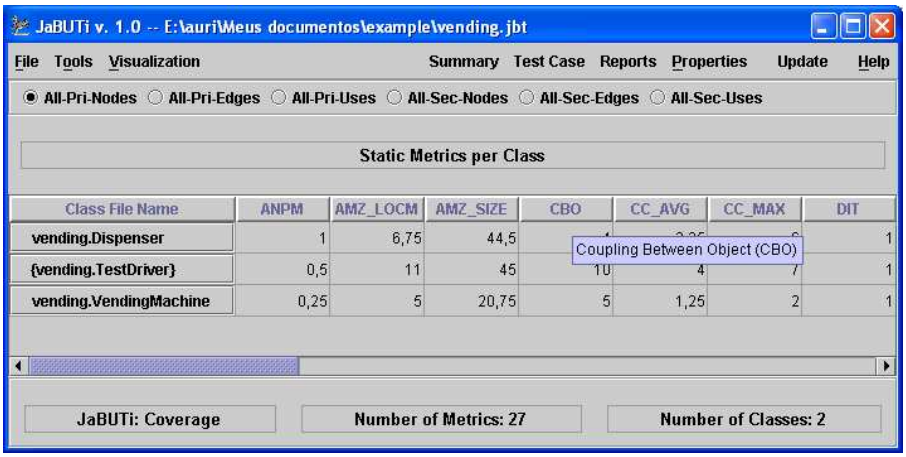
8.4 The Static Metrics GUI

The set of static metrics implemented in JaBUTi can be accessed by the Visualization → Complexity Metrics menu option. Figure 47(a) illustrates the window that will be displayed, considering the vending.jbt project file. Each line corresponds to a given user class and each column is the resultant value of a given static metric applied to such a class. Observe that not only the classes under testing are displayed but also the other user classes required by the base class. A user class not required to be instrumented appears between braces. The idea is to allow the tester to visualize the metrics with respect to all possible classes that can be instrumented such that he/she can decide later to select such classes to be tested.

By moving the mouser cursor onto the head of a given column, it is displayed a tip, giving a brief description of the corresponding metric of such a column. For example, Figure 47(b) shows the tip for the CBO metrics, responsible to measure the coupling between objects.



(a) Metrics view



(b) Metrics tool tip

Figure 47: Static Metrics Tool's graphical interface.

9 JaBUTi em dispositivos móveis

A ferramenta JaBUTi foi adaptada para ser utilizada no teste de programas Java que rodam em dispositivos móveis como PDAs ou telefones celulares. Mais precisamente, que estão de acordo com o perfil MIDP (Mobile Information Device Profile).

Essa seção descreve as diferenças na utilização da ferramenta para o teste desse tipo de software. As mudanças de procedimento dizem respeito, principalmente, à instrumentação e execução dos casos de teste. Como os programas instrumentados devem executar em dispositivos móveis,[7] o tipo de instrumentação deve ser adequada àquele ambiente. Além disso, os dados de execução (trace) devem ser analisados pela JaBUTi, no desktop.

Assim, a primeira mudança a ser feita é a instalação de um servidor que vai ser responsável pela aquisição dos dados de execução dos programas e a geração do arquivo de trace que é tratado pela JaBUTi. O servidor pode ser instalado através de um programa chamado diretamente na linha de comando ou de dentro da própria ferramenta.

Na chamada direta, o programa deve receber dois argumentos, como mostra a descrição abaixo:

```
> java -cp <classpath Jabuti> br.jabuti.device.ProberServer <port> <filename>
```

O primeiro argumento indica o número da porta à qual o servidor vai se anexar. O segundo é o nome de um arquivo de configuração que descreve quais são os programas que devem ser tratados pelo servidor. Um servidor pode tratar de mais de um programa em execução ao mesmo tempo. O formato do arquivo de configuração é bastante simples. Ele possui, para cada programa a ser tratado, duas linhas, contendo a identificação do programa e o nome do arquivo de trace onde os dados de execução devem ser gravados. Por exemplo:

```
PropExample
/home/user/Demos/PropExample.trc
Foo
/home/foo/foo.trc
```

No arquivo de configuração acima, dois programas poderão ser tratados pelo servidor. Um batizado de "'PropExample" e outro batizado de "Foo". Quando o servidor recebe dados de execução do primeiro, esses dados serão gravados no arquivo "/home/user/Demos/PropExample.trc" e do segundo, no arquivo "/home/foo/foo.trc". Note que o nome do programa não está relacionado com a sessão de teste criada para o teste. Esse nome é atribuído pelo testador no momento da instrumentação, como será descrito adiante.

