Program slicing with exception handling

Carlos Galindo
cargaji@vrain.upv.es
VRAIN
Universitat Politècnica de València
Valencia, Spain

Sergio Pérez
serperu@dsic.upv.es
VRAIN
Universitat Politècnica de València
Valencia, Spain

Josep Silva
jsilva@dsic.upv.es
VRAIN
Universitat Politècnica de València
Valencia, Spain

Abstract

Program slicing is a technique for program analysis and transformation with many different applications such as program debugging, program specialization, and parallelization. The *system dependence graph* (SDG) is the most commonly used data structure for program slicing. In this paper, we show that the presence of exception-handling constructs can make the SDG produce incorrect and sometimes even incomplete slices. We showcase the instances of incorrectness and incompleteness and we propose a framework for correctly handling exception-related instructions, which includes representation of all possible exception throwing and catching mechanisms, and a new kind of control dependence: conditional control dependence; which produces more precise slices in the presence of `catch` statements.

Keywords: program slicing, exception handling, system dependence graph, conditional control dependence

ACM Reference Format:
Carlos Galindo, Sergio Pérez, and Josep Silva. 2020. Program slicing with exception handling. In *Proceedings of Workshop on Tools for Automatic Program Analysis (TAPAS'20).* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 Introduction

Program slicing [14] is a technique for program analysis and transformation whose main objective is to extract a *slice* from a program: the set of statements that affect a specific set of variables at a given statement, called a *slicing criterion.* Program slicing has many practical applications, such as debugging [3], program specialization [10], software maintenance [4], etc. Initially, program slicing was defined for the imperative programming paradigm, but now it can be used with practically all programming paradigms. The most popular data structure used in program slicing is the *system dependence graph* (SDG), introduced in the late 1980s by Horwitz et al. [5]. It represents statements as nodes and the dependencies between them as arcs, so that the slice can be produced by traversing the graph starting from the slicing criterion. Just as program slicing, the SDG and its underlying elements have been extended to include modern programming languages and their features, such as non-terminating programs [12] or arbitrary control flow [2].

Exception handling is a common feature, present in most modern programming languages. There are several approaches to program slicing with exceptions, but all of them focus on a specific language, such as Java or C++. In reality, the instructions and constructs used in exception handling are quite similar across modern programming languages, with the notable exception of Go[*], which purposefully does not include an exception management system and instead relies on early error reporting and panics for important errors.

1.1 Motivation

Precisely due to the similarity between programming languages, the inclusion of exception-handling instructions in program slicing techniques is very similar such that most publications on program slicing with exceptions are generally applicable regardless of the language they are based on. One common approach is the one proposed by Allen and Horwitz [1], which in turn extended Sinha's proposal [13]. It is arguably the basis used in most publications in the area of exception-aware program slicing. It supports `throw`, `try`, `catch`, and `finally` instructions. Nevertheless, despite being valid for some combinations of the aforementioned instructions, it does not completely support all possible combinations, resulting in incomplete slices, as can be seen in Example 1.1.

Example 1.1 (Incompleteness when slicing `try-catch` constructs in [1])**.** Consider the Java program shown in Figure 1a, in which method `f` is the entrypoint. Two exceptions are thrown, one in each call to `g`, but only one of them is captured. Program slicing allows us to identify what parts of the program can produce the execution of method `g` by just selecting line 11 and an empty set of variables as the slicing criterion. The slice produced by Allen and Horwitz

[*] For more information on Go's design choices regarding exceptions, see https://golang.org/doc/faq#exceptions (retrieved May 2020).

can be seen in Figure 1b, and the SDG used to compute it is shown in Figure 1d. In the SDG, the slicing criterion is marked with a bold outline; and the statements included in the slice have been filled in grey. However, the correct slice would only remove line 5 from the code (see Figure 1c). As it can be seen, Allen and Horwitz do not include the `catch` statement, despite being necessary to execute the second call to g. Thus, the slice produced by this approach is not complete.

