Computer Sciences Department

Better Slicing of Programs With Jumps and Switches

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Better Slicing of Programs with Jumps and Switches

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Abstract

Program slicing is an important operation that can be used as the basis for programming tools that help programmers understand, debug, maintain, and test their code. This paper extends previous work on program slicing by providing a new definition of "correct" slices, by introducing a representation for C-style switch statements, and by defining a new way to compute control dependences and to slice a program-dependence graph so as to compute more precise slices of programs that include jumps and switches. Experimental results show that the new approach to slicing can sometimes lead to a significant improvement in slice precision.

1 Introduction

Program slicing, first introduced by Mark Weiser in [11], is an important operation that can be used as the basis for programming tools that help programmers understand, debug, maintain, and test their code. Slicing was defined by Weiser as the solution to a dataflow problem specified using the program's control-flow graph (CFG). Ottenstein and Ottenstein [8] provided a more efficient algorithm (reviewed below in Section 2.1) that uses the program-dependence graph (PDG) [4].

This paper makes the following four contributions in the area of program slicing:

Defining Correct Slices: Weiser defined a *correct* slice of a program P to be a projection of P with certain properties (see Section 3). Podgurski and Clarke [9] defined a notion of *semantic dependence* that can also be used as the basis for a definition of a correct slice; however, their definition did not take jump statements (`goto`, `break`, etc.) into account.

We give an example to illustrate a shortcoming of Weiser's definition, and offer a new definition, similar to the one for semantic dependence, that overcomes the problem with Weiser's definition, and also makes sense for programs with jump statements.

Language Extension: We discuss how to represent C-style switch statements in the CFG and the PDG. To our knowledge, this is the first time switch statements have been discussed as such, rather than assuming that they have been implemented at a low level using gotos. Handling switch statements is important because many slicing applications involve displaying the result of a slice to the programmer, or using the results to create new source code. Thus, for those applications, if a slice includes code from a switch, it needs to be displayed / represented in the new code as a switch rather than in some low-level form. Representing and slicing a switch in a low-level form and then mapping the results back to the source level may lead to a final result that is less precise than the one produced by working on the switch directly.

Improved Precision: Finding correct, minimal slices is an undecidable problem, whether correctness is defined according to Weiser, Podgurski/Clarke, or using the new definition proposed here. However, it is still a reasonable goal to design a slicing algorithm that is more precise than previous ones; i.e., to define a new algorithm that is correct, and also produces smaller slices than previous algorithms.

In this spirit, we introduce some example programs with jumps and switches for which previous slicing algorithms produce slices that include too many components. While the examples with jumps are somewhat artificial, the examples with switches are motivated by code from real programs. We show that the reason "extra" components are included in the slices has to do both with how control dependences are defined, and how slices are computed. We then give a new definition of control dependence and a new slicing algorithm that is more precise than previous algorithms in the presence of jumps and/or switches.

Experimental Results: While it is possible to produce artificial examples in which our new approach to slicing provides arbitrarily smaller slices than previous approaches, it is important to know how well it will work in practice. We provide some experimental results that show that while in most cases slice sizes are reduced by no more than 5%, there are examples of reductions of up to 35%.

2 Background

2.1 Slicing using the PDG

Informally, the slice of a program from statement S is the set of program components that might affect S, either by affecting the value of some variable used at S, or by affecting whether and how often S executes. More precise definitions have been proposed, and are discussed below in Section 3.

Slicing was originally defined by Weiser [11] as the solution to a dataflow problem specified using the program's control-flow graph (CFG). Ottenstein and Ottenstein [8] provided a more efficient algorithm that uses the program-dependence graph (PDG) [4]:

Algorithm 1 *(Ottensteins' algorithm for building and slicing the PDG)*

Step 1: *Build the program's CFG, and use it to compute data and control dependences: Node N is* **data dependent** *on node M iff M defines a variable x, N uses x, and there is an x-definition-free path in the CFG from M to N. Node N is* **control dependent** *on node M iff N postdominates one but not all of M's CFG successors.*[1]

Step 2: *Build the PDG. The nodes of the PDG are almost the same as the nodes of the CFG: a special enter node, and a node for each predicate and each statement in the program; however, the PDG does not include the CFG's exit node. The edges of the PDG represent the data and control dependences computed using the CFG.*

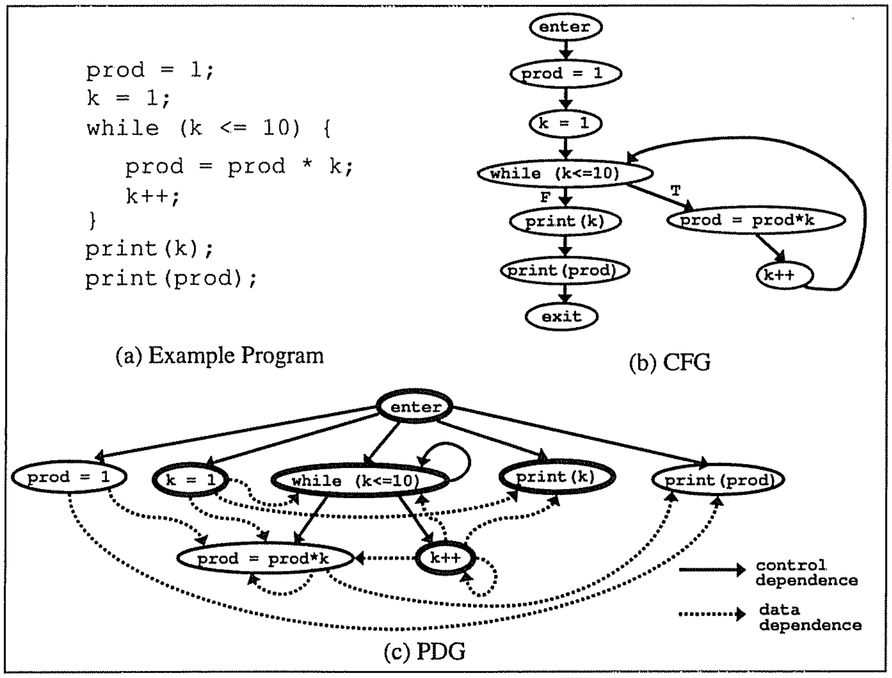
Step 3: *To compute the slice from statement (or predicate) S, start from the PDG node that represents S and follow the data- and control-dependence edges backwards in the PDG. The components of the slice are all of the nodes reached in this manner.*

