Analysis and Testing of Programs With Exception-Handling Constructs

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Abstract— **Analysis techniques, such as control flow, data flow, and control dependence, are used for a variety of software-engineering tasks, including structural and regression testing, dynamic execution profiling, static and dynamic slicing, and program understanding. To be applicable to programs in languages, such as Java and C++, these analysis techniques must account for the effects of exception occurrences and exception-handling constructs; failure to do so can cause the analysis techniques to compute incorrect results and thus, limit the usefulness of the applications that use them. This paper discusses the effects of exception-handling constructs on several analysis techniques. The paper presents techniques to construct representations for programs with explicit exception occurrences—exceptions that are raised explicitly through `throw` statements—and exception-handling constructs. The paper presents algorithms that use these representations to perform the desired analyses. The paper also discusses several software-engineering applications that use these analyses. Finally, the paper describes empirical results pertaining to the occurrence of exception-handling constructs in Java programs, and their effects on some analysis tasks.**

Keywords— **Exception handling, control-flow analysis, control-dependence analysis, data-flow analysis, program slicing, structural testing.**

I. Introduction

MANY software-engineering tasks, such as test-coverage analysis, test-case generation, regression testing, dynamic execution profiling, impact analysis, and static and dynamic slicing (e.g., [1], [2], [3], [4]), require information about the control flow, control dependence, and data dependence among statements in a program. Previous research has addressed the problems of computing such analysis information for individual procedures (*intraprocedural*)[1] [5] and for interacting procedures (*interprocedural*) [6]. Some of this research has addressed the problems of performing analyses for programs with transfers of control, such as `continue` and `goto` statements, that can affect the analyses at the intraprocedural level (e.g., [7]). Other research has addressed the problems of performing analyses for programs with transfers of control, such as `exit()` statements, that can affect the analyses at the interprocedural level [8]. To be applicable to programs written in languages, such as Java [9] and C++,[2] however, these analysis techniques should, to the extent possible, account for the effects of exception-handling constructs.

Exception-handling constructs provide a mechanism for raising exceptions and a facility for designating protected code by attaching exception handlers to blocks of code. Failure to account for the effects of exception-handling constructs in performing analyses can result in incorrect analysis information, which in turn can result in unreliable software tools. For example, a branch-coverage testing tool for C++ that fails to recognize the flow of control among exception-handling constructs cannot adequately measure the branch coverage of a test suite. As a further example, a slicing tool for Java that fails to recognize the flow of control among exception-handling constructs cannot accurately compute control and data dependence, which may result in incorrect slices.

The additional expense that is required to perform analyses that account for the effects of exception-handling constructs may not be justified unless these constructs occur frequently in practice. To determine the frequency with which Java programs use exception-handling constructs, we conducted a study in which we examined a variety of Java programs. For each subject, we determined the percentage of methods that contained either a `throw` or a `try` statement. The number of methods in the subjects ranged from 89 to 12,304. Table I lists the subjects and summarizes the results of the study.

The data in the table illustrate that, on average, 8.1% of the methods contain some form of exception-handling construct. In a previous study [10], with a smaller suite of Java subjects, we examined the occurrence of exception-handling constructs in classes. In that study, we observed that 23.3% and 24.5% of the classes contained `try` and `throw` statements, respectively. In another recent study, Ryder and colleagues [11] also studied the frequency with which Java programs use exception-handling constructs, and found that 16% of the methods that they examined contained exception-handling constructs. Our subjects include four of the subjects that were used in their study, which explains the differences in the results. The results of the two studies are similar for the four subjects—`jas`, `jasmin`, `joie`, and `jflex`—that were common to both studies. These results support our belief that, in practice, the use of exception-handling constructs in Java programs is significant enough that it should be considered during various analyses.

Recently, several researchers have considered the effects of exception-handling constructs on various types of analyses. One approach constructs control-flow representation for exception-handling constructs, and uses the representation to perform data-flow analyses [12]. Another approach considers the control flow caused by exceptions while performing points-to and data-flow analyses [13], [14]. Other research has analyzed the flow of exceptions, and built tools to facilitate understanding of the exceptional behavior of

[1] Analyses and representations that can be applied to individual procedures can also be applied to individual methods. Thus, we sometimes use "procedure" to mean both procedure and method.

[2] See `http://www.cygnus.com/misc/wp/` for ISO/ANSI C++ standard.

TABLE I
Frequency of occurrence of exception-handling constructs in Java programs.

Subject		Number of classes	Number of methods	Methods with EH constructs
Name	Description			
antlr	Framework for compiler construction	175	1663	175 (10.5%)
debug	Sun's Java debugger	45	416	80 (19.2%)
jaba	Architecture for analysis of Java bytecode	312	1615	200 (12.4%)
jar	Sun's Java archive tool	8	89	14 (15.7%)
jas	Java bytecode assembler	118	408	59 (14.5%)
jasmin	Java assembler interface	99	627	54 (8.6%)
java_cup	LALR parser generator for Java	35	360	32 (8.9%)
javac	Sun's Java compiler	154	1395	175 (12.5%)
javadoc	Sun's HTML document generator	3	99	17 (17.2%)
javasim	Discrete event process-based simulation package	29	216	37 (17.1%)
jb	Parser and lexer generator	45	543	55 (10.1%)
jdk-api	Sun's JDK API	712	5038	582 (11.6%)
jedit	Text editor	439	2048	173 (8.4%)
jflex	Lexical-analyzer generator	54	417	31 (7.4%)
jlex	Lexical-analyzer generator for Java	20	134	4 (3.0%)
joie	Environment for load-time transformation of Java classes	83	834	90 (10.8%)
sablecc	Framework for generating compilers and interpreters	342	2194	106 (4.8%)
swing-api	Sun's Swing API	1588	12304	583 (4.7%)
Total		3951	30400	2467 (8.1%)

programs [15], [16]. None of that research, however, considers the effects of exceptions on analysis techniques such as control dependence and program slicing.

To facilitate such analyses for software-engineering tasks, we investigated the effects of exception-handling constructs on various types of analyses, developed new techniques to perform these analyses in the presence of exceptions, and developed representations for the analysis information, which can be used for other analyses and applications. In this paper, we present our results for two analysis techniques: control-flow and control-dependence analyses. We also discuss briefly the use of our analysis information in two applications: program slicing and structural testing. We discuss the problems and solutions for Java-like exception-handling constructs; constructs in other languages, such as C++, can be analyzed similarly. In the Java exception-handling paradigm, an exception can be raised explicitly through a `throw` statement, or implicitly, through a call to a library routine or by the runtime environment. The techniques presented in the paper apply only to explicitly raised exceptions. Our current work includes investigation of ways to extend our techniques to include the analysis of implicitly raised exceptions. We also restrict our discussion to problems, representations, and analyses for exception-handling constructs; techniques for handling other features of object-oriented languages, such as polymorphism and object flow, are discussed elsewhere (e.g., [13], [17], [18]).

In this paper, apart from the study of the frequency with which exception-handling constructs occur in Java programs (Table I), we also present the results of two other empirical studies. We performed these studies using our program analysis system, Java Architecture for Bytecode Analysis (JABA), written in Java, that analyzes Java bytecode files.[3] The first empirical study evaluates the precision of the control-flow representations that we construct for exception-handling constructs, and suggests that exhaustive type-inference analysis may not be required for determining exception types for `throw` statements. The second empirical study examines the effects of exception-handling constructs on control dependences. The results from this study indicate that a control-dependence computation that ignores the effects of exception-handling constructs can fail to identify a number of dependences in a program. These omitted dependences can have significant impact on the accuracy of tools that require such dependences.

[3] JABA provides language-dependent analysis for Java programs (at the byte-code level) that is required for use in language-independent tools that are part of the Aristotle Analysis System [19].

The next section gives an overview of exception-handling constructs and specifies those constructs that our techniques handle. After introducing an example that is used throughout the rest of the paper, Section III discusses the effects of exception-handling constructs on several types of analyses. Next, Section IV presents our analysis techniques, the representations constructed by the techniques, and some empirical studies pertaining to the techniques. Then, Section V briefly discusses the use of our representations for program slicing and structural testing. Section VI evaluates our analysis techniques in terms of their accuracy and limitations, and discusses the tradeoffs involved in analyzing exception-handling constructs with various degrees of accuracy. Section VII discusses related work. Finally, Section VIII presents conclusions and potential future work.

II. Exception-Handling Constructs

This section provides an overview of exception-handling constructs in Java, our language model; details of the Java language can be found in Reference [9]. Other languages, such a C++ and Ada, provide similar exception-handling mechanisms.

In Java, an exception is an object: each exception is an instance of a class that is derived from the class `java.lang.Throwable`. An exception can be raised at any point in the program through a `throw` statement. The

```
try {
// guarded section
   . . .
}
catch (ExceptionType1 t1) {
// handler for ExceptionType1
   . . .
}
catch (ExceptionType2 t2) {
// handler for ExceptionType2
   . . .
}
   . . .
catch (Exception e) {
// handler for all exceptions
   . . .
}
finally {
// cleanup code
   . . .
}
```

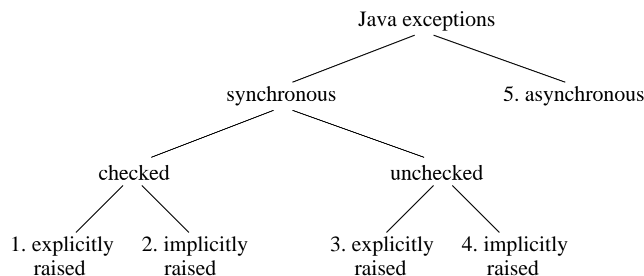


Fig. 1. The syntax of exception-handling constructs in Java (left), and a classification of Java exception types (right).

expression associated with the `throw` statement denotes the exception object. The expression can be a variable (e.g., `throw e`), a method call (e.g., `throw m()`), or a new-instance expression (e.g., `throw new E()`). A `throw` statement can appear anywhere in the program—it may or may not be enclosed in a `try` statement.

A `try` statement provides the mechanism for designating guarded code, by associating exception handlers with the code. A `try` statement consists of a `try` block, and optionally, a `catch` block and a `finally` block. The legal instances of a `try` statement are `try–catch`, `try–catch–finally`, and `try–finally`. The code on the left in Figure 1 shows a typical `try` statement. A `try` block contains statements whose execution is monitored for exception occurrences. A `catch` block, which may be associated with each `try` block, is a sequence of `catch` clauses that specify *exception handlers*. Each `catch` clause specifies the type of exception it handles, and contains a block of code that is executed when an exception of that type is raised in the associated `try` block. A `catch` clause also specifies a variable that is initialized with the handled exception, and whose scope is limited to the block of code for that `catch` clause. A `try` statement can have a `finally` block. The code in a `finally` block is always executed, regardless of how control transfers out of the `try` block. Control may exit a `try` block by reaching the last statement in the `try` block, through an exception that may or may not be handled in the associated `catch` block, or because of `break`, `continue`, or `return` statements.

Java follows the *non-resumable* model of exception handling: after an exception is handled, control does not return to the point at which the exception was raised, but continues at the first statement following the `try` statement where the exception was handled. A Java exception can be propagated up on the call stack: if a method raises but does not handle an exception, the exception is reraised in the context of the caller of that method.

Exceptions in Java can be classified according to several criteria; the graph on the right in Figure 1 shows the classification criteria. These criteria reflect the semantics of raising an exception, and impose requirements on the way in which an exception must be handled. For example, a Java exception can be synchronous or asynchronous. A *synchronous exception* occurs at a particular program point, and is caused by an expression evaluation, a statement execution, or an explicit `throw` statement. An *asynchronous exception*, on the other hand, can occur at arbitrary, nondeterministic points in the program. A synchronous exception can be checked or unchecked. For a *checked exception*, the compiler must find a handler or a signature declaration for the method that raises the exception. For an *unchecked exception*, the compiler does not attempt to find such a handler or a signature declaration. A synchronous exception is *explicitly raised* if the exception is raised by a `throw` statement in the application being analyzed. A synchronous exception is *implicitly raised* if the exception is raised through a call to a library routine or by the runtime environment. The source of an implicitly raised exception, therefore, lies outside the application being analyzed. For example, a call to the Java API method `java.util.Stack.pop()` can raise a `EmptyStackException`; an expression that dereferences an object reference can cause the Java runtime environment to raise a `NullPointerException`.

The techniques that we discuss in this paper do not apply to asynchronous exceptions; a safe approximation of program points that can raise such exceptions may include all statements in the program. The techniques also do not apply to implicitly raised exceptions. The analysis of these types of exceptions is beyond the scope of this paper; our current research includes investigating ways to extend our work to include them.