The source of this error is that in Allen and Horwitz's approach *catch* blocks are included only in a specific case: the slicing criterion is or requires a variable defined inside the *catch* block. This only happens when a statement of the *catch* block is included in the slice and, consequently, control dependencies force the *catch* itself to be included too. Unfortunately, this is insufficient, since it does not capture the complex control dependency involved in using *catch* blocks. This counter example shows that even empty *catch* blocks may be necessary in the slice.

1.2 Contributions

The main contribution of this work is a new approach to program slicing with exception handling which is #JJJ: Esto nos obliga a dejar online la prueba. Tambien se dice en las conclusiones proven complete in all cases (e.g., it solves the previous motivating problem). Moreover, the slices produced are strictly more precise than previous approaches. It is applicable to most modern programming languages, such as Java, C++, and JavaScript, among others. Our approach extends the techniques proposed by Allen and Horwitz [1], while also using other improvements regarding control dependence introduced by Kumar and Horwitz [9].

The rest of this paper is structured as follows: Section 2 describes our proposal, Section 3 compares our solution to similar approaches and other proposals in the recent past, and Section 4 summarizes our results.

2 Slicing exceptions

#CCC: Summary of changes: http://kaz2.dsic.upv.es:3000/gqhmcvuLQC2p2UXfClctaw

We present our solution as a set of modifications to the standard construction of the SDG. Our baseline employs basic improvements to control dependence computation such as the augmented control-flow graph (ACFG) [2] and the pseudo-predicate program dependence graph (PPDG) [9]. We organize our modifications in the different phases of creation of a slice: code to ACFG to PPDG to SDG, and finally traversal of the SDG. In order to clearly differentiate between each version of the graph, our graphs are prefixed by 'ES-', which stands for "exception-sensitive", so the ACFG becomes the ES-ACFG, the PPDG becomes the ES-PPDG, and the SDG becomes the ES-SDG.

2.1 Modifications to the ACFG to create the ES-ACFG

In this section we describe compositionally how to construct any ES-ACFG: we show the graph representation of each syntax construct individually, but using a general representation that can be composed with the other constructs.

Most instructions of the ACFG keep their traditional representation, but there are six constructs that need to be modified to properly account for exception handling; specifically procedure declarations, procedure calls and all structures that cause or catch exceptions. The rest of this subsection explains in detail these instructions and their correct representation. Figure 2 showcases a simple generalized version of each instruction. Arcs are not labeled for simplicity, but non-executable arcs are displayed with a dashed arc. We often use *true* and *false* to refer to executable and non-executable arcs, respectively.

Unconditional exception sources are instructions whose execution will always result on an exception being thrown or activated. They are represented as a pseudo-predicate#JJJ: No has explicado qué es un pseudo-predicate. Si no tienes espacio, quizás bastaría con poner "(pseudo-predicate) instructions" en la motivación, cuando los listas (pero hay que hacer algo con el finally), as a `return` statement would be. The *true* arc will be connected to the first `catch` instruction that can capture it, or otherwise to the *exception exit*. The *false* arc will be connected to the instruction that would be executed if the pseudo-predicate failed to throw the exception. Figure 2a shows a scheme.

Conditional exception sources are instructions whose execution may activate an exception. They have the same representation as unconditional sources, but instead of being pseudo-predicates, they are predicates; to account for the fact that the exception may or may not be thrown. Figure 2b shows an example, displaying the change from pseudo-predicate to predicate.

Exception catching structures

- **`try`** is represented as a pseudo-predicate, with its *true* arc connected to the first instruction within its body, and its *false* arc connected to the first instruction after the whole structure. A scheme is shown in Figure 2c.
- **`catch`** is represented either as a pseudo-predicate or a predicate, depending on whether all exception sources that are connected to it will be caught or not, respectively In both cases, its *true* arc is connected to the first instruction in its body, and its *false* arc is connected to the next `catch` node that will catch one of the exceptions or otherwise to the *exception exit* node. Both cases can be seen in Figures 2e and 2d.

```java
public void f() {
  try {
    g();
  }catch (Exception e) {
    e.printStackTrace();
  }
  g();
}

public void g() {
  throw new Exception();
}
```