Um exemplo de utilização do comando que instala o servidor seria:

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberServer 1988 config.txt
```

A instalação através da ferramenta JaBUTi é feita através da opção "Properties/Test Server". Com essa operação abre-se a janela mostrada na Figura 48. Nela o testador deve selecionar a porta em que o servidor será instalado e o arquivo de configuração. Pode, também, editar esse arquivo e salvá-lo, se necessário. O testador deve, ainda, selecionar a opção "Mobile device", que indica o tipo de servidor desejado.

[7] Quando nos referimos a dispositivos móveis incluímos os simuladores que, apesar de executarem no desktop, estão sujeitos aos mesmos tipos de limitações do perfil MIDP.

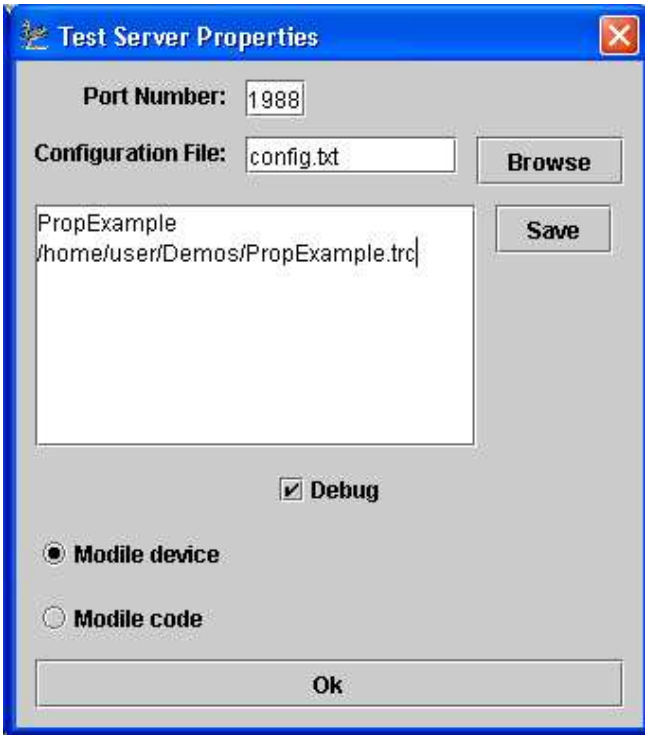


Figure 48: Instalação do servidor para dispositivos móveis.

Outra diferença na execução da sessão de teste para dispositivos móveis está na instrumentação e do programa em teste e na execução dos casos de teste. O programa é instrumentado e gera-se um arquivo .jar contendo todas as classes que compõem o programa, instrumentando-se aquelas que foram escolhidas na criação do projeto de teste. O comando que realiza a instrumentação é o seguinte:

```
java -cp <classpath Jabuti> br.jabuti.device.ProberInstrum <opções> <classe base>
```

A classe base refere-se ao nome da classe do MIDlet que se deseja testar. Deve-se notar que num único "pacote" é possível colocar-se diversos MIDlets distintos. Porém, somente um pode ser instrumentado de cada vez. As opções de instrumentação são as seguintes:

<-d diretório>: indica o diretório no qual se encontra o arquivo de projeto. É opcional e, se não for fornecido, assume-se o diretório corrente;

<-p projeto>: nome do arquivo de projeto, criado pela JaBUTi, que corresponde à sessão de teste. Argumento obrigatório;

<-o arquivo>: dá o nome do arquivo .jar onde serão gravadas as classes instrumentadas do programa. Como as classes instrumentadas fazem chamadas a métodos localizados em classes da JaBUTi, essas classes são, também, adicionadas ao arquivo de saída;

<-name midlet id>: é o nome que será dado ao programa em teste. É esse nome que identifica o MIDlet para o servidor de teste, como visto anteriormente;

<-h end. servidor>: esse parâmetro fornece o endereço onde o servidor de teste foi instalado, no formato "128.123.82.71:1988" ou "myserver.com.br:1988". É um parâmetro opcional. Caso não seja fornecido, os dados não serão enviados a nenhum servidor. Não utilizar essa opção torna

a execução do programa inútil em termos de teste, propriamente dito, mas pode ser útil para a depuração da ferramenta. Os dados de teste podem ser exibidos na saída padrão ou num arquivo, como será visto a seguir;

<-temp arquivo>: utiliza o arquivo especificado como depósito temporário dos dados de trace, no dispositivo. Isso permite que, em dispositivos que possuem sistema de arquivos, os dados fiquem armazenados ali, salvando espaço na memória principal. O nome "__STDOUT__" indica que os dados devem ser escritos na saída padrão do didpositivo móvel. Isso só faz sentido se a execução for feita num simulador no desktop, poi, em geral os dispositivos móveis não apresentam resultados na saída padrão;

<-mem valor>: especifica um threshold de memória disponível que deve ser respeitado para armazenamento dos dados de trace. Quando a quantidade de memória cai abaixo desse valor os dados são enviados para o servidor de teste, ou armazenados no arquivo temporário. O valor pode ser dado em bytes (por exemplo, 1024), em kbytes ou em mbytes (por exemplo, 128K ou 3M). É um parâmetro opcional e, se não fornecido, assume o valor zero, indicando que não existe threshold e os dados são sempre armazenados, até que a execução termine;

<-nokeepalive>: se utilizado, esse parâmetro indica que a conexão (TCP) entre o dispositivo e o servidor de teste não deve ser mantida durante toda a execução do programa. Assim, cada vez que dados devem ser transmitidos, uma nova conexão é criada. Isso pode representar economia nos dispositivos em que a utilização de rede é cara e paga em função do tempo de utilização. A utilização da opção "<-temp arquivo>" já determina que a conexão não será mantida viva pois todos os dados de execução são gravados no arquivo temporário e somente no final da execução do MIDlet os dados são enviados ao servidor.

Seguem-se alguns exemplos da utilização do instrumentador, com alguma combinações de parâmetros.

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberInstrum -name PropExample
-p Propexample.jbt -o PropExample.jar -h 200.188.151.130:2000 example.PropExample
```