III. Effects of Exception-Handling Constructs on Analysis Techniques

Exception-handling constructs belong to a class of control structures that cause arbitrary interprocedural control flow, and affect program-analysis techniques in similar ways. Other examples of such control structures include interprocedural jump statements, such as the `setjmp()`–`longjmp()` calls in C, and halt statements, such as the `exit()` call in C. Such constructs affect the flow of control across procedures, and in doing so, affect all analyses that are derived from control-flow analysis. The common effect of such control structures is that, at a call site, control may not return from the called procedure back to the call site. Instead, control may return to a different point in the calling procedure, or control may not return to the calling procedure at all. Through such an effect, the control structures influence program-analysis techniques, such as control-flow analysis, data-flow analysis, and control-dependence analysis.

The emphasis of our previous [20] and ongoing research is to characterize the control structures formally, to provide not only a better understanding of the common effects of the control structures on analysis techniques, but to facilitate the development of a uniform approach to performing accurate analyses in their presence. Although recent research has addressed some of the issues for program analyses and program understanding that arise in the presence of exception-handling constructs [13], [14], [12], [16], [15], none of that research describes the problems and the solutions for the general form of exception-handling constructs. Previous research [21], [7], [22] has addressed the problem of computing slices in the presence of control structures that cause arbitrary intraprocedural control flow, but those results do not apply to arbitrary control flow across procedures. We discuss related work in more detail in Section VII. In this paper, we restrict the discussion of the problems and solutions for exception-handling constructs.

In the remainder of this section, we first describe a program that we use to illustrate the concepts presented in the paper. We then discuss the effects of exception-handling constructs on three program-analysis techniques: control-flow analysis, data-flow analysis, and control-dependence analysis.

A. The Vending-Machine Program

The vending-machine program, shown in Figure 2, simulates the actions of a vending machine.[4] The machine lets a user insert coins, request a refund, or select an item using a numeric keypad. If the user selects a valid item and enters coins of value sufficient to cover the cost of the item, the machine dispenses the selected item. If the user makes an erroneous selection, the machine asks the user to reenter the selection; the user may reenter the selection or request a refund of the coins. The machine keeps track of the number of erroneous selections entered by a user. Once the number of erroneous selections exceeds a predetermined value, the machine aborts the transaction and returns the user's coins. Figure 3 explains the various error conditions that may arise during a transaction and presents a class hierarchy of exceptions that correspond to those conditions.

Method `main()` (lines 42–58) presents the user with the three options, and based on the user's action, invokes one of three methods, defined in the class `VendingMachine`, to process the action. Method `insert()` (lines 5–9) first ensures that the user has entered a valid coin, and then increments the current value by the value of the coin; `insert()` raises an exception if the user enters an invalid coin. Method `returnCoins()` (lines 10–14) refunds coins with a value equal to the current value, and resets the current value; `returnCoins()` raises an exception if the current value is zero. Method `vend()` (lines 15–28) accepts the user's selection, and if the current value is not zero, invokes method `dispense()` defined in the `Dispenser` class. Method `dispense()` (lines 29–41) performs several error checks to ensure that the selection is a valid item (line 30), the selection is available for dispensing (line 33), and the current value covers the cost of the selection (line 37). If any of these checks fails, the code raises an exception (line 40). If all checks pass, `dispense()` simulates dispensing of the item by printing a message (line 41). On successful completion of `dispense()`, `vend()` updates appropriate state variables (lines 19–20), and calls `returnCoins()` to return the balance to the user (line 21). If `dispense()` raises an exception that signals an erroneous selection (lines 32, 35), `vend()` handles the exception (line 22) and increments `currAttempts`. When `currAttempts` exceeds the constant `MAX_ATTEMPTS`, `vend()` rethrows the caught exception (line 27), which causes `main()` to abort the transaction.

We omit the details of methods, such as `value()` and `available()` in the `Dispenser` class, that are not relevant to our presentation; such methods raise no exceptions. For brevity, we also exclude the details of the constructors of some of the classes, and the initializations of constants such as `MAX_ATTEMPTS` and `MIN_SELECTION`.

B. Effects of Exceptions on Control-Flow Analysis

Control-flow analysis determines, for each program statement s, those statements in the program that could follow s in some execution of the program. Many program-analysis techniques, such as data-flow and control-dependence analyses, and software-engineering tasks, such as structural and regression testing, use control-flow information. These techniques typically construct a control-flow representation for the program being analyzed. For these analyses to be useful, and for these applications to be effective in the presence of exception-handling constructs, the control-flow representation should incorporate the exception-induced control flow.

The vending-machine program of Figure 2 exemplifies the complexity that the presence of exception-handling constructs can introduce in the control flow in a program.

[4] We adapted this example from the one by Kung and colleagues that appeared in Reference [23].

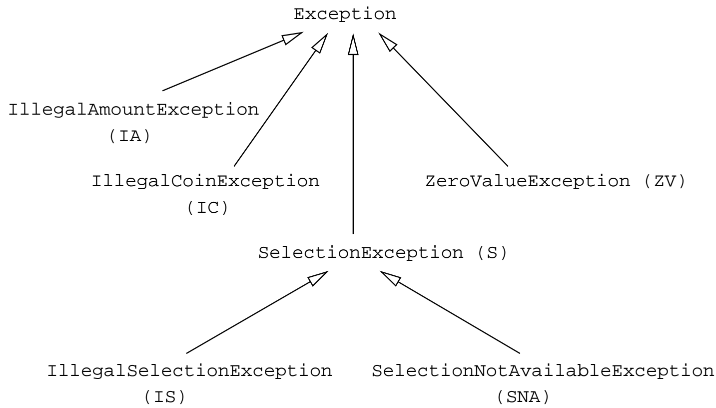
```
public class VendingMachine {

  private int totValue;
  private int currValue;
  private int currAttempts;
  private Dispenser d;

  public VendingMachine() {
 1  totValue = 0;
 2  currValue = 0;
 3  currAttempts = 0;
 4  d = new Dispenser();
  }

  public void insert( Coin coin ) {
 5  int value = valueOf( coin );
 6  if ( value == 0 ) {
 7    throw new IllegalCoinException();
    }
 8  currValue += value;
 9  showMsg( "current value = "+currValue );
  }

  public void returnCoins() {
10  if ( currValue == 0 ) {
11    throw new ZeroValueException();
    }
12  showMsg( "Coins returned" );
13  currValue = 0;
14  currAttempts = 0;
  }

  public void vend( int selection ) {
15  if ( currValue == 0 ) {
16    throw new ZeroValueException();
    }
    try {
17    d.dispense( currValue, selection );
18    int bal = d.value( selection );
19    totValue += currValue - bal;
20    currValue = bal;
21    returnCoins();
    }
22  catch( SelectionException s ) {
23    currAttempts++;
24    if ( currAttempts < MAX_ATTEMPTS ) {
25      showMsg( "Enter selection again" );
      }
      else {
26      currAttempts = 0;
27      throw s;
      }
    }
28  catch( ZeroValueException z ) {
    }
  }
}
```

```
public class Dispenser {
  public void dispense( int currVal, int sel ) {
29  Exception e = null;
30  if ( sel < MIN_SELECTION || sel > MAX_SELECTION ) {
31    showMsg( "selection "+sel+" is invalid" );
32    e = new IllegalSelectionException();
    }
    else {
33    if ( !available( sel ) ) {
34      showMsg( "selection "+sel+" is unavailable" );
35      e = new SelectionNotAvailableException();
      }
      else {
36      int val = value( sel );
37      if ( currVal < val ) {
38        e = new IllegalAmountException( val-currVal );
        }
      }
    }
39  if ( e != null ) {
40    throw e;
    }
41  showMsg( "Take selection" );
  }
}
```

```
  public static void main() {
42  VendingMachine vm = new VendingMachine();
43  while ( true ) {
      try {
        try {
44        switch( action ) {
45          case INSERT: vm.insert( coin );
46          case VEND:   vm.vend( selection );
47          case RETURN: vm.returnCoins();
          }
        }
48      catch( SelectionException s ) {
49        showMsg( "Transaction aborted" );
50        vm.returnCoins();
        }
51      catch( IllegalCoinException i ) {
52        showMsg( "Illegal coin" );
53        vm.returnCoins();
        }
54      catch( IllegalAmountException i ) {
55        int val = i.getValue();
56        showMsg( "Enter more coins"+val );
        }
      }
57    catch( ZeroValueException z ) {
58      showMsg( "Value is zero.  Enter coins" );
      }
    }
  }
```

Fig. 2. Java code for the vending-machine program: class `VendingMachine` (top), class `Dispenser` (bottom left), and method `main()` (bottom right).

For example, in method `insert()`, control does not reach line 8 if the predicate in line 6 evaluates to true; instead, the exception raised in line 7 terminates the execution of `insert()`, and transfers control to a caller of `insert()`. For further example, consider the call to `dispense()` in line 17. Following the call, control may not return to the call site: if `dispense()` raises an exception, control may return to line 22 of `vend()` or control may not return to `vend()` at all. Through such effects, exception-handling constructs can influence control flow not only within a method, but



Exception	Condition
`IllegalAmount`	User selects an item that costs more than the value of the coins inserted
`IllegalCoin`	User inserts an illegal coin
`ZeroValue`	User selects an item, or requests a refund without inserting any coins
`IllegalSelection`	User enters a number that does not correspond to a valid selection
`SelectionNot-Available`	User selects an item that is temporarily unavailable

Fig. 3. Hierarchy of exception-related classes (and their abbreviated names) for the vending-machine program (left), and conditions that cause various exceptions to be raised (right).

across methods, and can introduce complex control-flow paths in a program.

The control-flow relation that exists in a program can be represented as a *control-flow graph* (CFG) in which nodes represent statements, and edges represent the flow of control between statements [24].

Recent work [12] describes an intraprocedural representation of Java exception-handling constructs. That work, however, does not consider several issues related to control flow. For example, the work does not consider the control flow caused by the presence of `finally` blocks, and it does not model the propagation of exceptions by methods. In Section IV-A, we analyze the control flow caused by exception-handling constructs, and describe our approach for creating intraprocedural and interprocedural representations of programs that contain those constructs.

C. Effects of Exceptions on Data-Flow Analysis

Data-flow analysis techniques compute data-flow facts, such as definition-use pairs, reaching definitions, available expressions, and live variables, that hold at different program points. Data-flow information is used in activities such as program slicing [25], [26], [27], data-flow testing [1], [2], [28], and compiler optimizations [24]. A data-flow problem can be formulated as a set of equations that compute data-flow facts, and those data-flow facts are computed and propagated iteratively throughout the program, using a control-flow representation. The solution of the data-flow problem is the fixed-point solution of the equations. In the presence of exception-handling constructs, the data-flow facts must be propagated also along the exceptional control-flow paths, so that the computed data-flow solutions approximate conservatively the true data-flow solutions.

To illustrate, consider the effect of exception-handling constructs on the computation of definition-use pairs. A *definition-use pair* is a pair (d, u), where d is a statement that defines a variable v (references and changes v), u is a statement that uses v (references but does not change v), and there is a path in the program from d to u along which v is not redefined. Exception-handling constructs may cause a definition-use computation to miss definition-use pairs in two ways. First, a definition-use pair may not be detected because the pair occurs along only an exceptional-control flow path that is not modeled by the control-flow representation. For example, in the vending-machine program, there exists such a pair that includes statement 42, where `vm` is defined, and statement 53, where `vm` is used. This definition-use pair is not detected if the exceptional control flow from statement 7 to statement 51 is not modeled by the control-flow representation. Second, exception-handling constructs introduce additional definition-use pairs in a program through the exception object. The definition of exception object `e` in statement 38, and its subsequent use as `i` in statement 55 is an example of such a definition-use pair.

A data-flow relation can be represented as a *data-dependence graph* in which nodes represent program statements and edges represent the data dependence between statements. In such a graph, for definition-use pairs, a data-dependence edge exists between nodes n_1 and n_2 if (n_1, n_2) is a definition-use pair.

Several researchers have recently addressed the problem of performing data-flow analyses in the presence of exception-handling constructs. Some researchers [13], [14] do not explicitly create a control-flow representation for exceptions; instead, they modify the data-flow analyses to compute and traverse the intraprocedural and interprocedural exceptional control-flow paths while performing the desired analyses. Other researchers [12] represent some exceptional control flow explicitly, and modify the data-flow analyses to compute the remaining exceptional control flow while performing the analyses. With the control-flow representation that we define in Sections IV-A.1 and IV-A.2, existing algorithms for data-flow analyses require either no modifications or minor modifications to function in the presence of exception-handling constructs. The other approaches work as well for performing the data-flow analyses; our representation provides an alternative approach to performing the analyses.