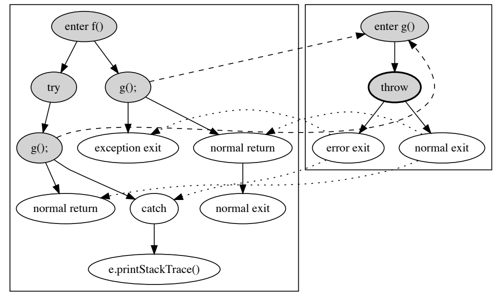
(a) The program

```java
public void f() {
  try {
    g();
  }


  g();
}

public void g() {
  throw new Exception();
}
```

(b) Allen and Horwitz's slice

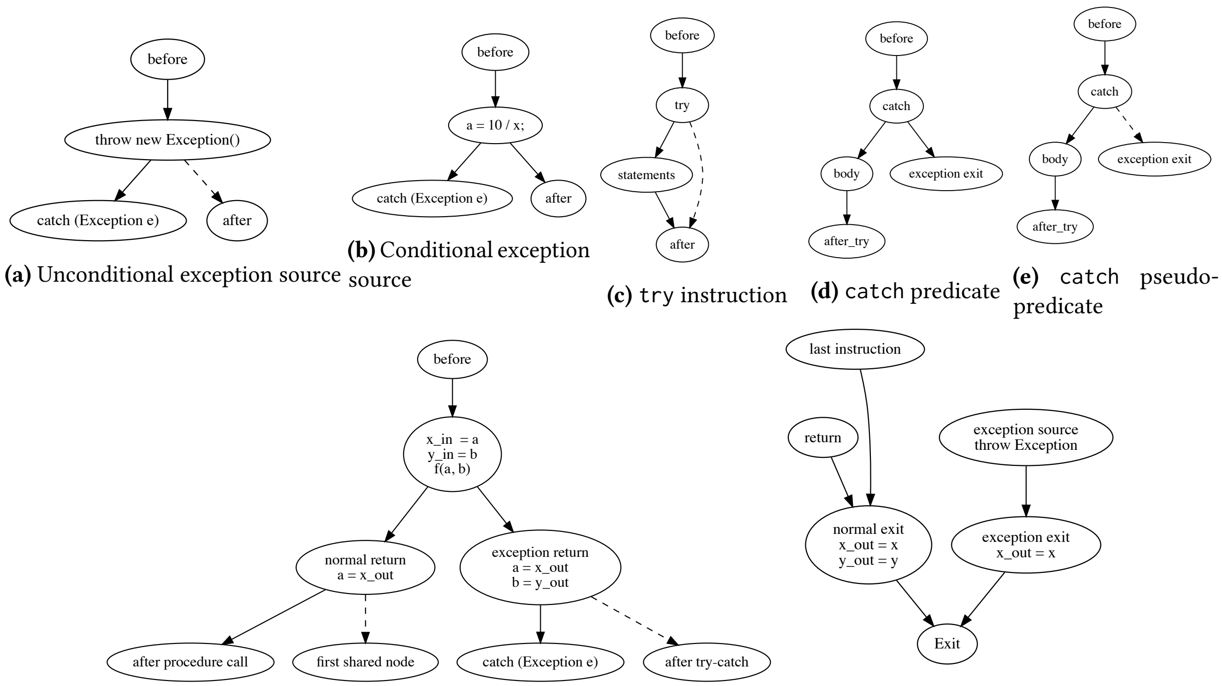
```java
public void f() {
  try {
    g();
  }catch (Exception e) {

  }
  g();
}

public void g() {
  throw new Exception();
}
```

(c) The correct slice



(d) Allen and Horwitz' SDG associated with Figure 1b.

Figure 1. Java program that throws two exceptions but captures only the first one, its slices, and one SDG representation.



(a) Unconditional exception source **(b)** Conditional exception source **(c)** `try` instruction **(d)** `catch` predicate **(e)** `catch` pseudo-predicate **(f)** Procedure call with exceptions **(g)** Procedure declaration exit with exceptions

Figure 2. ACFGs of the structures relevant to exception handling.