Example: Figure 1 shows a program that computes the product of the numbers from 1 to 10, its CFG, and its PDG. The nodes in the slice of the PDG from "`print(k)`" are shown using bold font. (For the purposes of control-dependence computation, an edge is added to the CFG from the *enter* node to the *exit* node; to avoid clutter, those edges are not shown in the CFGs given in this paper).

2.2 Handling Jumps

Early slicing algorithms (including Weiser's and the Ottensteins') assumed a structured language with conditional statements and loops, but no jump statements (such as `goto`, `break`, `continue`, and `return`). Both [2] and [3] pointed out that if a CFG is used in

[1] By definition, every CFG node postdominates itself. Thus, if a node M has CFG successors m_1 and m_2, then unless m_1 postdominates m_2, m_1 is control-dependent on M (and similarly for m_2).



(a) Example Program

(b) CFG

(c) PDG

Figure 1: Example program, its CFG, and its PDG. The PDG nodes in the slice from "`print(k)`" are shown in bold.

which a jump statement is represented as a node with just a single outgoing edge (to the target of the jump), then no other node will be control dependent on the jump, and thus it will not be in the slice from any other node. For example, Figure 2(a) shows a modified version of the program from Figure 1, now including a `break` statement. Figures 2(b) and 2(c) show the program's CFG and the corresponding PDG. Note that in this PDG, there is no path from the `break` to "`print(k)`" or to "`print(prod)`", and therefore the `break` is (erroneously) not included in the slices from those two print statements even though the presence of the `break` can affect the values that are printed.

The solution proposed by [2] and [3] involves using an augmented CFG, called the ACFG, to build a dependence graph whose control-dependence edges are different from those in the PDG used by Algorithm 1. We will refer to the new dependence graph as the *APDG*, to distinguish it from the PDG.

Algorithm 2 *(Building and Slicing the APDG)*

Step 1: *Build the program's ACFG. In the ACFG, jump statements are treated as pseudo-predicates. Each jump statement is represented by a node with two outgoing edges: the edge labeled true goes to the target of the jump, and the (non-executable) edge labeled false goes to the node that would follow the jump if it were replaced by a no-op. Labels are treated as separate statements; i.e., each label is represented in the ACFG by a node with one outgoing edge to the statement that it labels.*

Step 2: *Build the program's APDG. Ignore the non-executable ACFG edges when computing data-dependence edges; do not ignore them when computing control-dependence edges. (This way, the nodes that are executed only because a jump is present, as well as those that are not executed but would be if the jump were removed, are control dependent on the jump node, and therefore the jump will be in-*

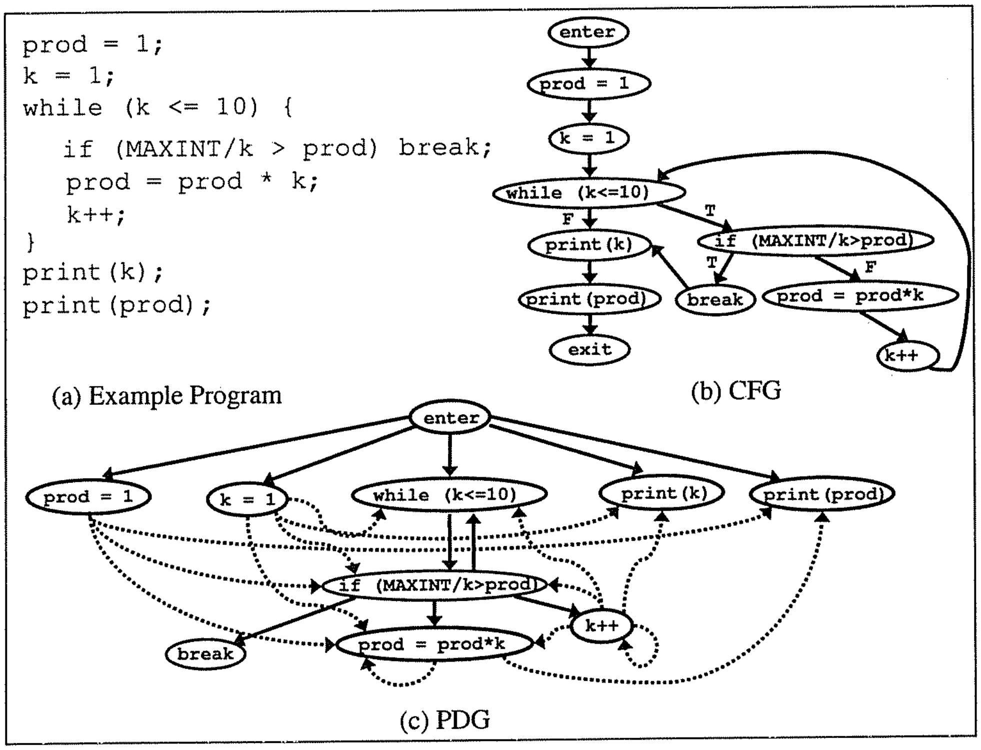


Figure 2: Example program with a break statement, its CFG, and its PDG.

cluded in their slices.)