D. Effects of Exceptions on Control-Dependence Analysis

Control-dependence analysis [5] determines, for each program statement, the predicates that control the execution of that statement. Informally, a statement s is control dependent on (p, 'L')—where p is a predicate and 'L' is the label associated with one of p's branches—if, in the CFG, there are two edges out of the node for p such that following the edge labeled 'L' causes the node for s to be reached definitely, whereas following the other edge may cause that node not to be reached [29]. A statement in procedure P that is control dependent on no predicates in P is control dependent on entry into P. Control-dependence information is required for analyses, such as slicing, that are used for software-engineering tools, such as debuggers, impact analyzers, and regression testers.

Traditional definitions of, and algorithms for computing, control dependence [5], [29], [30], [31] function at the intraprocedural level, and inaccurately model the control dependences when they are applied to programs that contain exception-handling constructs. One factor that causes the traditional definitions and algorithms to be inadequate is the presence of *potentially non-returning call sites* (PNRCs) [8]: call sites to which control may not return from the called methods. Through their effects on interprocedural control flow, exception-handling constructs cause PNRCs in a program, and necessitate the computation of interprocedural control dependence. For example, in the vending-machine program, the call site in line 17 is a PNRC because, following the call, control may return to statement 22 rather than to statement 17, or control may not return to `vend()` at all. This causes statements that follow the call site, such as statement 20, to be control dependent on conditional statements in the called methods. For example, statement 20 is control dependent on (39, 'F'), which belongs in `dispense()`. Traditional techniques, however, identify statement 20 as control dependent on entry into `vend()`.

In the presence of exception-handling constructs, control dependences of certain statements—those that appear in a `catch` block—might be computable only in the interprocedural context; such statements have no intraprocedural control dependences. For example, the execution of statements 51–53, which belong to `main()`, is controlled by decisions that are made in `insert()`. Therefore, to identify the control dependences for such statements, interprocedural control dependences must be computed.

The control-dependence relation is represented as a graph. A *control-dependence graph* (CDG) [5] contains a node for each predicate and statement in a procedure, and an edge labeled 'L' from predicate p to statement s if s is control dependent on (p, 'L'). A unique root node denotes the entry predicate, and represents the control dependences of those statements that are reached when control enters the procedure.

Past work that has attempted the computation of interprocedural control dependence [32] considers only the effects of halt statements, and suffers from several drawbacks. Recent work [8] has addressed those drawbacks, but considers only the effects of halt statements. In Section IV-B, we present an approach that computes interprocedural control dependences in the presence of exception-handling constructs.

IV. Analysis Techniques to Accommodate Exception-Handling Constructs

In this section, we describe techniques for control-flow and control-dependence analysis that account for the effects of exception-handling constructs, and therefore, can be applied to programs that contain such constructs.

A. Control-Flow Analysis

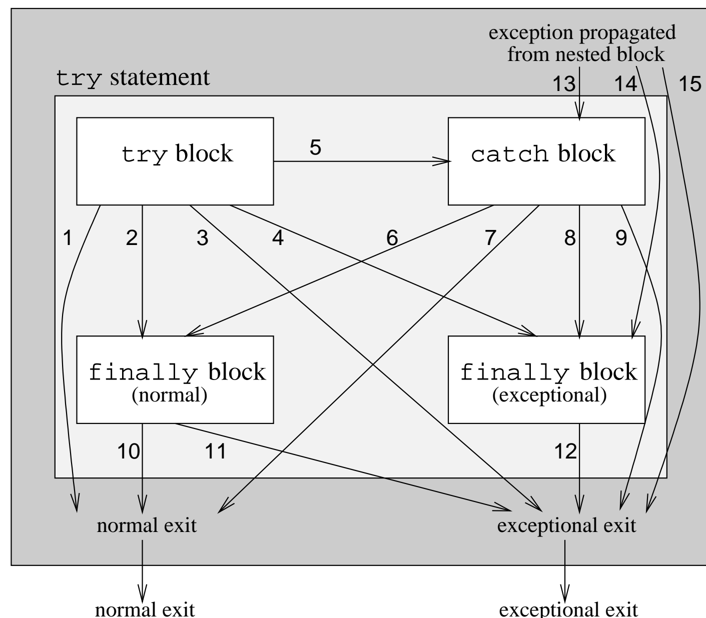
As we discussed in Section III-B, the presence of exception-handling constructs creates control-flow paths within and across methods. To be precise, the intraprocedural and interprocedural control-flow representations must contain these paths.

A.1 Intraprocedural analysis

When an exception is raised in a `try` block, control transfers to the `catch` clause that handles the raised exception. This `catch` clause may be associated with the `try` block in which the exception is raised, or may be associated with a lexically enclosing `try` block. The parameter of the matching `catch` clause is bound to the thrown object, and the handler code is executed. Following the execution of the handler code, normal execution resumes at the first statement that follows the `try` statement in which the exception was handled. Before control exits a `try` statement, the `finally` block of the `try` statement is executed, if it exists, regardless of whether control exits the `try` statement with an unhandled exception.

The block-level control-flow graph, shown in Figure 4, summarizes the control flow into and out of a `try` statement. The figure shows a `try` statement and its component blocks; the conditions causing the control flow between the blocks are numbered and listed next to the figure. As the figure illustrates, there are several control-flow paths within a `try` statement. For example, the path (5, 8, 12) is taken if the `try` block raises an exception, the `catch` block handles the exception but raises another exception, and the `finally` block raises no exception. Paths starting at edges 13, 14, or 15 are taken if a nested `try` statement propagates an exception. For example, path (13, 6, 11) is taken if a nested `try` statement propagates an exception that is handled in the `catch` block, and then the `finally` block raises another exception.

Figure 4 illustrates that a Java `finally` block can execute in one of two contexts: a normal context or an exceptional context. A `finally` block executes in a *normal context* when (1) control reaches the end of a `try` block or a `catch` block, or (2) control leaves a `try` statement because of an unconditional transfer statement, such as `break`, `continue`, or `return`. A `finally` block executes in an *exceptional context* when control leaves a `try` statement because of an unhandled exception. The context of execution of a `finally` block determines where control



1 try block raises no exception; no finally block
2 try block raises no exception; finally block specified
3 try block raises exception; catch block does not handle exception; no finally block
4 try block raises exception; catch block does not handle exception; finally block specified
5 try block raises exception; catch block handles exception
6 catch block handles exception; finally block specified
7 catch block handles exception; no finally block
8 catch block handles exception, raises another exception; finally block specified
9 catch block handles exception; raises another exception; no finally block
10 finally block raises no exception
11 finally block raises exception
12 finally block propagates previous exception, or raises another exception
13 nested block propagates exception; catch block handles exception
14 nested block propagates exception; catch block does not handle exception; finally block specified
15 nested block propagates exception; catch block does not handle exception; no finally block

Fig. 4. Intraprocedural control flow in Java exception-handling constructs.

flows from that `finally` block: In a normal context, control flows to the statement that follows the `try` statement, or control flows to the target of an unconditional transfer statement; in an exceptional context, control flows to an enclosing `finally` block, an enclosing `catch` handler, or control exits the method with an unhandled exception.

To represent exceptional-handling constructs, a CFG constructed by our algorithm contains nodes that represent `throw` statements, `catch` handlers, and `finally` blocks, and edges that represent the normal and exceptional control flow caused by those constructs. A throw node can have multiple successors in a CFG; these successors are determined by the types of exceptions that can be raised at the corresponding `throw` statement. To determine the potential exception types, we perform type inference, and create one outgoing edge from the throw node for each type of exception.[5] We label each edge with the type of exception that causes that edge to be traversed during program execution. The multiple successors of a throw node are based on exception types because distinct exception types can cause control to be transferred to distinct program points. Figure 5 presents the CFGs for the methods of the vending-machine program that are constructed using our approach. The `throw` statement in line 40 of the program can raise one of three types of exceptions: `IA`, `IS`, or `SNA`. Therefore, the CFG node for that statement has three outgoing edges—one for each type of exception—that are labeled with the corresponding exception types. If a `throw` statement raises only one type of exception, the CFG node for that statement has a a single labeled outgoing edge. For example, node 11 has a single outgoing edge labeled 'ZV' because the corresponding `throw` statement raises an exception whose type is always `ZV`.

A method may propagate an exception by raising, but not handling, that exception. To model the propagation of exceptions by a method, the CFG contains exceptional-exit nodes. An *exceptional-exit node* is an exit point in the CFG that has a type T associated with it, and represents the propagation of an exception of type T by the corresponding method. A method may propagate an exception that was raised directly in that method, or indirectly, through a called method. The CFG of a method has as many exceptional-exit nodes as the distinct types of exceptions that are raised directly, but not handled, in the method. In Figure 5, the CFG for `vend()` has three exceptional-exit nodes because `vend()` propagates three types of directly raised exceptions: `IS`, `SNA`, and `ZV`. The CFGs for `insert()` and `returnCoins()` have one exceptional-exit node each because both these methods propagate one type of directly raised exception. Method `vend()` propagates an indirectly raised exception, `IA`, through the call to `dispense()`; the exceptional-exit nodes for such exceptions are created in the interprocedural representation (Section IV-A.2).

In the CFG, the node for a `catch` handler that handles directly raised exceptions has incoming edges for those exceptions. The node for a `catch` handler that handles only indirectly raised exceptions, however, has no incoming edges in the CFG; such a node has incoming edges in the interprocedural representation. Because all handlers in the vending-machine program handle only indirectly raised exceptions, the catch nodes for those handlers have no incoming edges.

A `finally` block can execute in different contexts such that following the execution of statements in the block, control flows to different points in different contexts. There are two alternative approaches to model such control flow

[5]Section IV-A.3 provides further discussion of type inferencing.

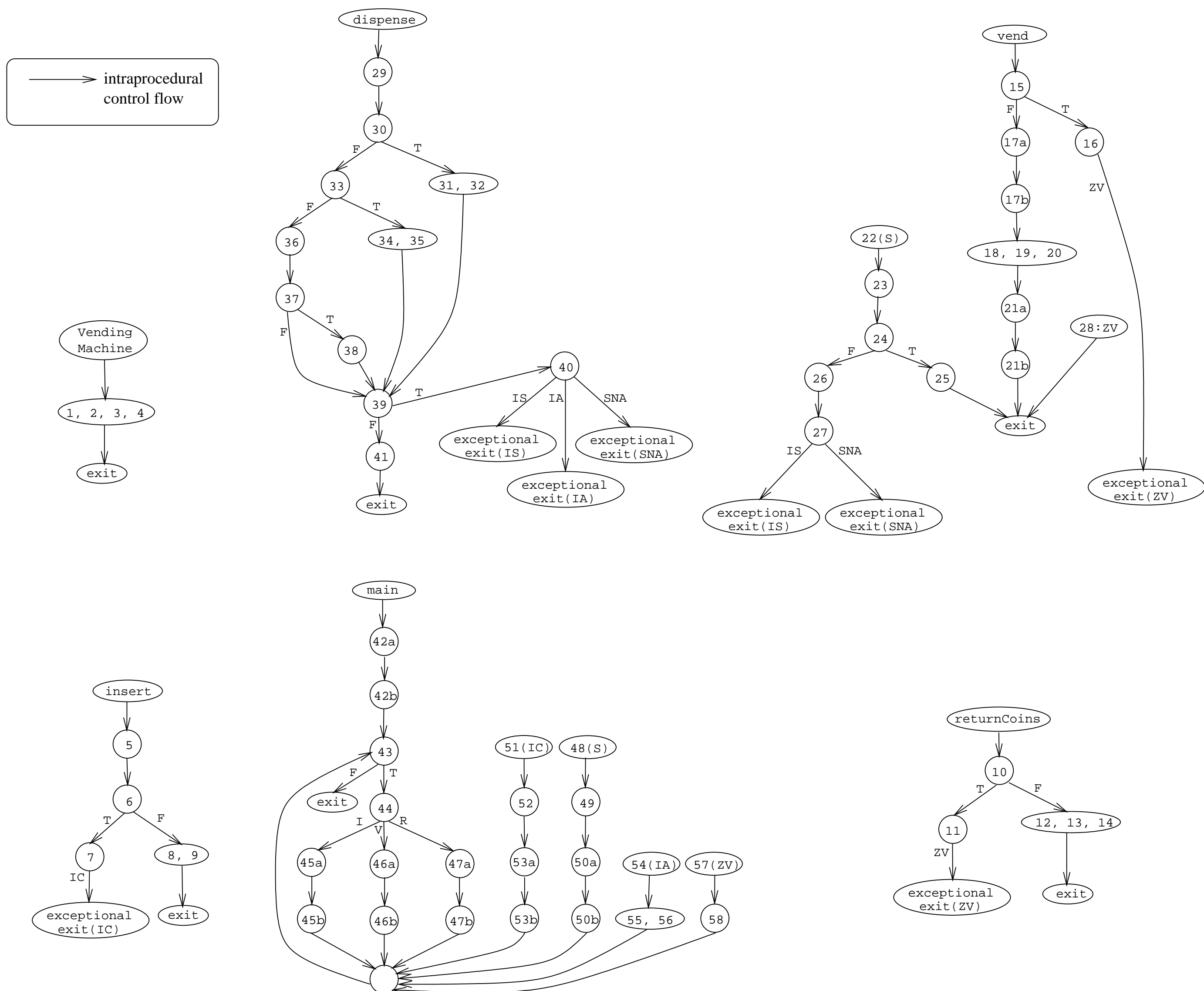


Fig. 5. The control-flow graphs for methods of the vending-machine program constructed by our approach.

without introducing paths that represent invalid entry–exit sequences for `finally` blocks. One approach creates a separate CFG for each `finally` block, and inserts call nodes to the `finally` blocks for both contexts of execution. The other approach avoids creating a separate CFG for each `finally` block, and instead inlines a `finally` block once for each of its different contexts of execution. The second approach becomes impractical if `finally` blocks appear frequently and are large. For simplicity of presentation, the vending-machine program excludes `finally` blocks. Reference [33] describes examples that illustrate the control-flow representation for `finally` blocks.