Nesse exemplo, o programa, cuja sessão de teste está descrita no projeto chamado "PropExample", recebeu o nome de "PropExample", que também é o nome dado ao arquivo .jar de saída. Os dados de trace serão enviados ao endereço "200.188.151.130:2000" e a classe do MIDlet é "example.PropExample". Como não foi estabelecido um threshold de memória, todos os dados serão armazenados e somente enviados no final da execução do programa. Mesmo assim, a conexão entre o dispositivo e o servidor de teste é aberta no início da execução do MIDlet e permanece aberta até o final do envio dos dados.

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberInstrum -name PropExample
-p Propexample.jbt -o PropExample.jar -h 200.188.151.130:2000 -nokeepalive
example.PropExample
```

O mesmo do exemplo anterior, porém a conexão não permanece aberta o tempo todo. Ela só é criada no início da execução, para que seja verificada se realmente pode ser criada e depois, no final, quando os dados forem enviados.

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberInstrum -name PropExample
-p Propexample.jbt -o PropExample.jar -h 200.188.151.130:2000 -nokeepalive
-mem 512M example.PropExample
```

Nesse caso, os dados são enviados periodicamente, quando a quantidade de memória disponível estiver abaixo do valor estabelecido, ou seja 512 mega-bytes. Como é improvável que algum dispositivo tenha uma memória livre desse tamanho, o que deve ocorrer é que a cada dado de trace coletado, este seja imediatamente enviado para o servidor. Como a opção "-nokeepalive" foi utilizada, isso significa que a cada dado coletado, uma nova conexão é criada, o que pode interferir sobremaneira na execução do MIDlet.

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberInstrum -name PropExample
-p Propexample.jbt -o PropExample.jar -h 200.188.151.130:2000 -nokeepalive
-temp /root1/temp.txt example.PropExample
```

Com a utilização do arquivo temporário, os dados de trace são sempre enviados para esse arquivo e somente no final enviados para o servidor. Assim não são criadas, constantemente, conexões.

```
java -cp Jabuti-bin.zip br.jabuti.device.ProberInstrum -name PropExample
-p Propexample.jbt -o PropExample.jar -temp __STDOUT__ example.PropExample
```

Os dados de teste coletados são apresentados na saída padrão do dispositivo. Como não foi fornecido o threshold de memória esse resultado só é apresentado no final da execução.

Depois de instrumentadas as classes, é necessário ainda mais um passo para que o programa possa ser executado. É a pré-verificação do bytecode e o empacotamento num único arquivo. Isso é feito com o comando descrito a seguir:

```
> java -cp <classpath Jabuti> br.jabuti.device.Preverify <opções>
```

Os argumentos fornecidos para a execução são os seguintes:

<-source arquivo>: esse argumento é obrigatório e indica qual é o arquivo .jar onde estão as classes originais do programa a ser carregado no dispositivo móvel. Note-se que, como comentado anteriormente, esse arquivo pode conter diversos MIDlets, além daquele sendo testado;

<-instr arquivo">: é o nome do arquivo .jar que foi criado no passo anterior, a instrumentação. O que o programa irá fazer é substituir no arquivo original, as classes que foram instrumentadas, mantendo as demais como estão;

<-o arquivo>: indica o nome do arquivo .jar de saída. É um argumento opcional e, caso não seja fornecido, assume-se o mesmo nome do arquivo original. Nesse caso, o arquivo original é sobrescrito;

<-jad arquivo>: especifica o nome do arquivo .jad a ser gerado, com as informações sobre o "pacote" gerado. É opcional e, se não for fornecido, nada é gerado;

<-WTK diretório>: a JaBUTi não realiza a pré-verificação por si só. Ela utiliza o toolkit de desenvolvimeto wireless da SUN para efetuar tal tarefa. Por isso, o testador deve indicar qual é o diretório onde encontra-se o WTK.

Um exemplo de sua utilização seria:

```
java -cp Jabuti-bin.zip br.jabuti.device.Preverify -source Demos.jar
-instr PropExample.jar -o Demos.jar -jad Demos.jad -WTK /home/user/WTK22
```

Concluído esse passo, o programa está pronto para ser executado num simulador ou dispositivo móvel. Os dados, dependendo do tipo de instrumentação, pode ser enviado ao servidor selecionado ou simplesmente escrito num arquivo temporário. Deve-se notar que na maioria dos dispositivos, o usuário deve fornecer autorização para algumas operações privilegiadas como a criação de uma conexão de rede ou leitura/escrita de arquivos. Por isso, a instrumentação pode alterar o comportamento do MIDlet, fazendo com que o programa seja interrompido e tal autorização solicitada. Isso porém, não deve representar problema pois, após a exibição de uma janela de solicitação de autorização, como a da Figura 49, o programa segue normalmente.

Para se executar o programa utilizando o simulador do WTK pode-se utilizar o comando:

```
/home/user/WTK22/bin/emulator.exe -Xdescriptor:Demos.jad
```

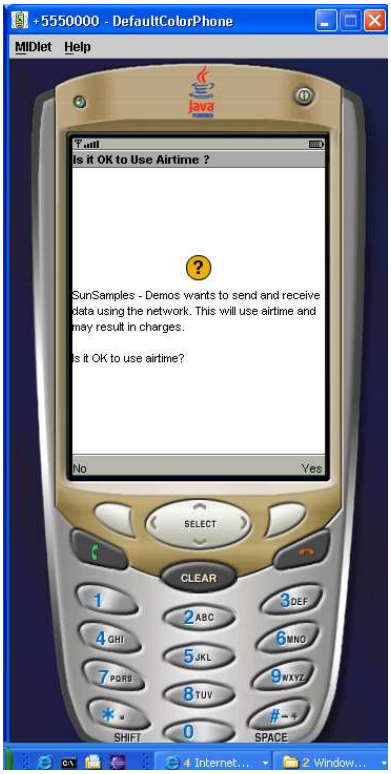


Figure 49: Execução no emulador: autorização para criar conexão.

10 JaBUTi Evolution

Currently, JaBUTi is composed by a coverage analysis testing tool, a slicing too, and a static metrics tool for Java programs. The tool uses the Java bytecode (.class files) instead of the Java source code

to collect the information necessary to perform its activities. This characteristics allows the tool to be used to test any kind of Java program, including Java components.

Since most part of the testing criteria currently developed for component based testing are functional testing criteria, by implementing a set of structural testing criteria applied directly in the Java bytecode, JaBUTi enables the structural testing of Java components and also the identification of which part of such components needs more test or has not yet been covered.

Even when no source code is available, the tester can at least identify which part of the bytecode requires more test, or, in case of a fault is identified, which part of the component is more probable to contain that fault. This information can be given to the component provider such that the component user can receive another corrected version of the component.

Improvements forth coming of JaBUTi are:

- Development of additional testing criteria to deal not only with intra-method testing but also with inter-method and inter-class testing;
- Development of additional heuristic to improve the slicing tool, such that a smart debugging and a ease fault localization to be possible. We intent to investigate different slicing criteria, including the ones that consider also data-flow information, to implement on JaBUTi different heuristics to help the tester on fault localization and smarting debug;
- Development of a set of complexity metrics to help the definition of a incremental testing strategy considering the complete hierarchy of the classes under testing;
- Evaluation, development and implementation of heuristics to automatically identify part of the infeasible testing requirements;
- Implementation of algorithms to optimize the number of testing requirements to be evaluated, using the essential-branches' concept;
- Improvement in the graphical interface to ease the testing activity as much as possible.

Moreover, to show the benefices of the tool, experiments will be carried out exploring the different aspects of JaBUTi.

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