Step 3: *To compute the slice from node S, follow data- and control-dependence edges backwards from S as in Algorithm 1. A label L is included in a slice iff a statement "`goto L`" is in the slice.*

Example: Figure 3 shows the ACFG for the program in Figure 2(a), and the corresponding APDG. (The non-executable *false* edge out of the `break` in Figure 3(a) is shown using a dotted arrow.) Note that in Figure 3(b), there are control-dependence edges from the `break` to "`prod = prod * k`" and to "`k++`"; therefore, the `break` is (correctly) included in every slice that includes one of those two nodes.

3 Semantic Foundations for Slicing

In his seminal paper on program slicing [11], Weiser defined a slice of a program P from point S with respect to a set of variables V to be any program P' such that:

- P' can be obtained from P by deleting zero or more statements.
- Whenever P halts on input I, P' also halts on input I, and the two programs produce the same sequences of values for all variables in set V at point S if it is in the slice, and otherwise at the nearest successor to S that is in the slice.

One problem with this definition is that it can be inconsistent with the intuitive idea that the slice of a program from point S is the set of program components that might *affect* S. For example, Figure 4 shows a program, the slice that a programmer would probably produce if asked to slice the program from statement [6] with respect to variable `z`, and another slice that is correct according to Weiser's definition, but that does not match our intuition about slicing. Furthermore, the requirement that a slice be an executable program may be too restrictive in some contexts (e.g., when using slicing to understand how a program works, or to understand the effects of a proposed change). In those cases, it might be more appropriate

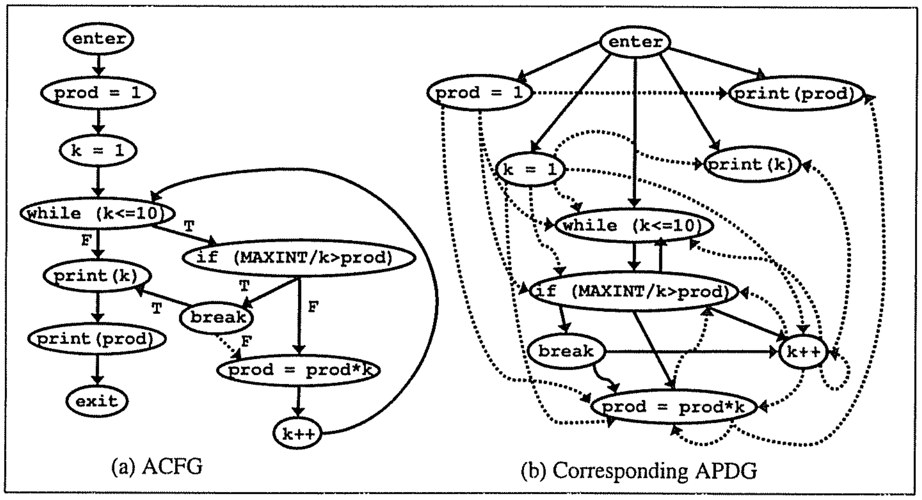


Figure 3: ACFG and the corresponding APDG for the example with a `break`.

to define the slice of a program simply to be a subset of the program's components, rather than an executable projection of the program.

Given these observations, we propose to define the slice of program P from component S to be the components of P that might have a semantic effect on S. But what does it mean for a statement or predicate X to have a semantic effect on another statement/predicate S? To make that notion more precise, we consider what happens when a new program P' is created by modifying X or removing it from program P as follows:

X is a normal predicate: P' is created by replacing X with a different predicate that uses the same set of variables as X. (For example, in the program whose ACFG is shown in Figure 3, the predicate "`MAXINT/k > prod`" could be replaced by any other predicate that uses only variables `k` and `prod`, such as: "`k < prod`", or "`k != 0 && prod > 22`".)

X is a pseudo-predicate (a jump statement): P' is created by removing statement X from P.

X is a non-jump statement: P' is created by replacing X with a different statement that uses and defines the same sets of variables as X. (For example, in the program whose ACFG is shown in Figure 3, the statement "`prod = prod*k`" could be replaced by any other statement that uses only variables `prod` and `k`, and that defines variable `prod`, such as: "`prod = k + prod`", or "`prod = prod-k-4`".)

Definition 0 *(Semantic effect): X has a* ***semantic effect*** *on S iff there is some program P' created by modifying or removing X from P as defined above, and some input I such that:*

- *Both P and P' halt on I.*
- *The two programs produce a different sequence of values for some variable used at S.*

Note that the sequence of values produced for a variable used at S can differ either because the two sequences are of different lengths, or because their k^{th} values differ (for some k).

Program	Intuitive Slice	Also Correct by Weiser's Definition

`[1] x = 2;`
`[2] y = 2;`
`[3] w = x * y;`
`[4] x = 1;`
`[5] y = 3;`
`[6] z = x + y;`
	`[4] x = 1;`
	`[5] y = 3;`
	`[6] z = x + y;`
		`[1] x = 2;`
		`[2] y = 2;`
		`[6] z = x + y;`

Figure 4: Example illustrating a shortcoming of Weiser's definitions of a correct slice.