Figure 6 provides an overview of the CFG-construction algorithm [33]. The algorithm operates in three steps: First, the algorithm creates an incomplete CFG in which throw nodes have no outgoing edges; next, the algorithm performs type inferencing using the incomplete CFG to determine potential exception types for `throw` statements;[5] finally, the algorithm completes the CFG by adding outgoing edges from the throw nodes, and creating the necessary exceptional-exit nodes and nodes that represent execution of `finally` blocks in exceptional contexts. The first step of the algorithm can be implemented using either an

algorithm `ConstructCFG`
input AST : abstract-syntax tree for procedure P
output CFG : control-flow graph for procedure P

begin `ConstructCFG`
/* Step 1: construct incomplete CFG */
1. construct control-flow graph with no outgoing edge from throw nodes
/* Step 2: perform type inference[5] */
2. perform intraprocedural flow-sensitive type analysis
3. perform interprocedural flow-insensitive type analysis
/* Step 3: construct complete CFG */
4. create outgoing edges from throw nodes
5. create exceptional-exit nodes for propagated exception types
6. create nodes for execution of `finally` blocks in exceptional contexts

end `ConstructCFG`

Fig. 6. Overview of the CFG-construction algorithm.

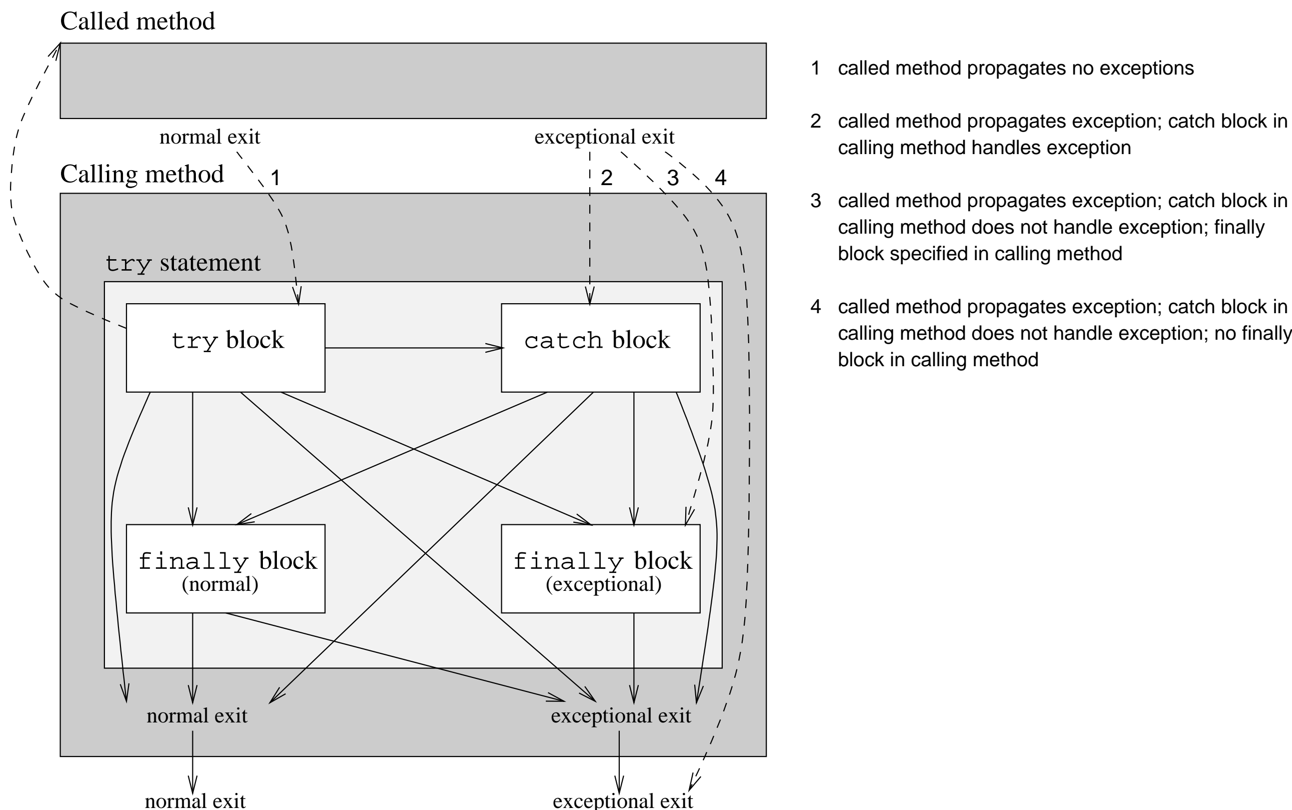


Fig. 7. Interprocedural control flow in Java exception-handling constructs.

abstract-syntax tree, as described in Reference [33], or the Java bytecodes. Our Java analysis tool, JABA,[3] constructs the CFGs using the bytecode-based implementation of the algorithm.

A.2 Interprocedural analysis

The propagation of exceptions on the call stack creates interprocedural exceptional control flow. Interprocedural control flow is represented in an interprocedural control-flow graph. An *interprocedural control-flow graph* (ICFG) for a program $\mathcal{P}$ consists of CFGs for each method or procedure in $\mathcal{P}$; at each call site, the call node is connected to the entry node of the called method by a call edge, and the exit node of the called method is connected to the corresponding return node by a return edge.

Figure 7 presents an interprocedural block-level control-flow graph (similar to Figure 4) that shows the called method B at the top, and its caller A below it. The call to B within A's `try` block is shown by a call edge. Following the execution of B, control can return to A in one of four ways; the edges corresponding to these returns are labeled in the figure. If B propagates no exceptions, control returns normally to the statement following the call site in A. However, if B propagates an exception, control does not return to the call site. If the `try` block in A has an associated `catch` handler that handles the raised exception, control flows to that handler. If there is no such `catch` handler associated with the `try` block but that block has a corresponding `finally` block, control flows to the `finally` block. If neither of the above is true, method A also propagates the exception, and the search for a handler continues in the caller of A.

To represent the interprocedural exceptional control flow, the ICFG contains exceptional-return edges. An *exceptional-return edge* is an interprocedural edge that connects an exceptional-exit node of the called method to a catch node, a node for a `finally` block, or an exceptional-exit node of the calling method.

Figure 8 shows the ICFG for the vending-machine program. Each call node is connected to the entry node of the CFG of the called method by a call edge; the exit node of that CFG is connected to the corresponding return node by a return edge. If a method propagates an exception that is caught in the caller of that method, the exceptional-exit node for that exception type is connected to the appropriate node in the caller by an exceptional-return edge. For example, `insert()` propagates `IC` that is caught in statement 51 of `main()` (the caller of `insert()`). Therefore, the exceptional-exit node in the CFG for `insert()` is connected, by an exceptional-return edge, to node 51 in the CFG for `main()`. A method may propagate an exception that is not handled in the immediate caller of that method, but is handled in a method that lies further up in the call chain. For example, `main()` calls `vend()`, and `vend()` calls `dispense()`. `dispense()` propagates an exception of type `IA`; `vend()`, however, does not handle the exception but propagates it up to `main()`. The chain of exceptional-return edges in the ICFG reflects the exception

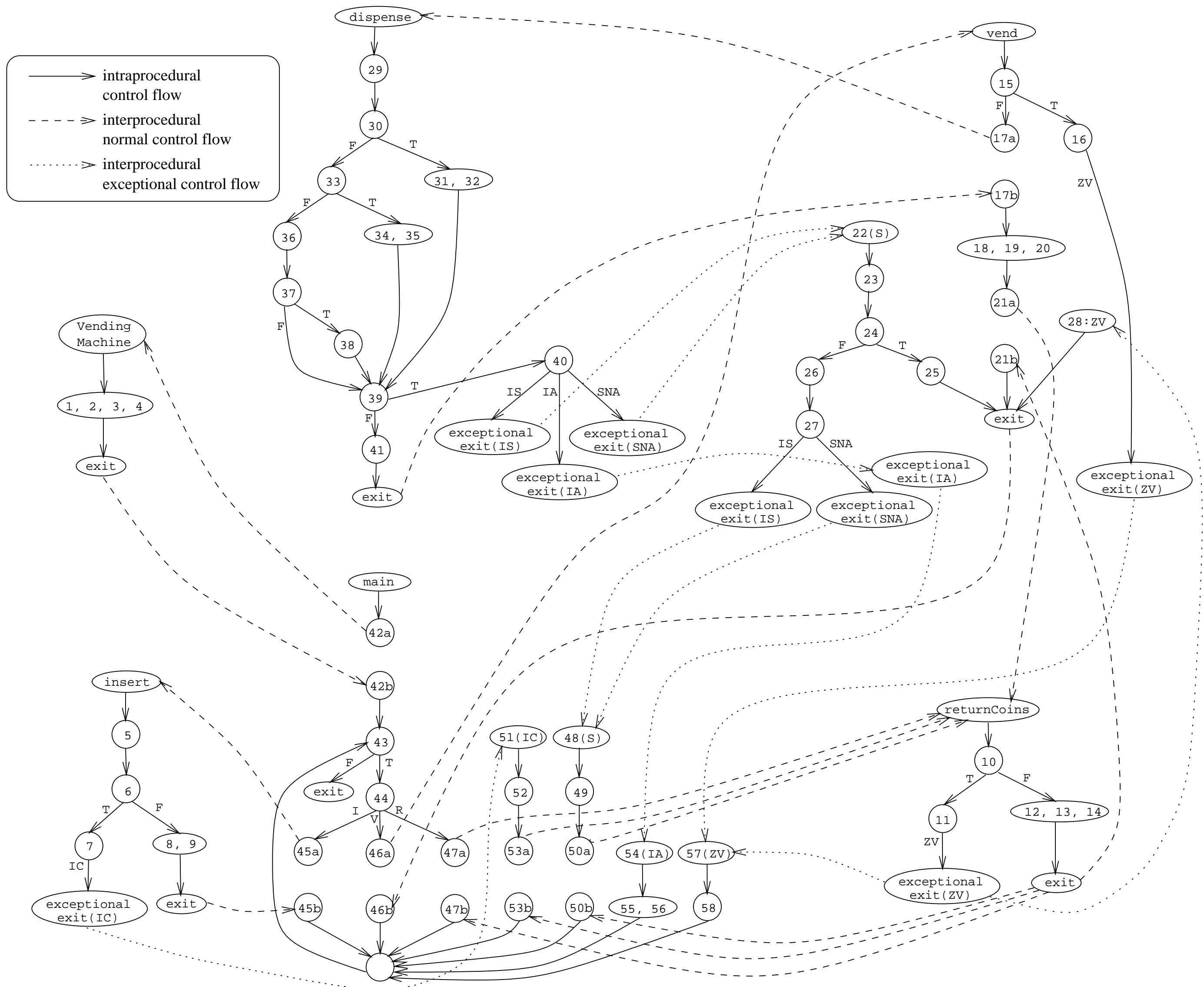


Fig. 8. The interprocedural control-flow graph for the vending-machine program constructed by our approach.

propagation: the exceptional-exit node for type `IA` in the CFG for `dispense()` is connected to the exceptional-exit node for the same type in the CFG for `vend()`, which in turn is connected to catch node 54 in the CFG for `main()`.