Procedures that may throw or propagate exceptions Calls to these procedures are represented as: one procedure call node, where the arguments are evaluated and the call made; one *normal return* node, which is reached only if no exception was propagated through the procedure; and one *exception return* node, which is reached when an uncaught exception was thrown in the method call.

The procedure call is a predicate, whose *true* arc is connected to *normal return* and the *false* arc, to *exception return*.

Normal return is a pseudo-predicate, whose *true* arc is connected to the following instruction, and its *false* arc is connected to the first instruction executed regardless of whether the *normal return* or *exception return* is executed.

Exception return is a pseudo-predicate, whose *true* arc is connected to the first `catch` node that may capture it (or otherwise to *exception exit*, and its *false* arc is connected to the first node after the `try-catch`, or otherwise to the *Exit* node.

```
1  void main(int x) {
2      try {
3          throw new Exception();
4      } catch (Exception e) { }
5      log(x);
6  }
```

Figure 3. Simple code that throws and catches an exception

The two *return* nodes contain assignments for modified global variables and parameters passed by reference. A scheme is shown in Figure 2f.

Procedure declarations with exceptions The *Exit* node is split into three nodes: normal exit, exception exit and exit.

- ***normal exit*** This performs the function of the old *Exit* node. It is represented as a statement, whose arc is connected to *Exit*.
- ***exception exit*** This is the equivalent to *normal exit*, but for exceptions.
- ***Exit*** A sink node, guaranteeing the common requirement of CFGs having only one sink.

In the presence of IO, `formal-out` are moved to the specialized exit nodes, for increased precision. Figure 2g shows exit of a procedure with exceptions.

An additional variable must be tracked throughout procedures that throw exceptions: the *active exception*; which is declared in exception sources and used in *exception exit* and `catch` nodes.

2.2 Modifications to the PPDG to create the ES-PPDG

Example 1.1 reveals that the SDG proposed by Allen and Horwitz can generate incomplete slices: *catch* blocks are not correctly represented. A *catch* block is a statement that is only relevant if the program execution does not occur normally. For this reason, the control dependencies they induce are slightly different from the ones generated by other statements. Instead of influencing other statements with their presence, it is their absence what may lead to a non-desired behaviour. We can illustrate this with the code in Figure 3 and considering three different slicing scenarios that allow us to analyse how does the presence or absence of the catch statement affect the other statements:

1. **Only the `throw` statement is part of the slice**. There is no reason for including the `catch` block in the slice if `log(x)` is not included. The slice would be lines 1, 3, and 6.
2. **Only `log(x)` is part of the slice**. If only `log(x)` is in the slice, although the `catch` statement controls it, since there is no possible statement inside the `try-catch` block to raise an exception that the `catch` captures, the catch statement does not influence the execution of `log(x)`. The slice would be lines 1, 5, and 6.

Algorithm 1 ES-PPDG transformation

Input: PPDG $G = (N, A_c, A)$.
Output: ES-PPDG $G' = (N', A')$.
Initializations: $A_{cc1} = \emptyset$, $A_{cc2} = \emptyset$.

for all $c \in \mathit{CatchNodes}$ **do**
{Move the arcs from A_c to A_{cc1}.}
  for all $(c, n) \in A_c$ **do**
    if $n \notin \mathit{getBlockInstructs}(c)$ **then**
      $A_c = A_c \setminus (c, n)$
      $A_{cc1} = A_{cc1} \cup (c, n)$
    end if
  end for
{Generate the arcs of A_{cc2}.}
  for all $n \in \mathit{getTryBlockInstructs}(c)$ **do**
    if $\mathit{isExceptionSource}(n) \land (n, c) \in A_c^*$ **then**
      if $\forall n' \mid (n, n') \in A_c^* \land (n', c) \in A_c^* \land n \neq n' \neq c \,.\, \neg isPseudoPred(n')$ **then**
        $A_{cc2} = A_{cc2} \cup (c, n)$
      end if
    end if
  end for
end for
$A' = A \cup A_c \cup A_{cc1} \cup A_{cc2}$
$G' = (N', A')$

3. **Both the `throw` statement and `log(x)` are part of the slice**. This situation is the counterpart of the previous one. In this case, `log(x)` is included in the slice, but there is also an exception source inside the `try` block that is part of the slice. Thus, to preserve the normal execution of the program and reach the `log(x)` statement, the `catch` block cannot be omitted. The slice would be the whole program.