Definition 0 is similar to the definition of *finitely demonstrable semantic dependence* given by Podgurski and Clarke in [9]. However, that definition did not take jump statements into account: according to their definition, no program component is ever semantically dependent on a jump; therefore, if a correct slice from S is defined to include all components on which S is semantically dependent, jump statements will never be included in a slice. This is clearly contrary to one's intuition, and therefore is a shortcoming of the Podgurski/Clarke definition.

As usual with any interesting property of a program, determining which components have a semantic effect on a given component S, according to Definition 0, is an undecidable problem. Therefore, we must say that a (correct) slice of program P from component S is any superset of the components of P that have a semantic effect on S.

Note that using Definition 0, statements [4] and [5] in the example program in Figure 4 (but not statements [1] and [2]) have a semantic effect on statement [6]. Therefore, a correct slice from statement [6] must include statements [4] and [5] (but not statements [1] and [2]), which is consistent with our intuition about that slice.

4 Representing Switch Statements

Consider a C switch statement of the form:

```
switch (E) {
        case e1: S1; break;
        case e2: S2; break;
          ...
        case en: Sn; break;
        default: S;
}
```

Clearly, "switch(E)" should be represented in the CFG (and the ACFG) using a (normal) predicate node with $n+1$ outgoing edges: one to each case including the default. If there were no default, the $n+1^{st}$ edge should go to the first statement following the switch (because in C, if the value of the switch expression does not match any case label, and there is no default then execution continues immediately after the switch).

Now consider how to represent the case labels. One's initial intuition might be that they are similar to other labels in a program (the targets of goto statements). However, there is an important difference: if a program includes "goto L1", then label L1 must be in the program, or it is not syntactically correct. If there is *no* "goto L1", then it doesn't matter whether label L1 is in the program: its presence or absence has no semantic effect. However, these observations are not true of a case label. Removing a case label from a program never causes a syntax error, but *can* have a semantic effect. For example, if expression E in the code given above evaluates to e2, then statement S2 will execute. However, if "case e2" is removed, then statement S2 will not execute; instead, statement S will execute. Therefore, it makes sense for "case e2" to be in the slice from S2 as well as in the slice from S.

This suggests that, like jumps, case labels should be represented using pseudo-predicates in the ACFG. The target of the outgoing *true* edge from a case-label node should be the first statement inside the case, and the target of the outgoing *false* edge should be the node that represents the default label if there is one, and otherwise the first statement that follows the switch (because if the case label is removed, and the switch expression matches that value, then execution proceeds with the first statement after the switch). The target of the outgoing *false* edge from the default case should always be the first statement that follows the switch.

Example: Figure 5 shows the ACFG for the switch statement given above (for $n = 3$).

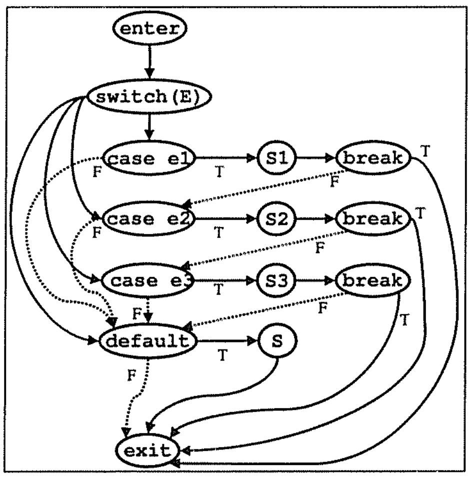


Figure 5: ACFG for a switch statement.

5 Motivation for a New Slicing Algorithm

Figure 6 gives three examples where Algorithm 2 (see Section 2.2) produces slices that include unwanted components. (In these examples, we assume that switch statements are represented in the ACFG as discussed above in Section 4.) The first column in Figure 6 gives a code fragment, with one statement enclosed in a box. The second column shows the ideal slice from the boxed statement (according to Definition 0 given above in Section 3). The third column shows the slice computed using Algorithm 2. The first two examples involve switches, while the third example involves only gotos.

Note that in the first example the slice from S3 should include the `break` from the previous case, because the presence/absence of that `break` affects whether or not S3 executes. In particular, consider what happens when expression E evaluates to e2. If the `break` is *not* in the program, S3 executes, while if the `break` *is* in the program, S3 does not execute.

In the second example, the slice from S should include neither "`if (P)`" nor "`return`". Whatever the value of predicate P, statement S will not execute (because either the `return` or the `break` prevents execution from "falling through" from "`case e1`" to "`case e2`"). Similarly, whether or not the `return` is in the program makes no difference since it is followed by the `break` (and thus S is always prevented from executing).

In all three examples, extra components are included in the slices computed using Algorithm 2 because of a chain of control-dependence edges. For instance, the APDG for the second example includes the following chain: `case e1` $\rightarrow$ `if (P)` $\rightarrow$ `return` $\rightarrow$ `break` $\rightarrow$ `case e2` $\rightarrow$ S. Thus, since Algorithm 2 follows all control-dependence edges backwards, all of those components are included in the slice from S[2]. In this example, each individual control-dependence edge represents a possible semantic effect: "`case e1`" has a semantic effect on "`if (P)`", which has a semantic effect on "`return`", which has a semantic effect on "`break`", which has a semantic effect on "`case e2`", which has a semantic effect on S. However, the backwards closure of the control-dependence relation starting from S yields a superset of the components that have a semantic effect on S; i.e., the "semantic-effect" relation is not transitive.