The ICFG-construction algorithm [33] iteratively determines, for each method, those propagated exception types that are raised indirectly in the method, and adds exceptional-exit nodes to the CFG of the method for those exception types. For example, the ICFG-construction algorithm determines that `vend()` propagates `IA` such that `IA` is raised indirectly in `vend()` (through the call to `dispense()`), and adds an exceptional-exit node for type `IA` to the CFG of `vend()`. Figure 9 provides a high-level view of the algorithm. The algorithm initializes a *worklist* with the methods in the program (line 1), and then repeatedly removes a method N from the *worklist* and processes all callers of N, until the *worklist* becomes empty (lines 2–14). For each call site that calls N, the algorithm creates call and return edges (line 5). The exception types that are propagated by N (indicated by the exceptional-exit nodes in the CFG of N) are raised indirectly in M. Therefore, for each such exception type, the algorithm adds an exceptional-exit node and nodes for `finally` blocks to the CFG of M (line 7), if such nodes are required; for example, if an exception type is propagated by N and is not caught by M, the algorithm adds an exceptional-exit node for that type to the CFG of M. For each exception type propagated by N, the algorithm also creates an exceptional-return edge (line 8). If the algorithm adds an exceptional-exit node to the CFG of M, it adds M to the *worklist* (line 10), to ensure that all callers of M are reprocessed.

Like other iterative data-flow algorithms, the ICFG-construction algorithm can be implemented efficiently to process methods in a reverse topological order of the program's call multigraph.[6] Such an implementation processes

[6]A *call multigraph* for a program $\mathcal{P}$ contains a node N for each method in $\mathcal{P}$, and an edge from node N_i to node N_j for each call site, in the method corresponding to N_i, that calls the method cor-

```
algorithm ConstructICFG
input     CFG : control-flow graph for each method in P
output    ICFG : interprocedural control-flow graph for P
declare   worklist : methods that are processed iteratively

begin ConstructICFG
 1.  initialize worklist with methods in P
 2.  while worklist is not empty
 3.      remove method N from worklist
 4.      foreach call site in method M that calls N
 5.          create call edge, return edge
 6.          foreach exceptional-exit node in the CFG of N
 7.              add exceptional-exit node, nodes for finally blocks
                 to the CFG of M, if required
 8.              create exceptional-return edge
 9.              if an exceptional-exit node added to the CFG of M
10.                  add M to worklist
11.              endif
12.          endfor
13.      endfor
14.  endwhile
end ConstructICFG
```

Fig. 9. Overview of the ICFG-construction algorithm.

each non-recursive method only once, and the recursive methods iteratively, as shown in Figure 9, until a fixed point is reached.

A.3 Type inferencing for exception types

The CFG construction requires information about exception types that can be raised at `throw` statements. Type information can be computed with varying degrees of precision. More precise type information at a `throw` statement includes fewer spurious exception types—types that cannot be raised at the `throw` statement in any execution of the program. The precision of the type inference determines the extent to which infeasible paths[7] are introduced in the control-flow representations. An imprecise (but safe) approximation of exception types causes the addition of unnecessary edges emanating from throw nodes; programs paths that contain such edges are infeasible.

Type-inference algorithms (e.g., [34], [35]) attempt to determine the types for each expression in a program by solving type constraints or by propagating local type information throughout a program. Such techniques have been applied traditionally to optimization of dynamically dispatched function calls. Recent work [13] uses points-to analysis to infer types in programs that contain exception-handling constructs.

Type inference for exception types is required only for those `throw` statements whose exception types cannot be determined by an inspection of the `throw` statement; the expressions of such `throw` statements are variables or method calls. For example, a `throw` statement, such as the one in line 11 of the vending-machine program, requires no type inference because its expression is a new-instance expression; the only type of exception that can be raised at that statement is `ZV`. The `throw` statement in line 40, however, requires type inference because it raises the exception object referenced by a variable, and different exception objects are created and assigned to that variable along different paths to the `throw` statement.

TABLE II

TYPES OF `throw` STATEMENT EXPRESSIONS.

Subject	`throw` statements	`throw` statement expressions		
		new instance	variable	method call
antlr	262	252	10	0
debug	61	56	5	0
jaba	220	219	1	0
jar	13	13	0	0
jas	215	215	0	0
jasmin	56	55	1	0
javacup	30	29	1	0
javac	129	127	2	0
javadoc	5	5	0	0
javasim	37	37	0	0
jb	56	55	1	0
jdk-api	703	683	20	0
jedit	76	76	0	0
jflex	49	49	0	0
jlex	3	3	0	0
joie	81	79	2	0
sablecc	142	142	0	0
swing-api	352	336	4	12
Total	2490	2431	47	12

Our empirical evidence, based on the subjects listed in Table I, suggests that, in practice, the expressions of an overwhelming majority of `throw` statements are new-instance expressions, and therefore, require no type-inference analysis. Table II lists the types of throw-statement expressions that appear in our subjects. As the data illustrates, out of the 2490 `throw` statements that appear in the subjects, only 59 have either a variable or a method call as their expressions. Among these `throw` statements, a variable expression appears four times more frequently than a method-call expression. The remaining `throw` statements, which constitute over 97% of the total `throw` statements, require no type-inference analysis. Therefore, we believe that the use of an exhaustive type-inference algorithm for inferring exception types may not be justified.

To determine types for `throw` statements whose expressions are not new-instance expressions, we consider four computationally inexpensive approaches. The first approach is a conservative approximation that includes all subtypes of the relevant exception type. For example, to determine the exception types for the `throw` statement in line 40 of the vending-machine program, the conservative-approximation approach identifies all subtypes of class `Exception` as the potential exception types.

The second approach is an intraprocedural flow-sensitive analysis[8] [33]. The analysis performs an iterative data-flow analysis starting at a `throw` statement that raises an exception object dereferenced through a variable, and searches backwards for statements that assign a type to that variable. If the analysis reaches statements that define the types on all paths to the `throw` statement, the analysis precisely identifies the exception types that (statically) reach the `throw` statement. For example, this approach traverses

responding to N_j.

[7]A path is *infeasible* if there exists no input to the program that causes the path to be executed.

[8]A *flow-sensitive* analysis considers the control flow among statements, whereas a *flow-insensitive* analysis ignores the control flow.

TABLE III
EFFECTIVENESS OF THE TYPE-INFERENCE APPROACHES.

Type-inference approach	Number of throw statements with					Average number of types
	single type	2–10 types	11–20 types	21–30 types	>30 types	
Conservative approx	26	6	3	0	12	13.3
Intra FS analysis	28	6	3	0	10	11.5
Inter FI analysis	29	8	2	8	0	5.6
Intra FS and inter FI analyses	31	8	1	7	0	4.9

backward on all paths from the `throw` statement in line 40, and precisely determines the types `IA`, `IS`, and `SNA` for that `throw` statement. The analysis traverses backwards only in the method that contains the `throw` statement. On reaching the method boundary (at the method entry, a call node, or a catch node), the analysis uses the conservative-approximation approach, and includes in the solution all subtypes of the relevant exception type. The intraprocedural flow-sensitive analysis is similar to the intraprocedural type propagation described in Reference [36].

The third approach, similar to rapid type analysis [37], is an interprocedural flow-insensitive analysis: it starts with the conservative approximation, and refines that approximation by examining object-creation sites and return types of all library calls. The refined approximation contains only those types that are either instantiated in the program or returned by a library routine. For example, to determine exception types for the `throw` statement in line 27, the interprocedural analysis first approximates `S`, `IS`, and `SNA` as the potential exception types. The analysis then examines object-creation sites and return types of library calls, and eliminates `S` from the type-inference solution. The interprocedural flow-insensitive analysis can omit potential exception types from the type-inference solution because a library routine can return an exception object by encapsulating it in a class, and the analysis would fail to detect that exception type.

The final approach is a combination of the intraprocedural flow-sensitive and the interprocedural flow-insensitive analyses. This approach first performs the flow-sensitive analysis, and if that analysis results in a conservative approximation, the approach uses the flow-insensitive analysis to improve the precision of the type inference information.

To evaluate these four approaches, we performed an empirical study. The goal of the study was to compare the precision of the type-inference information computed using the approaches. Using each of the four approaches, we determined the potential exception types for the 47 `throw` statements in the subjects that mention a variable. Table III presents the data from the empirical study. For each type-inference approach, the table lists the number of `throw` statements for which the number of inferred exception types fall in various ranges.

The data in the table shows that the conservative approximation computed a single type for 26 `throw` statements, but computed over 30 types for 12 `throw` statements. For two of those 12 `throw` statements, the intraprocedural flow-sensitive analysis succeeded in reducing the number of exception types to one. However, the intraprocedural flow-sensitive analysis did not cause a significant reduction in the inferred types compared to the conservative approximation. The average number of exception types decreased marginally from 13.3, for the conservative approximation, to 11.5, for the intraprocedural flow-sensitive analysis. The interprocedural flow-insensitive analysis, however, caused a significant reduction in the inferred types. With the interprocedural flow-insensitive analysis, no `throw` statement had more than 30 exception types. When the interprocedural flow-insensitive analysis was used in isolation, the average number of exception types was 5.6; when used in conjunction with the intraprocedural flow-sensitive analysis, the average number of types was 4.9.

The results from the study indicate that, in practice, the intraprocedural flow-sensitive analysis may not offer much benefit over the conservative approximation approach. The interprocedural flow-insensitive analysis improves significantly the precision of the type-inference solution, but as noted, the analysis may omit potential types from the solution. The scarcity of the data points is a threat to the validity of these observations; further experimentation is required to establish the veracity or the fallacy of the observations.

A.4 Complexity of control-flow analysis

The cost of `ConstructCFG` is linear in the size of a method if the method contains no `throw` statements. To process a `throw` statement, `ConstructCFG` (1) performs type inferencing, and (2) determines CFG successors based on the inferred types. The cost of type inferencing depends on which approach to type inferencing is used. The cost of the conservative approximation is $O(ET)$, where ET is the number of types in the exception hierarchy. The cost of the intraprocedural flow-sensitive analysis is $O(N + ET)$ for reducible control flow, and $O(N^2 + ET)$ otherwise—N is the number of nodes in the CFG for a method. The interprocedural flow-insensitive analysis requires a preprocessing time that is linear in the number of statements in a program; this expense is incurred only once. The approach then builds a list of instantiated types, and uses the list to eliminate exception types that cannot be raised. If CT is the number of types that are created in a program, the cost of the flow-insensitive analysis is $O(CT * ET)$.

Let T be the number of `throw` statements in a method, and let H and F be the numbers of `catch` handlers and `finally` blocks, respectively, that enclose a call site in a method. Let $wcc(TI)$ be the worst-case complexity of type inferencing and IT be the number of inferred exception types. For each type that is inferred for a `throw` statement, `ConstructCFG` searches for a target among the enclosing `catch` handler and processes enclosing `finally` blocks. Therefore, the cost of processing a `throw` statement

is $O(wcc(TI) + IT * (H + F))$. The overall cost of the CFG construction is $O(N + (wcc(TI) + IT * (H + F)))$.

The cost of `ConstructICFG` is bounded by the number of methods that it processes and the cost of processing each method. If M is the number of methods in a program, in the worst case, `ConstructICFG` may process $O(M^2)$ methods. For each method, the algorithm examines all call sites in the method, and for a given call site, the algorithm iterates over the exceptional-exit nodes in the called method. For each exceptional-exit node, `ConstructICFG` searches for a `catch` handler and processes `finally` blocks in the calling method. If C and X are the numbers of call sites and the number of exceptional-exit nodes, respectively, in a method, the cost of processing a method is $O(C * X * (H + F))$, where H and F are the number of `catch` handlers and `finally` blocks, respectively, that enclose a call site. Therefore, the cost of ICFG construction is $O(M^2 * C * X * (H + F))$. In practice, $(H + F)$ is a small constant. Moreover, X can also be bound by a constant, by using an approach to ICFG construction that uses a threshold value for distinct exception types. Such an approach distinguishes exception types until the number of exception types exceeds the threshold; once the number exceeds the threshold, the approach summarizes the exception types using a single exceptional-exit node. Our future work will investigate such approaches to constructing the ICFG. `ConstructICFG` processes a polymorphic call site by creating a distinct call edge for each method that can be called (statically) through subtyping; therefore, the cost of creating call and return edges is $O(C * M)$.

B. Control-Dependence Analysis

In Section III-D, we discussed that exception-handling constructs affect the control-dependence relations by causing potentially non-returning call sites (PNRCs), and necessitate the computation of interprocedural control dependence.

Interprocedural control dependence is defined by applying the traditional definition of control dependence [5], [29] to an interprocedural inlined flow graph [8]. An *interprocedural inlined flow graph* (IIFG) of a program $\mathcal{P}$ contains, for each method, a copy of the CFG of the method for each context in which the method appears in $\mathcal{P}$. As in an ICFG, call, return, and exceptional-return edges connect the CFGs in an IIFG; however, unlike an ICFG, at each call site, a distinct copy of the CFG of the called method is inlined. Thus, an IIFG can be exponential in the size of a program, and is infinite for recursive programs.