These scenarios reveal a new kind of control dependence which is conditional. The `catch` instruction controls `log(x)` only if an exception that it can capture can be thrown, because the absence (rather than the presence) of the `catch` would change the number of times that `log(x)` is executed. This fact makes the control dependence of `catch` blocks completely different from any control dependence seen before. We call this new control dependence *conditional control dependence*.

Definition 2.1 (Conditional control dependence)**.** Let $P = (N, A)$ be a PPDG. We say a node $a \in N$ is conditional control dependent on a pair of nodes $b, c \in N$, if the presence of a allows the execution of c when b is executed and the absence of a prevents it.

Algorithm 1 describes the process to transform a PPDG into an ES-PPDG through the definition of the conditional control dependency sets CC1 and CC2. This algorithms makes use of 4 different methods with descriptive names. For instance, function `getBlockInstructs/1`, that receives a `catch` node as argument, returns a set with all the instructions into the `catch` block. Additionally, set *CatchNodes* contains all the `catch` nodes of the graph. In Algorithm 1 the use of A_c^* represents the reflexive and transitive closure of A_c.

Algorithm 1 analyses every catch node independently and divides its processing in two steps, the generation of the CC1 arcs, and the generation of the CC2 arcs. In the first part, it selects every outgoing control arc from a catch node and move it from the A_c set to the A_{cc1} set if this statement it points to is not inside the catch block. In the second part, all the nodes inside the try block are selected one by one, and two conditions decide whether a CC2 arc needs to be added to the graph or not: (i) the node represents a conditional or unconditional exception source and (ii) there is a control path in the PPDG from the exception source to the catch node which is pseudo-predicate free. If these two conditions are fulfilled, an arc from the catch node to the exception source is added to the set A_{cc2}. Finally, all the sets of arcs are put together in the set A' and the final ES-PPDG is returned.

2.3 From ES-PPDGs to the final ES-SDG

The creation of the ES-SDG can be described as the union of all the ES-PPDGs for each of the program's procedures, where the additional interprocedural and summary dependencies are generated. The creation of call, parameter-in, parameter-out and summary arcs is the same as in the SDG. The main difference between the common SDG and the ES-SDG is the treatment of the different possible exit contexts. Every ES-PPDG may have two different *Exit* nodes: normal exit and exception exit. For this reason, the ES-SDG features an additional kind of arc: the return arc, which connects a `exit` node in the declaration to its corresponding `return` node in the call. These can be seen in Figure 4, where dotted arcs connect each *exit* to their corresponding *return* counterparts.

2.4 Slicing the ES-SDG

The ES-SDG introduces various structural changes and a new kind or arcs: the conditional control dependence. Therefore, we need to determine how this new arcs are treated by the slicing algorithm. The new graph traversal is based on the slicing algorithm proposed by Horwitz et al. in [6] but with some new considerations due to all the introduced elements: return arcs, conditional arcs, and new instructions being handled as pseudo-predicates. It can be summarized with the next 4 rules:

1. The graph is traversed in two sequential passes. In the first pass, output (param-out and return) arcs are ignored; and in the second pass, input (param-in and call) arcs are ignored. Each pass ends when there are no more new arcs to traverse.
2. If a node n is reached via a conditional arc of type t, it will not be included in the slice unless it has also been reached by another conditional type of type t', such that $t \neq t'$. If included in the slice, no arcs will be traversed from n, unless it is reached via another non-conditional arc.
3. Conditional arcs of type CC1 are transitive, even when the intermediate node is not included in the slice. As an example, if $a \rightarrow^{CC1} b \rightarrow^{CC1} c$, if c is in the slice, a and b are both reachable via a conditional arc of type CC1, even when b is not in the slice.
4. Control dependency arcs that reach a node n will not be traversed if n is a pseudo-predicate and n has only been reached via control dependency arcs. Conditional control dependency arcs are not considered control dependency arcs for this matter. This #Deleted: last consideration is based on the traversal restriction introduced by Kumar and Horwitz [9] for the slicing of the PPDG.