It is also possible to have an example in which even an individual control dependence (computed using the ACFG) does not reflect a semantic effect, as illustrated in Figure 7. In this example, the APDG includes a control-

[2]Furthermore, the entire backward closure from predicate P of the control- and data-dependence relations will be included in the slice computed by Algorithm 2, making it arbitrarily larger than the ideal slice.

Code Fragment	Ideal Slice	Slice computed using Algorithm 2

switch (E) {
case e1: S1; break;
case e2: S2; break;
case e3: $\boxed{\texttt{S3;}}$ break;
}
	$\boxed{\texttt{switch (E)}}$ {
	case e1: S1; break;
	case e2: S2; $\boxed{\texttt{break;}}$
	$\boxed{\texttt{case e3:}}$ $\boxed{\texttt{S3;}}$ break;
	}
		$\boxed{\texttt{switch (E)}}$ {
		$\boxed{\texttt{case e1:}}$ S1; $\boxed{\texttt{break;}}$
		$\boxed{\texttt{case e2:}}$ S2; $\boxed{\texttt{break;}}$
		$\boxed{\texttt{case e3:}}$ $\boxed{\texttt{S3;}}$ break;
		}

switch (E) {
case e1: if (P) return;
break;
case e2: $\boxed{\texttt{S;}}$
}
	$\boxed{\texttt{switch (E)}}$ {
	case e1: if (P) return;
	$\boxed{\texttt{break;}}$
	$\boxed{\texttt{case e2:}}$ $\boxed{\texttt{S;}}$
	}
		$\boxed{\texttt{switch (E)}}$ {
		$\boxed{\texttt{case e1:}}$ $\boxed{\texttt{if (P)}}$ $\boxed{\texttt{return;}}$
		$\boxed{\texttt{break;}}$
		$\boxed{\texttt{case e2:}}$ $\boxed{\texttt{S;}}$
		}

if (P1) goto L1;
if (P2) goto L3;
goto L2;
L1: $\boxed{\texttt{S;}}$
L2: ...
L3: ...
	$\boxed{\texttt{if (P1)}}$ $\boxed{\texttt{goto L1;}}$
	if (P2) goto L3;
	$\boxed{\texttt{goto L2;}}$
	$\boxed{\texttt{L1:}}$ $\boxed{\texttt{S;}}$
	$\boxed{\texttt{L2:}}$ ...
	L3: ...
		$\boxed{\texttt{if (P1)}}$ $\boxed{\texttt{goto L1;}}$
		$\boxed{\texttt{if (P2)}}$ $\boxed{\texttt{goto L3;}}$
		$\boxed{\texttt{goto L2;}}$
		$\boxed{\texttt{L1:}}$ $\boxed{\texttt{S;}}$
		$\boxed{\texttt{L2:}}$ ...
		$\boxed{\texttt{L3:}}$ ...

Figure 6: Examples for which Algorithm 2 produces slices with extra components.

dependence edge from "`if (P)`" to `S1` because `S1` postdominates the *true* successor of the `if` in the ACFG, but does not postdominate its *false* successor (because the `goto`'s non-executable *false* edge bypasses `S1`). However, "`if (P)`" cannot in fact affect the execution of `S1`; it always executes, regardless of whether `P` evaluates to *true* or to *false*.

These examples motivate the need for a new definition of control dependence to avoid control-dependence edges like the one in Figure 7 that do not reflect a semantic effect. They also motivate the need for a new way to compute slices that does not involve taking the transitive closure of the control-dependence edges, since, as discussed above, the semantic-effect relation is not transitive.

6 New Definition of Control Dependence and New Slicing Algorithm

Recall that the definition of control dependence used in Algorithm 1 is as follows:

Definition 1 *(Original control dependence): Node N is* ***control dependent*** *on node M iff N postdominates, in the CFG, one but not all of M's CFG successors.*

To permit control dependence on jumps, Algorithm 2 replaces "CFG" with "ACFG" in the definition of control dependence:

Definition 2 *(Augmented control dependence): Node N is* ***control dependent*** *on node M iff N postdominates, in the ACFG, one but not all of M's ACFG successors.*

Unfortunately, as illustrated in Figure 7, Definition 2 is too liberal; it can cause a spurious control dependence of N on M due to the presence of an intervening pseudo-predicate. For example, in the ACFG in Figure 7, node `S1` fails to postdominate the *false* successor of the `if` only because of the non-executable edge from "`goto L1`" to `S2`. Since the execution of `S1` *is* affected by the presence/absence of the `goto` it *should* be considered to be control dependent on the `goto`; however, (as noted previously), `S1` will execute regardless of the value of predicate `P`, and therefore it should *not* be considered to be control dependent on the `if`. So in this case,

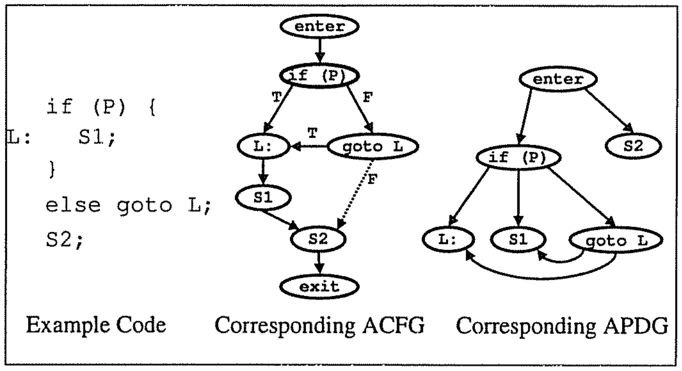


Figure 7: Example in which a control dependence does not reflect a semantic effect.

the actual influence of "`goto L1`" on statement `S1` causes an apparent (but spurious) influence of "`if (P)`" on `S1`.