Defining interprocedural control dependence using an IIFG causes the control-dependence relation to provide a closer approximation to semantic dependences [8]. Such a definition of control dependence distinguishes each context in which a method can be called, and computes *node-based interprocedural control dependences*: distinct control dependences for each context of execution of a statement. However, computing node-based control dependences may not be practical because of the exponential size of an IIFG. An alternative approach is to ignore the context-based distinctions, and compute *statement-based interprocedural control dependences*: control dependences that exist in at least one context of execution of a statement. Statement-based control dependences are not as precise as node-based control dependences because the computation summarizes the control dependences that exist in different contexts; however, statement-based control dependences preserve the desirable property of approximating semantic dependences [8].

The interprocedural control-dependence algorithm computes statement-based control dependences without constructing an IIFG. The algorithm proceeds in two phases: Phase 1 identifies PNRCs that are caused by `throw` statements and halt statements, and uses this information to compute partial control dependences; Phase 2 uses partial control dependences to compute statement-based interprocedural control dependences.

B.1 Computation of partial control dependences

The first step of Phase 1 identifies call sites that are PNRCs. To identify PNRCs, the first step computes, for each call site, the set of nodes to which control can return following the call site. A call site, where control returns to only the associated return node, is definitely returning, and has no effect on control dependences. A call site, where control can return to nodes other than the corresponding return node, is a PNRC, and that call site affects the control dependences of statements that follow the call site. For example, the set of nodes to which control can return following the call at node 17a includes nodes 17b, 22, and ex-exit (IA); that call site, therefore, is a PNRC.

The PNRC-identification algorithm [38] uses a call multigraph to propagate iteratively information about exception types and halt statements from called methods to their callers. At each call site, using the information propagated from the called method, the algorithm computes the potential return sites. If a halt statement is reachable from the called method, the algorithm adds a super-exit node (explained later in this section) to the set of return sites for the call site.

The call-multigraph-based PNRC algorithm is flow-insensitive, and therefore, can suffer from imprecision in the presence of statically unreachable code. A more precise version of the algorithm, which is based on the ICFG, identifies and removes statically unreachable code before performing the PNRC analysis. In practice, however, we do not expect the imprecision caused by statically unreachable code to be significant.

After computing the set of return sites for each call site, Phase 1 of the control-dependence computation constructs an augmented control-flow graph that summarizes the effects of external control dependences on statements in a method. An *augmented control-flow graph* (ACFG) for a method M is a control-flow graph, augmented with placeholder nodes that represent predicates in other methods on which statements in M are control dependent. For each PNRC in M, the ACFG contains a unique conditional node, *return predicate*, that acts as a placeholder

Fig. 10. The augmented control-flow graph for method **vend()** (left), and the augmented control-dependence graph for method **vend()** (right).

TABLE IV
INTRAPROCEDURAL CONTROL DEPENDENCES FOR **vend()** COMPUTED USING THE CFG, AND PARTIAL CONTROL DEPENDENCES FOR THE SAME METHOD COMPUTED USING THE ACFG.

Node	Control dependent on (in CFG)	Control dependent on (in ACFG)	Node	Control dependent on (in CFG)	Control dependent on (in ACFG)
15	(entry,'T')	(entry,'T')	23	undefined	(RP17b,'22')
16	(15,'T')	(15,'T')	24	undefined	(RP17b,'22')
17a	(15,'F')	(15,'F')	25	(24,'T')	(24,'T')
17b	(15,'F')	(RP17b,'17b')	26	(24,'F')	(24,'F')
18, 19, 20	(15,'F')	(RP17b,'17b')	27	(24,'F')	(24,'F')
21a	(15,'F')	(RP17b,'17b')	28	undefined	(RP21b,'28')
21b	(15,'F')	(RP21b,'21b')	exit	(15,'F')(24,'T')	(RP17b,'17b')(24,'T')
22	undefined	(RP17b,'22')			

for the predicates on which return from the called method is control dependent. A return-predicate node has an edge (labeled with the target of the edge) to each node that is a potential return site for the corresponding PNRC. An ACFG also contains a unique node, *super exit*, that represents all exits from M.

Figure 10 shows the ACFG for method `vend()`. The ACFG contains two return-predicate nodes, RP17b and RP21b, because the call sites in statements 17 and 21 are PNRCs. Node RP17b has three outgoing edges, one to each node that appears in the set of return sites for call node 17a; the edge to the exceptional-exit node is labeled by the type of that exceptional-exit node. Similarly, node RP21b has an outgoing edge to each node that appears in the set of return sites for call node 21a.

Partial control dependences are the intraprocedural control dependences that are computed by applying a traditional technique for computing control dependences [5], [30], [31] to the ACFG. The partial control dependences for nodes that are control dependent on predicates in called methods contain a return-predicate node. For example, the partial control dependences of node 17b include return-predicate node RP17b because node 17b is control dependent on the predicate in statement 39 of method `dispense()`.

Table IV lists the intraprocedural control dependences and the partial control dependences for the nodes in the CFG for `vend()`. The comparison shows that the control dependences computed using the ACFG differ from those computed using the CFG for eleven nodes, whereas they are the same for the remaining six nodes. Those six nodes—nodes 15, 16, 17a, 25, 26, and 27—are not reachable from

the PNRCs in `vend()`, and therefore, are unaffected by the PNRCs. The conditions that control the execution of the corresponding statements do not change because of the PNRCs.

An augmented control-dependence graph for a procedure represents the partial control dependences for that procedure. An *augmented control-dependence graph* (ACDG), like the CDG, contains a node for each predicate and statement in a procedure, and an edge from predicate p to statement s if the partial control dependences for s include predicate p. A unique entry node represents the control dependences of those statements that are reached when the procedure is called. If p represents a return predicate and s is control dependent on (p, 'L'), the ACDG contains an edge from the node corresponding to 'L' to s; thus, the ACDG contains no return-predicate nodes.

The graph on the right in Figure 10 shows the ACDG for method `vend()`. Each node that is control dependent on (p, 'L')—where p represents a return predicate—is made control dependent on the node corresponding to 'L' in the ACDG. For example, Table IV shows that node 21a is control dependent on (RP17b, '17b'). Therefore, in the ACDG, there exists an edge from node 17b to node 21a. As the graph illustrates, the ACDG can have disconnected components. The disconnected components represent the effects of external control dependences: Each root node of a component represents a point where control enters a procedure, and where external predicates control those statements that are reached definitely from that entry point but may not be reached otherwise. The unique entry node, and other nodes, such as catch nodes and return nodes for PNRCs, represent such program points, and therefore, appear as root nodes in the ACDG. These nodes serve as placeholders for external predicates.

Partial control dependences have several useful applications: they can be used for computing slices [25], for computing procedure-level control dependences, and for computing interprocedural control dependences [8].

B.2 Computation of interprocedural control dependences

Partial control dependences contain correct control dependences for all nodes that are control dependent on non-placeholder nodes. However, to compute statement-based interprocedural control dependences, the partial control dependences that contain placeholder nodes—representing entry or return predicates—must be adjusted. Phase 2 of the control-dependence computation performs this adjustment, and identifies for each node, the predicate nodes on which that node is control dependent.

To compute interprocedural control dependences, Phase 2 constructs an interprocedural representation of the program by connecting the ACDGs using call, return, and exceptional-return edges. Figure 11 displays the graph constructed during Phase 2 of the control-dependence computation. The control-dependence computation constructs the graph, and traverses it once for each node that is control dependent on a placeholder. For each such node, the computation traverses the graph backwards along all paths, starting at the node, and identifies the closest predicates that are reachable from the node; that node is control dependent on those predicates. To identify such predicates, the traversal along a path stops when it reaches a control-dependence edge whose source is a non-placeholder; Figure 11 shows such edges with a different arrowhead to distinguish them from control-dependence edges whose sources are placeholders.

For example, to identify the control dependences of node 20, the computation traverses backwards in the graph, starting at node 20. On reaching the control-dependence edge (39, exit), whose source is a non-placeholder, the computation stops, and thus, identifies node 20 as control dependent on (39, 'F').

The control-dependence computation processes a throw node with multiple control-dependence successors like a predicate. Thus, for example, traversing backwards from node 23, the computation reaches node 40 along the edges labeled 'IS' and 'SNA'. The computation, therefore, identifies (40, 'IS') and (40, 'SNA') as the conditions that control node 23.

In some cases, the closest predicate that is reachable from a node may not be the one on which the node is control dependent. This occurs if, while traversing from a node n, the algorithm reaches a predicate node p along outgoing edges whose labels constitute the complementary set.[9] In such cases, n is not control dependent on p because, irrespective of the decision made at p, n is definitely reached. Therefore, to identify correct control dependences, the traversal must continue from p. For example, while processing node 50a, the computation reaches node 27 along edges that are labeled 'IS' and 'SNA'; these two edges constitute the complementary set of labels for that predicate. Therefore, the traversal must continue from node 27, and identify (24, 'F') as the condition that controls node 50a.

Figure 12 presents an overview of `ComputeInterCD`, the algorithm that computes statement-based interprocedural control dependences; additional details of the algorithm, along with a proof of its correctness, can be found in Reference [38]. `ComputeInterCD` takes three inputs: (1) the ACDGs for the methods in a program, (2) the list of nodes that are control dependent on return predicates (CDRP), and (3) the list of nodes that are control dependent on entry predicates (CDEP). The algorithm initializes *ICDG* by connecting the ACDGs using call, return, and exceptional-return edges (line 1), and then traverses *ICDG*, starting at each node that is control dependent on a placeholder. The algorithm processes CDRP and CDEP nodes in separate passes because the traversal of the graph differs for the two types of nodes.

The algorithm first processes CDRP nodes (lines 2–19). For each such node M, the algorithm traverses *ICDG* backwards starting at M to identify the closest predicates that are reachable from M (line 3). If during the traversal the algorithm reaches an entry node N (line 4), the algorithm

[9] The *complementary set* of labels for a predicate node is the set of labels associated with outgoing edges from that node in the CFG. For example, {'IS', 'SNA'} is the complementary set of labels for node 27.

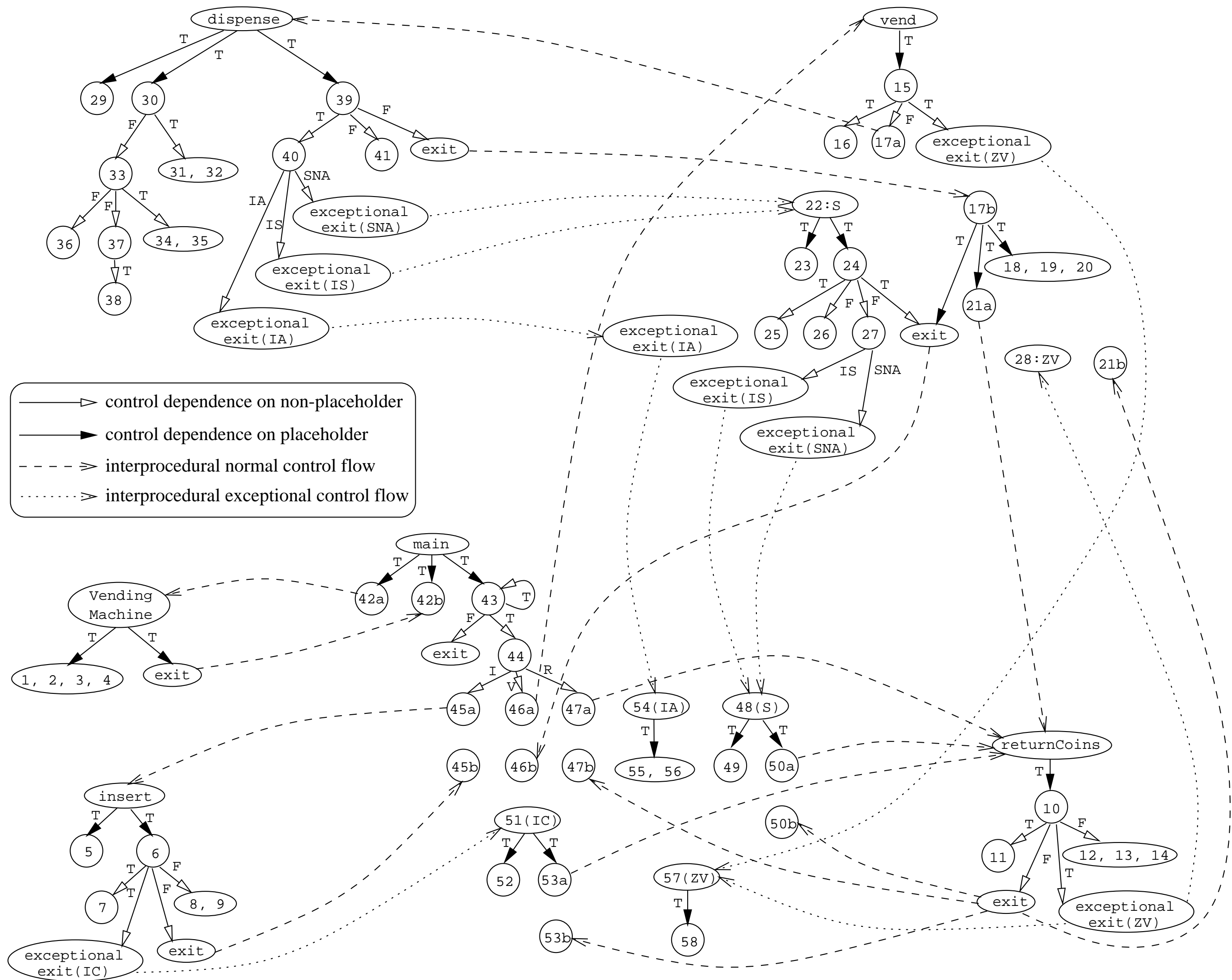


Fig. 11. The graph for the vending-machine program used for computing interprocedural control dependences: the ACDGs for the methods are connected using call, return, and exceptional-return edges.