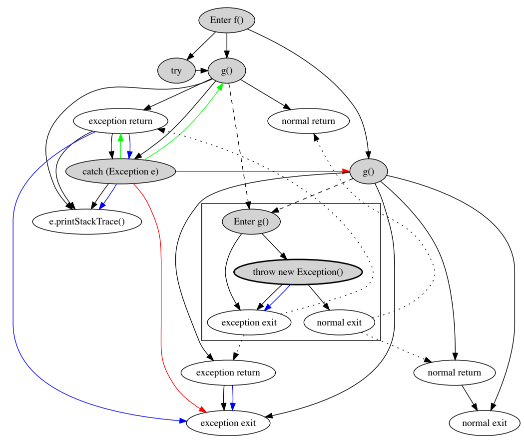


Figure 4. The ES-SDG associated to the program in Example 1.1

The complexity of the new traversal algorithm remains linear with respect to the number of nodes and arcs in the ES-SDG. This is because the changes to the algorithm are to stop the traversal when certain conditions are met; therefore lowering the amount of nodes reached. Additionally, each condition check can be made in linear time.

Example 2.2 shows the ES-SDG for the motivating example, sliced with the same criterion.

Example 2.2 (A correctly generated slice for the program in Example 1.1)**.** If we apply our algorithm to the problem shown in our motivating example (Example 1.1), we obtain the ES-SDG shown in Figure 4. If we then choose as slicing criterion $\langle$`throw`$, \emptyset\rangle$ in line 11, the *Enter g()* node is included, which in turn includes both calls to procedure g. The first call causes the inclusion of the `try` and *Enter f()* nodes. Finally, thanks to the conditional arcs, the `catch` node is included, so the exceptions generated by `g`'s first call can be caught and `g`'s second call can be executed.

3 Related work

We have already explained the evolution of the SDG to treat exceptions with the definition of the ACFG and the PPDG (see Section ??). #JJJ: Enlace roto Here, we want to complement by commenting some approaches that have been a milestone in this area and that have inspired our work or are related to it. One of the most relevant initial approaches to exception-aware program slicing was Allen and Horwitz [1], which took advantage of the existing representation of unconditional jumps to represent exception-causing instructions, such as `throw`. Regarding exception-catching constructs, they simulated the real control flow and added non-executable control flow to generate the extra dependencies they needed. Despite this, they failed to account for the conditional need of `catch` statements, even when in the original program no exception will escape from it, and therefore, from a pure control flow approach, the whole `try-catch` block cannot influence any instruction after it.

Later, Jiang et al. [7] described a solution for C++. *catch* nodes are represented similar to an *if-else* chain, each trying to capture the exception before deferring onto the next *catch* or propagating it to the calling method. They also were aware of the necessity of representing data dependencies from procedure calls to *catch* nodes, but did not generalize that concept to all exception sources and usages. Other approaches include Prabhu et al. [11], which centered around the exception system of C++, and its specific quirks and design choices; and Jie et al. [8], which combined object orientation and exception handling. Jie et al. focused on the object-oriented side, rather than on the exception side, for which they used an approach similar to Jiang et al.'s or Allen and Horwitz's.

4 Conclusions

Program slicing is a powerful software analysis technique, powered by the system dependence graph, a directed graph that represents instructions and their dependencies. In this paper, we have presented a new approach for program slicing with exception handling, based on previous publications and focusing on creating a general algorithm that is valid for most programming languages with exception handling.

We have presented a counterexample to the current state of the art, which reveals a problem of incompleteness present in the literature; and we have proposed a solution, which we have proven complete. This solution also improves the correctness of slices by using a new notion of control dependency called *conditional control dependency*, which allows for the conditional inclusion of *catch* statements only when there is a statement that requires an exception to be caught, and at the same time, there exists a source of exceptions. Thus, we limit the inclusion of *try-catch* instructions and exception sources to the minimum necessary to generate complete slices.