The solution to this dilemma is to replace only the *second* instance of "CFG" with "ACFG" in Definition 1:

Definition 3 ***(Control dependence in the presence of pseudo-predicates)****: Node N is* ***control-dependent*** *on node M iff N postdominates, in the CFG, one but not all of M's ACFG successors.*

We will refer to a dependence graph that includes control-dependence edges computed using Definition 3 as a PPDG (pseudo-predicate PDG) to distinguish them from the PDGs whose control-dependence edges are computed using Definition 1, and the APDGs whose control-dependence edges are computed using Definition 2.

Example: The program and ACFG from Figure 7 are given again in Figure 8, with the corresponding PPDG. Note that neither label `L` nor statement `S1` is control dependent on "`if (P)`".

Definition 3 addresses the problem of control-dependence edges that do not reflect semantic effects. The next problem that needs to be addressed is the fact that even when every control-dependence edge does represent a semantic effect, the backward closure of control-dependence edges from a node S may include nodes that have no semantic effect on S. For example, consider again the PPDG in Figure 8. If the slice from node `S1` includes all nodes reached by following control-dependence edges backwards, then "`if (P)`" will (erroneously) be in the slice because of the chain of control-dependence edges: `if (P)` $\rightarrow$ `goto L` $\rightarrow$ `S1`.

To address this problem, we need the following definition:

Definition 4 ***(IPD)****: The* ***immediate post dominator (IPD)*** *of a set of ACFG nodes is the node that is the least-common ancestor of that set of nodes in the CFG's postdominator tree.*

Consider a (normal or pseudo) predicate P, with ACFG successors $n_1...n_k$, and let $D = \text{IPD}(n_1...n_k)$. Intuitively, P may affect the execution of a program component S only if there is a path in the CFG from one of P's ACFG successors to S that does not include node D. (If there is such a path, we say that *S* ***is controlled by*** *P.*) The value of P (for a normal predicate), or its presence/absence (for a pseudo-predicate) determines which of its ACFG successors is executed. The execution of the nodes along the paths from those ACFG successors to D are also affected by the value (or presence/absence) of P. However, since whenever P is executed, execution will al-

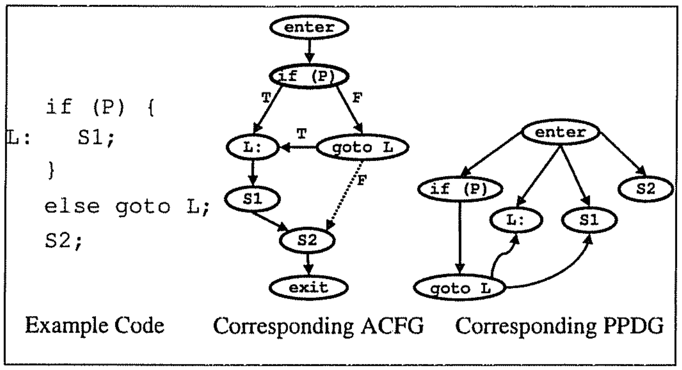


Figure 8: Example from Figure 7 with the corresponding PPDG.

ways reach D (barring an infinite loop or other abnormal termination), the execution of nodes "beyond" D are not affected by P.

As discussed above, following control-dependence edges backwards from S in the PPDG can cause "extra" nodes to be included in the slice from S. In terms of the "is controlled by" relation, this is because there may be a chain of control-dependence edges in the PPDG from a predicate P to S, yet S is not controlled by P. However, we have proved the following Theorem (the proof is given in the Appendix):

Theorem: Node S is controlled by (normal or pseudo) predicate P iff there is a chain of control-dependence edges in the PPDG:

$$P \rightarrow M_1 \rightarrow M_2 \rightarrow ... \rightarrow M_k \rightarrow S$$

such that every M_i in the chain is a normal predicate node. (Note that there may also be no M_i's at all; i.e., there may be a single control-dependence edge $P \rightarrow S$.)

This Theorem tells us that it is not necessary to follow control-dependence edges back from a pseudo-predicate; for any predicate P such that there is a node S in the slice that is controlled by P, P will be picked up by following chains backwards only from normal predicates.

The new algorithm for building and slicing the PPDG is given below.

Algorithm 3 *(Building and slicing the PPDG)*

Step 1: *Build the ACFG as described above for Algorithm 2.*

Step 2: *Build the PPDG: Ignore the non-executable ACFG edges when computing data-dependence edges; compute control-dependence edges according to Definition 3.*

Step 3: *To compute the slice from node S, include S itself and all of its data- and control-dependence predecessors in the slice. Then follow backwards all data-dependence edges, and all control-dependence edges whose targets are not pseudo-predicates; add each node reached during this traversal to the slice. Include label* `L` *in the slice iff a statement "*`goto L`*" is in the slice.*

Examples:

1. Using Algorithm 3, the slice from `S1` of the program in Figure 8 would include the nodes for `S1`, "`goto L`", `L`, and the *enter* node. It would not include the node for "`if (P)`" because, since "`goto L`" is a pseudo-predicate, its incoming control-dependence edge would not be followed back to the `if` node.