continues to traverse backwards along those call edges incident on N that represent valid call–return sequences at that point (line 5). If the algorithm reaches a predicate node P along an edge labeled 'L' (line 7), the algorithm checks whether P has been reached along edges whose labels constitute a complementary set of labels for P. If this is not the case (line 8), the algorithm adds (P, 'L') to the control dependences for node M, and terminates the traversal of *ICDG* along that path (line 9). If, on the other hand, P has been reached along edges that constitute a complementary set of labels for P, the algorithm removes from $CD(M)$ conditions that involve P because predicate P does not control the execution of M (line 11); the algorithm also continues to traverse *ICDG* starting at P (line 12). Finally, if during the traversal the algorithm reaches a node P such that the control dependences of P have been resolved—that is, $CD(P)$ includes no placeholders—the algorithm adds $CD(P)$ to $CD(M)$ and terminates the traversal along that path. For example, while processing node 10, the algorithm reaches node 50a, whose control dependences were resolved previously. Therefore, the algorithm adds (24, 'F')—the control dependences of node 50a—to the control dependences of node 10, and does not traverse *ICDG* further along that path.

After processing all CDRP nodes, the algorithm processes CDEP nodes (lines 20–29). The algorithm proceeds in a similar manner. For each node M that is control dependent on an entry predicate, the algorithm traverses *ICDG* backwards If, during the traversal, the algorithm reaches a node whose control dependences have already been resolved (line 25), the algorithm adds that node's control dependences to M's control dependences (line 26). If, during the traversal, the algorithm reaches a predicate node P along an edge labeled 'L' (line 22), the algorithm adds (P, 'L') to the set of control dependences for M (line 23). For example, while traversing backwards from node 29, the algorithm reaches predicate node 15, and adds (15, 'F') to the set of control dependences for node 29. On reaching

```
algorithm ComputeInterCD
input    ACDG : ACDG of each procedure P in program 𝒫
         CDEP : nodes whose partial CD includes an entry pred.
         CDRP : nodes whose partial CD includes a return pred.
output   interCD : interprocedural control dependences for 𝒫
declare  ICDG : graph constructed by connecting the ACDGs using
         call, return, and exceptional-return edges
         CD(N) : control dependences of node N

begin ComputeInterCD
 1.  initialize ICDG by connecting ACDGs at call sites
     /* Pass 1: resolve control dependences of CDRP nodes */
 2.  foreach node M in CDRP
 3.      walk ICDG starting at M
 4.      if an entry node is reached
 5.          walk ICDG along relevant call edges
 6.      endif
 7.      if a predicate node P is reached (along edge labeled 'L')
 8.          if P is not reached along complementary labels
 9.              add (P, 'L') to CD(M)
10.          else
11.              remove conditions involving P from CD(M)
12.              traverse ICDG starting at P
13.          endif
14.      else
15.          if a node P is reached such that CD(P) includes no
             placeholders
16.              add CD(P) to CD(M)
17.          endif
18.      endif
19.  endfor
     /* Pass 2: resolve control dependences of CDEP nodes */
20.  foreach node M in CDEP
21.      traverse ICDG starting at M
22.      if a predicate node P is reached (along edge labeled 'L')
23.          add (P, 'L') to CD(M)
24.      else
25.          if a node P is reached such that CD(P) includes no
             placeholders
26.              add CD(P) to CD(M)
27.          endif
28.      endif
29.  endfor
end ComputeInterCD
```

Fig. 12. Overview of the algorithm for computing interprocedural control dependences.

a predicate node, the algorithm does not test for and resolve complementary set of labels, which conforms to our definition of interprocedural control dependence [8].

Table V lists the interprocedural control dependences for nodes in the CFG of method `vend()`. As the table illustrates, for each node whose partial control dependences include a placeholder (Table IV), the placeholders are replaced with the actual predicates on which that node is control dependent.

B.3 Complexity of control-dependence analysis

Phase 1 of the control-dependence analysis identifies PNRCs and computes partial control dependences. Given an ICFG, the PNRC analysis requires a traversal of the ICFG; therefore, the cost of the PNRC analysis is linear in the size of the ICFG. To compute partial control dependences, Phase 1 applies an existing technique for control-dependence computation [30], [31], [5], [39] to the ACFG of each method; the costs of these techniques vary from linear [30], [39] to quadratic [31], [5] in the size of the graph to which they are applied.

Phase 2 of the control-dependence analysis uses the algorithm `ComputeInterCD`, which traverses $ICDG$ once for each node that is control dependent on a placeholder. Therefore, the worst-case complexity of `ComputeInterCD` is $O(N * (N + E))$, where N and E are the number of nodes and edges, respectively, in $ICDG$. In practice, however, we expect the algorithm to visit, during a traversal, only a fraction of the nodes and edges in $ICDG$, and thus, exhibit an almost linear (in N) behavior. The algorithm also incurs expense in processing $CD(M)$. This expense can be reduced by storing $CD(M)$, which is a set of conditions of the form (N, 'L'), using a hash table, with N as the key.

TABLE V
INTERPROCEDURAL CONTROL DEPENDENCES FOR `vend()`.

Node	Control dependent on	Node	Control dependent on
15	(44,'V')	23	(40,'SNA')(40,'IS')
16	(15,'T')	24	(40,'SNA')(40,'IS')
17a	(15,'F')	25	(24,'T')
17b	(39,'F')	26	(24,'F')
18, 19, 20	(39,'F')	27	(24,'F')
21a	(39,'F')	28	(10,'T')
21b	(10,'F')	exit	(39,'F')(24,'T')
22	(40,'SNA')(40,'IS')		

B.4 Effects of exceptions on partial control dependences

To determine the extent to which the presence of exception-handling constructs affects control dependences, we conducted a preliminary empirical study. The goal of the study was to examine how the presence of exception-handling constructs causes partial control dependences to differ from intraprocedural control dependences. For each subject, using JABA, we constructed the CFGs and the ACFGs for the methods in that subject. To factor out the effects of halt statements on control dependences, we replaced each halt statement[10] with a no-op. We then used the analysis tools from Aristotle Analysis System to construct two CDGs for each method, one using the CFG for that method and the other using the ACFG for that method. Finally, for each node in the CFG (excluding non-statement nodes such as entry and exit), we determined whether that node had different control dependences in the two CDGs.

Figure 13 presents the results of the study. It shows, for each subject, the percentage of nodes that have the same partial and intraprocedural control dependences, and those that have different partial and intraprocedural control dependences. The number at the top of each bar represents the number of nodes in the CFGs of the corresponding subject. The figure illustrates that the control dependences of a significant number of the nodes were affected. On average, the control dependences of over 41% of the nodes were affected by the presence of exception-handling constructs. The percentage of affected nodes ranged from 5.0%, for `jflex`, to 57.2%, for `swing-api`.

These results are preliminary in that they do not indicate the actual differences in the control dependences;

[10] The library method `System.exit()` is the halt statement in Java.

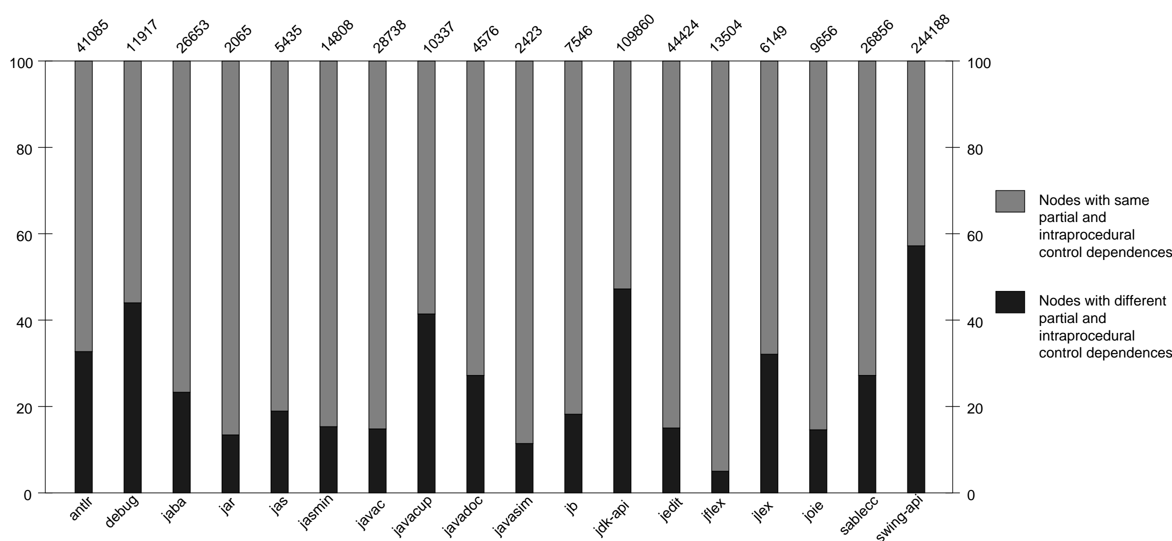


Fig. 13. Effects of exception-handling constructs on partial control dependences.

further empirical studies are required to determine such differences. Further experimentation is also required to study the effects of the differences in control dependences on other analysis techniques, such as slicing, that use control dependences.

V. Other Analyses and Applications

Control-flow and control-dependence analyses are useful for software-engineering and maintenance tasks, such as slicing and structural testing. The representations and analyses described in the previous section can be applied to perform slicing and testing of programs that contain exception-handling constructs.

A. Program Slicing

Program slicing is a technique for identifying transitive control and data dependences in a program. A *backward slice* for a program P, computed with respect to a *slicing criterion* $< s, V >$, where s is a program point and V is a set of program variables referenced at s, includes statements in P that may influence the values of the variables in V at s [27]. A slice can also be computed in the forward direction; a forward slice includes those statements in P that are influenced by the values of the variables in V at s.

There are two alternative approaches to computing slices that either propagate solutions of data-flow equations using a control-flow representation [27], [25] or perform graph reachability on dependence graphs [26]. The slicing algorithms presented in References [27] and [26] make the limiting assumption that, at each call site, control definitely returns from the called procedure, and therefore, consider only intraprocedural control dependences while computing the slices. When applied to programs that contain control structures, such as halt statements and exception-handling constructs, those techniques fail to include those statements in the slices that are related to the slicing criterion through the effects of the control structures on control dependence. Reference [25] extends the slicing algorithm of Reference [27] to use partial control dependences during the computation of slices; that extension correctly accounts for the effects of halt statements on control dependence while computing the slices. Using our control-flow representations, and with minor modifications, that extension can be adapted to compute slices that also account for the effects of exception-handling constructs. In recent work [20], we have also extended the alternative slicing technique—one that uses dependence graphs to compute slices—to account for the effects of exception-handling constructs on control dependence.

B. Structural Testing

Structural testing techniques [40] develop test cases to cover various structural elements of a program. Control-flow-based structural testing criteria use the flow of control in a program to guide the selection test cases or to assess the adequacy of a test suite. For example, in branch testing [41], test cases are developed by considering inputs that cause certain branches in the program under test to be executed. Similarly, in path testing [42], [43], test cases are developed to execute certain paths in the program. Data-flow-based testing criteria use the data-flow relationships to guide the selection of test cases or to assess the adequacy of a test suite [44], [28], [45], [46]. For example the all-uses criterion [46] requires that each definition-use pair in the program under test be covered by test cases.