References

[1] Matthew Allen and Susan Horwitz. 2003. Slicing Java Programs That Throw and Catch Exceptions. *SIGPLAN Not.* 38, 10 (June 2003), 44–54.

[2] Thomas Ball and Susan Horwitz. 1993. Slicing Programs with Arbitrary Control-flow. In *Proceedings of the First International Workshop on Automated and Algorithmic Debugging (AADEBUG '93)*. Springer-Verlag, London, UK, UK, 206–222.

[3] Richard A. DeMillo, Hsin Pan, and Eugene H. Spafford. 1996. Critical Slicing for Software Fault Localization. *SIGSOFT Softw. Eng. Notes* 21, 3 (May 1996), 121–134. https://doi.org/10.1145/226295.226310

[4] Ákos Hajnal and István Forgács. 2012. A Demand-Driven Approach to Slicing Legacy COBOL Systems. *Journal of Software Maintenance* 24, 1 (2012), 67–82. http://dblp.uni-trier.de/db/journals/smr/smr24.html#HajnalF12

[5] Susan Horwitz, Thomas Reps, and David Binkley. 1988. Interprocedural Slicing Using Dependence Graphs. In *Proceedings of the ACM SIGPLAN 1988 Conference on Programming Language Design and Implementation* (Atlanta, Georgia, USA) *(PLDI '88)*. ACM, New York, NY, USA, 35–46. https://doi.org/10.1145/53990.53994

[6] Susan Horwitz, Thomas Reps, and David Binkley. 1990. Interprocedural Slicing Using Dependence Graphs. *ACM Transactions Programming Languages and Systems* 12, 1 (1990), 26–60.

[7] S. Jiang, S. Zhou, Y. Shi, and Y. Jiang. 2006. Improving the Preciseness of Dependence Analysis Using Exception Analysis. In *2006 15th International Conference on Computing*. IEEE, 277–282. https://doi.org/10.1109/CIC.2006.40

[8] H. Jie, J. Shu-juan, and H. Jie. 2011. An approach of slicing for Object-Oriented language with exception handling. In *2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC)*. 883–886. https://doi.org/10.1109/MEC.2011.6025605

[9] Sumit Kumar and Susan Horwitz. 2002. Better Slicing of Programs with Jumps and Switches. In *Proceedings of the 5th International Conference on Fundamental Approaches to Software Engineering (FASE 2002) (Lecture Notes in Computer Science (LNCS))*, Vol. 2306. Springer, 96–112.

[10] Anirban Majumdar, Stephen J. Drape, and Clark D. Thomborson. 2007. Slicing Obfuscations: Design, Correctness, and Evaluation. In *Proceedings of the 2007 ACM Workshop on Digital Rights Management* (Alexandria, Virginia, USA) *(DRM '07)*. ACM, New York, NY, USA, 70–81. https://doi.org/10.1145/1314276.1314290

[11] Prakash Prabhu, Naoto Maeda, and Gogul Balakrishnan. 2011. Interprocedural Exception Analysis for C++. In *Proceedings of the 25th European Conference on Object-oriented Programming (ECOOP'11)*. Springer-Verlag, Berlin, Heidelberg, 583–608. http://dl.acm.org/citation.cfm?id=2032497.2032536

[12] Venkatesh Prasad Ranganath, Torben Amtoft, Anindya Banerjee, John Hatcliff, and Matthew B. Dwyer. 2007. A New Foundation for Control Dependence and Slicing for Modern Program Structures. *ACM Trans. Program. Lang. Syst.* 29, 5 (Aug. 2007), 27–es. https://doi.org/10.1145/1275497.1275502

[13] S. Sinha and M. J. Harrold. 1998. Analysis of programs with exception-handling constructs. In *Proceedings. International Conference on Software Maintenance (Cat. No. 98CB36272)*. IEEE, 348–357. https://doi.org/10.1109/ICSM.1998.738526

[14] Mark Weiser. 1981. Program Slicing. In *Proceedings of the 5th international conference on Software engineering (ICSE '81)* (San Diego, California, United States). IEEE Press, Piscataway, NJ, USA, 439–449.