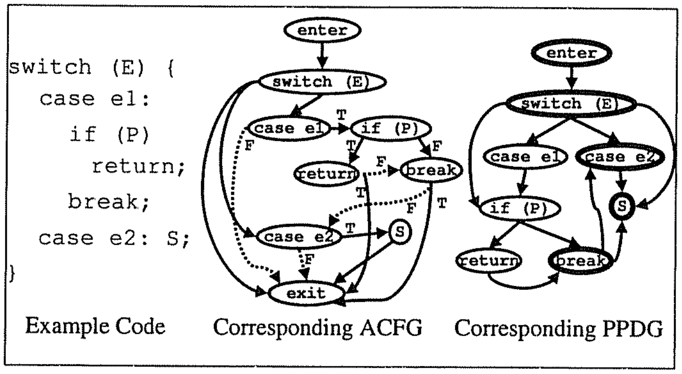


Figure 9: Example PPDG and its slice from S using Algorithm 3.

2. Figure 9 shows the code, ACFG, and PPDG for the second example in Figure 6. Bold font is used to indicate the nodes that would be in the slice from statement S computed using Algorithm 3. Note that "`case e1`", "`if (P)`", and "`return`" are correctly omitted from the slice.

6.1 Pseudo-predicates with outgoing data dependences

Algorithm 3 (implicitly) assumed that pseudo-predicates affect flow of control, but not flow of values (i.e., that pseudo-predicates have no outgoing data dependences). If this assumption is violated, then the slice from node S may include pseudo-predicate P not because P controls the execution of S, but because P affects the value of some variable used at S (or the value of some variable used by another predicate that does control the execution of S). This can happen, for example, if statements of the form "`return exp`" are represented using a single pseudo-predicate node (rather than using two nodes: an assignment to a special "return value" variable, followed by an unconditional jump to the end of the current procedure).

When a slice includes a pseudo-predicate P because of its effect on the flow of values, it is necessary to include P's control-dependence parents in the slice (i.e., it is necessary to follow control-dependence edges back from P). Therefore, if a PPDG can include pseudo-predicates with outgoing data-dependence edges, Step 3 of Algorithm 3 must be modified: when a data-dependence edge is followed backwards from some node n to pseudo-predicate P, then P's incoming control-dependence edges *should* be followed backwards (as well as its incoming data-dependence edges, if any).

6.2 Complexity

The time required for Algorithm 3 includes the time to build the PPDG and the time to compute a slice. Like previous slicing algorithms that use a dependence graph, the time for slicing itself is extremely efficient, requiring only time proportional to the size of the slice (the number of nodes and edges in the sub-PPDG that represents the slice).

The only difference in the time required to build the PPDG as compared to the time required to build the APDG is for the computation of control dependences. Computing control dependences can be done for both the APDG and the PPDG in time $O(E+C)$, where E is the number of edges in the ACFG and C is the number of control-dependence edges. However, C may be different for the APDG and PPDG. For example, in Figure 9, the PPDG includes edges from "`switch (E)`" to "`if (P)`" and to S that would not be in the corresponding APDG. Figures 7 and 8 illustrate control-dependence edges that are in the APDG but not in the PPDG.

7 Interprocedural Slicing

The Ottensteins' algorithm for intraprocedural slicing using the PDG was extended to interprocedural slicing using the *System Dependence Graph* (SDG) in [6]. The approach is as follows:

1. Use interprocedural dataflow analysis to determine what non-local variables might be used or modified by each procedure; for each procedure and procedure call, add an explicit input parameter for each variable that might be used or modified, and an explicit output parameter for each variable that might be modified.

2. Build the PDG for each procedure (including nodes to represent calls, input parameters, and output parameters), and connect the PDGs with edges that represent procedure calls and parameter passing.

3. Compute and add *summary edges* to represent the (transitive) effects that each procedure's input parameters might have on its output parameters. This is done essentially by performing intraprocedural slices from the nodes that represent the final values of the output parameters (an iterative process is used to account for recursion).

4. To compute the slice from node S, use a two-phase approach: Phase 1 follows edges backwards from S, including the interprocedural edges that represent calls made *to* S, but not those that represent calls made *from* S. Phase 2 starts from all nodes reached during Phase 1, and follows edges backwards again; this time including the interprocedural edges that represent calls made from S, and ignoring those that represent calls made to S.

Extending that algorithm for interprocedural slicing to be consistent with the approach presented here is quite straightforward:

- The control-dependence edges in the PDGs should be computed using Definition 3.

- When the summary edges are computed via intraprocedural slicing, the slices should not follow control-dependence edges whose targets are pseudo-predicates.

- Similarly, when an interprocedural slice is computed, the control-dependence edges whose targets are pseudo-predicates should be followed only if the target is the source of the slice.

8 Experimental Results

To evaluate our work, we implemented Algorithms 2 and 3, and used each of them to compute slices in four C programs (information about the programs, the number of slices taken in each, and the average sizes of those slices is given in the table in Figure 10). Slices were taken from all of the nodes that could be reached by following one control-dependence edge forward from a node representing a switch case, and then following five data-dependence edges forward. This ensured that every slice would include a switch, but (by starting further along the chain of data dependences) avoided, for example, slices that would include *only* switch cases and breaks.

More details about the experimental results are given in the tables in Figures 11 and 12. Figure 11 presents information about the differences in the sizes of the individual slices taken using the two algorithms. The first column gives the number of cases where the two algorithms produced slices of exactly the same size. The other columns give the number of cases where the slice produced by Algorithm 2 was larger than the slice produced by Algorithm 3; the second column gives the number of cases where the size difference was between 1 and 10, the third column gives the number of cases where the size difference was between 11 and 20, etc.

	lines of source code	number of APDG/PPDG nodes	number of slices	Av. slice size (# of nodes)	
				Alg 2	Alg 3
gcc.cpp	4,079	16,784	1,932	11,693	11,670
byacc	6,626	21,239	468	2,119	2,110
CADP	12,930	35,965	499	7,921	7,905
flex	16,236	31,354	1,716	8,150	8,082

Figure 10: Information about the C programs used in the experiments.