Exception-handling constructs introduce new structural elements, such as exceptional control-flow paths, that should be considered for coverage by structural testing techniques. Existing tools for developing structural test cases for Java programs, such as `JavaScope`,[11] provide simple coverage criteria, such as the coverage of `throw` statements and `catch` handlers. Such criteria require the coverage of statements that raise exceptions and those that

[11]Sun Microsystems has discontinued the development and support of `JavaScope`; previously, documentation on `JavaScope` was available at www.sun.com/suntest/products/JavaScope.

catch exceptions, and are similar in nature to the traditional criteria that require the coverage of statements or branches. Previous work has shown that criteria, such as branch testing, have weak fault-detection capabilities [47], [48]. We therefore expect the all-throw and all-catch criteria to also be weak in detecting faults. The criteria do not require the testing of various exceptional control-flow paths; they do not consider the different types of exceptions that can be raised at a statement, or the complex control and data interactions, both within and across modules, that can result in the presence of exception-handling constructs. There are simple types of faults, such as a missing handler, that may not be detected by these criteria. For example, consider a faulty version of the vending-machine program that is missing the `catch` handler in line 54. That handler catches exceptions of type `IA` that are raised by the `throw` statement in line 40. To detect this fault, a test case must cause that `throw` statement to raise an exception of type `IA`. However, the all-throw criterion simply requires that the `throw` statement be covered, and does not consider the types of exceptions. Therefore, a test case might cover that statement but raise an exception of type other than `IA`; a test suite developed in such a manner satisfies the all-throw criterion but fails to detect the fault.

In recent work [49], we have developed a family of exception testing criteria to adequately test the behavior of exception-handling constructs. These criteria subsume[12] the all-throw and all-catch criteria, and test exception-handling constructs with varying degrees of thoroughness. For example, some of the criteria examine activations and deactivations of exception objects, and require the coverage of various paths between the activations and deactivations. It is possible that, in practice, exception handling may be used in ways such that the coverage of `throw` statements and `catch` handler suffices for testing most of the interactions caused by exception-handling constructs. However, in some cases, it is beneficial to have a hierarchy of testing criteria that offer the testers flexibility in the level of testing that they perform. Furthermore, by exploring the different types of interactions caused by exception-handling constructs, the criteria provide a better understanding of the types of interactions that are significant. Such insight is valuable not only to provide automated support for test-case generation, but also to verify the interactions informally through inspection. Our current work includes theoretical and empirical evaluations of the exception testing criteria.

VI. Safety, Precision, and Practical Utility of the Techniques

Program-analysis techniques often deal with intractable problems whose correct solutions either have a prohibitive expense associated with their computation or are uncomputable. Faced with such impediments, different approaches to performing the analyses compute solutions that are approximations to the true solutions. Such approximations lead to an evaluation of the approaches in terms of the relative safety and precision of the solutions computed by the approaches. A *safe solution* is one that omits no necessary element from the solution whereas a *precise solution* is one that includes no spurious element in the solution. Although increase in safety and precision increase the usefulness of a solution, in practice, the benefits of a safer and more precise analysis must be weighed against the cost of performing the additional analysis. Both safety and precision involve tradeoffs with the efficiency of the technique, and different approaches sacrifice either, depending on the level of precision and safety that is desired in the application of the solutions. For certain applications, such as compiler optimizations, safety is required, to avoid invalid program transformations, whereas, for other applications, such as reverse engineering, safety is desirable but not strictly necessary [50].

Our approach to the analysis of exception-handling constructs suffers both unsafety and imprecision. Our approach is unsafe because it ignores the control flow caused by implicit exceptions. Implicit exceptions are raised either in library routines or by the runtime environment. One approach to analyze implicit exceptions that are raised in library routines is to create summarized CFGs for those library methods that propagate exceptions, and add them to the ICFG. The summarized CFG for a library method would contain nodes for only the entry, the exit, and the exceptional exits.

To analyze implicit exceptions that are raised by the runtime environment, however, representing each potential control flow with explicit control-flow edges may cause the control-flow representation to become too unwieldy to be useful. Moreover, considering the effects of such implicit exceptions on program-analysis techniques may cause the techniques to generate solutions that are too large to be useful. For example, if a statement s can raise runtime exceptions, a statement that follows s is control dependent on s because s determines whether that statement executes. If statements that raise runtime exceptions occur very frequently, their effects would cause the control-dependence relation to be too cumbersome to be useful. On the other hand, ignoring such implicit exceptions, causes the control-dependence analysis to miss dependences, some of which may be significant.

In future work, we will investigate how the analysis of implicit exceptions affects software-engineering and software-maintenance tasks, and practical utility tools that support those tasks. Depending on the particular application and the desired cost of analysis, we may be willing to accept the unsafety, or we may be able to summarize implicit exceptions and consider their effects on analysis techniques differently than the effects of explicit exceptions.

The four type-inference approaches that we described in Section IV-A.3 offer different levels of precision and safety in the information that they generate. The most precise of the four approaches is the one that combines flow-sensitive and flow-insensitive analyses, but that approach can still include unnecessary types in the type-inference solution.

[12] A criterion *subsumes* another if any test suite that satisfies the first criterion also satisfies the second criterion.

The approaches that use the flow-insensitive analysis can omit potential exception types from the type-inference solution, and therefore, are unsafe. The unsafety and imprecision of these approaches causes missing paths and infeasible paths, respectively, in the control-flow representations. Such effects on control-flow representations affect applications that use the representations. For example, the presence of infeasible paths causes test requirements that are generated using a structural testing criteria to be satisfied by no input to the program. Missing paths causes test requirementsto fail to test certain relationships in a program, and therefore, inadequately test the program.

VII. Related Work

Choi and colleagues [12] describe an intraprocedural control-flow representation called the factored control-flow graph (FCFG) to analyze efficiently programs written in languages, such as Java, that may have frequently occurring exceptional control flow. The FCFG represents exceptional control flow caused by both explicit and implicit exceptions. For explicit exceptions, the approach creates edges that are similar to the edges created in our approach. For implicit exceptions, however, the approach does not create edges from each potentially exception-throwing instruction (PEI) because such instructions occur very frequently. Instead, the approach merges several such instructions in the same basic block, and creates factored control-flow edges from the basic block to `catch` handlers to summarize the exceptional control flow for that basic block. The approach creates one factored edge for each type of implicit exception that can be raised by the statements in a basic block. The approach derives the target of the implicit exceptional exits from each PEI in a basic block on demand. Choi and colleagues also describe modifications to data-flow analysis techniques, such as reaching-definition and live-variable analysis, that allow the techniques to work correctly on the FCFG. That work differs from ours in several ways. First, the work does not model the propagation of exceptions across methods. Although Choi and colleagues discuss alternative representations for interprocedural control flow, their current tool does not construct interprocedural representations. Second, the work does not describe the behavior of, and representations for, `finally` blocks. Third, the work does not discuss issues relating to inferring exception types, and how they affect precision of the FCFG and the analyses performed on the FCFG. Finally, the scope of the work is limited to data-flow analysis, and it does not consider the effects of exceptions on control dependence, slicing, and structural testing.

Chatterjee and Ryder [13] describe an approach to performing points-to analysis that incorporates exceptional control flow in languages such as Java. Their approach derives the exceptional control flow during the points-to analysis, and does not represent it explicitly in an interprocedural control-flow graph. Their approach does not consider implicit exceptions. In subsequent work [14], Chatterjee and Ryder provide an algorithm for computing definition-use pairs that arise because of exception variables, and along exceptional control-flow paths. In this work, however, they ignore the control flow within `finally` blocks. Chatterjee and Ryder do not describe representations for exceptional control flow, and the scope of their work is limited to points-to and data-flow analysis.

Schaefer and Bundy [16] analyze the flow of exceptions in Ada programs, and extract information that describes how exceptions are propagated across modules. They define several relations that let them specify formally the set of exceptions propagated by different blocks of code. The goal of their analysis is to identify potential violations in the code of application-specific guidelines that govern the usage of exception handling. Robillard and Murphy [15] have similar goals for Java programs. They describe a tool that extracts the flow of exceptions in a Java program, and generates views of the exception structure. These views enable a developer to reason about the flow of exceptions across modules, and identify program points where exceptions are caught unintentionally, or where finer-grained exception handling may be possible. The tool extracts potential implicit exceptions by examining module interface and documentation. The techniques described by both Schafer and Bundy [16] and Robillard and Murphy [15] omit reporting several common implicit exceptions because including them can generate too much information, which adversely affects the usability of their tools. Their techniques are primarily intended for program understanding and detection of inconsistencies in coding. Therefore, they do not consider the effects of exceptions on various program-analysis techniques and testing. Using our control-flow representations, we can generate information that is similar to the information generated by their techniques.

Melski and Reps [51] present techniques for interprocedural path profiling, and briefly discuss how path profiles for interprocedural exceptional control flow may be generated. Their work neither describes representations for exceptional control flow, nor analyzes the effects of exceptional control flow on program-analysis techniques.

Other researchers have addressed the problem of computing accurate slices for programs that contain arbitrary intraprocedural control flow [21], [7], [22]. Such control flow is caused by intraprocedural `goto` statements and statements such as `break` and `continue`. Because statements, such as `break` and `continue`, neither control other statements nor use data values, they are never included in a slice. References [21], [7], [22] present solutions in which the statements are included in the slices, when necessary. The same problem can occur in the presence of exception-handling constructs: statements, such as `throw` and `catch` can be excluded from slices. Our slicing technique for exception-handling constructs [20] ensures that `throw` and `catch` statements are included in the slices, when necessary.

Ryder and colleagues [11] conducted a study of the usage patterns of exception-handling constructs in Java programs. They studied a suite of thirty-one Java programs, which contained from two to 2,096 methods. They examined 10,161 methods, and found that, on average, 16%

of the methods contained either a `throw` statement or a `try` statement. Our subjects contain four of the subjects that were included in their study. For those four subjects, our results are consistent with theirs. Their study thus offers further evidence to support our belief that exception-handling constructs are used frequently in Java programs.

VIII. Conclusions

We have discussed the effects of exception-handling constructs on analysis techniques such as control flow, data flow, and control dependence. We have presented techniques to create intraprocedural and interprocedural representations for Java programs that contain exception-handling constructs. These representations are useful for performing other analyses and constructing other representations. The representations show explicitly the exception types that can be raised at `throw` statements, and exception types that are propagated across methods. Therefore, the representations can provide a valuable aid in understanding the behavior of exception-handling constructs. We have also presented an algorithm for computing control dependences in the presence of exception-handling constructs.

We have presented the results of three empirical studies that we performed using JABA, our analysis tool for Java programs. In the first empirical study, we determined the frequency with which exception-handling constructs occur in Java programs. The results from that study indicate that, in practice, exception-handling constructs can occur frequently: 8.1% of the 30,400 methods that we examined contained either a `throw` statement or a `try` statement (Table I).

In the second empirical study, we evaluated the need for, and approaches to performing, type inferencing for determining exception types at `throw` statements. Based on the results from these studies, we made several observations:

- Type inferencing to determine exception types at `throw` statements may not be required for a majority of the `throw` statements. In over 97% of the `throw` statements in our subjects, the exception object is instantiated at the `throw` statement (Table II).
- A `throw` statement that does not instantiate the exception object is more likely to raise an exception that is referenced by a variable than an exception that is returned by a method call. In our subjects, 80% of the `throw` statements that do not mention a new-instance expression mention a variable (Table II).
- The conservative approximation for determining exception types worked well for over half of the `throw` statements for which it was used, but generated very imprecise results for a quarter of the `throw` statements (Table III).
- In cases where a `throw` statement mentions a variable, the exception object is rarely instantiated in the method that contains the statement. Therefore, the intraprocedural flow-sensitive type-inference analysis failed to provide any significant improvement in the precision of the type-inference information (Table III).

These observations provide insight into the usage patterns of exception-handling constructs in Java programs. They can help guide the development of a practical approach to analyze exception-handling constructs, and improve the techniques that we have developed.

In the third empirical study, we evaluated the effects of exception-handling constructs on control-dependence analysis. The results of that study indicate that the control dependences of a significant number of statements are affected by the presence of exception-handling constructs (Figure 13). Control dependences computed for such statements by traditional techniques can omit necessary dependences and include unnecessary dependences. Incorrect control dependences affect the computation of program slices. Further experimentation with control-dependence computation and program slicing will reveal the extent to which the presence of exception-handling constructs affect these techniques.

We have discussed how our representations and analyses can be used for other applications such as program slicing and structural testing. We have also evaluated our approach for analyzing exception-handling constructs in terms of the safety and the precision of the approach. Our approach ignores the exceptional control flow caused by implicit exceptions.

In future work, we will investigate the effects of implicit exceptions on analysis techniques, and ways to perform the analysis of implicit exceptions. We will evaluate empirically the efficiency of our techniques for constructing control-flow representations for exception-handling constructs. We will also evaluate empirically the trade-offs among alternative representations and among different type-inference approaches. These experiments, along with others that combine dynamic analysis with static analysis, would help evolve an approach that incorporates the best trade-offs in practice. Finally, we will conduct further empirical studies to evaluate the effects of exception-handling constructs on control-dependence computation, program slicing, and structural testing.

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