	0	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
gcc.cpp	2	0	48	1881	0	1	0	0	0	0
byacc	0	229	239	0	0	0	0	0	0	0
CADP	18	152	160	169	0	0	0	0	0	0
flex	0	0	5	127	48	41	8	79	1405	3

Figure 11: Differences in slice sizes using the two algorithms.

	0%	5%	10%	15%	20%	25%	30%	35%
gcc.cpp	2	1918	3	1	8	0	0	0
byacc	0	438	18	7	5	0	0	0
CADP	18	481	0	0	0	0	0	0
flex	0	1572	0	5	13	52	66	8

Figure 12: Percent reduction in slice sizes achieved using Algorithm 3.

Figure 12 presents information about how much the use of Algorithm 3 reduced the sizes of the slices. The first column gives the number of cases where there was no reduction in slice size (a 0% reduction). The other columns give the number of cases where the reduction in size falls within the range specified by the previous and current column headers. For example, the second column gives the number of cases where there was a size reduction greater than 0% and less than or equal to 5%; the third column gives the number of cases where there was a size reduction greater than 5% and less than or equal to 10%.

Note that in almost all cases Algorithm 3 did produce smaller slices than Algorithm 2. Although this led to only a small reduction in the total size of the slice in most cases, there were some cases in both gcc.cpp and byacc where Algorithm 3 provided reductions in slice sizes of more than 15%, and some cases in flex where it provided reductions in slice sizes of more than 30%.

9 Related Work

Choi-Ferrante: The paper by Choi and Ferrante [3] that presents Algorithm 2 also includes a second algorithm: Given a node S, it starts with the slice from S computed using Algorithm 1, then adds `goto` statements to the slice to form a program that will always produce the same sequence of values for the variables used at S as the original program. This technique may produce smaller slices than those produced using Algorithm 2. However, the `goto`s that are added are not necessarily in the original program; therefore, it satisfies neither Weiser's definition of a correct slice, nor Definition 0 from Section 3.

Agrawal: Agrawal [1] also gives an algorithm that involves adding jump statements to the slice computed using the standard PDG, but the statements that he adds *are* from the original program. He states that this algorithm produces the same results as Algorithm 2; however, no proof is provided.

Harman-Danicic: More recently, Harman and Danicic [5] have defined an extension to Agrawal's algorithm that produces smaller slices by using a refined criterion for adding jump statements (from the original program) to the slice computed using Algorithm 1. When applied to programs without switches, it may or may not produce slices that satisfy Definition 0. This is because their algorithm includes some nondeterminism: when there are cycle-free paths from a predicate to its immediate-postdominator both via its *true* and its *false* branches, then the jump statements along either of the paths can be chosen to be in the slice.

Unfortunately, when applied to programs with switch statements, this algorithm can be as imprecise as Algorithm 2. For example, when used to slice the switch statement in the first example in Figure 6, it produces exactly the same slice as Algorithm 2.

Another disadvantage of this algorithm as compared to ours is that the worst-case time to compute a slice can be quadratic in the size of the CFG, while our algorithm is linear in the size of the computed slice.

Sinha-Harrold-Rothermel: In [10], Sinha, Harrold, and Rothermel discuss interprocedural slicing in the presence of arbitrary interprocedural control flow; e.g., statements (like `halt`, `setjmp-longjmp`) that prevent procedures from returning to their call sites. That issue is orthogonal to the one addressed here (better slicing of programs with jumps and switches); thus, the two approaches can be combined to handle programs with arbitrary interprocedural control flow as well as jumps and switches.

10 Summary

We have provided a new definition for a "correct" slice, a new definition for control dependences, and a new slicing algorithm. The algorithm has essentially the same complexity as previous algorithms that compute slices using program dependence graphs, and is more precise than previous algorithms when applied to programs with jumps and switch statements.

The motivation for this work was the observation that slices of code with switch statements computed using the approach to handling jumps proposed by [2, 3] (as implemented in the CodeSurfer [7] programming tool) often include many extra components, which is confusing to users of the tool. We expect that the new approach will have an important practical benefit (to users of slicing tools) as well as being an interesting theoretical advance.

11 APPENDIX: Theorem Proof

THEOREM:

(A) Node S is controlled by (normal or pseudo) predicate P iff

(B) there is a chain of control-dependence edges in the PPDG:

$$P \rightarrow M_1 \rightarrow M_2 \rightarrow \ldots \rightarrow M_k \rightarrow S$$

such that every M_i in the chain is a normal predicate node. (Note that there may also be no M_i's at all; i.e., there may be a single control-dependence edge $P \rightarrow S$.)

PROOF

Lemma 1: If P is a (normal or pseudo) predicate with ACFG successors $n_1 ... n_k$, and D = IPD($n_1 ... n_k$), and there is a D-free path p in the CFG from n_i to S (for some i); then there is some n_j (j possibly $= i$) such that S does not postdominate n_j in the CFG.

Proof of Lemma 1: Assume that S does postdominate all of $n_1 ... n_k$. In this case, either S is D, or S postdominates D. However, S cannot be D, since by assumption path p (which includes S) is D-free. By definition of postdomination, both D and S are on every path from n_i to *exit*, and D precedes S on that path. Therefore, D must be in path p, which contradicts the assumption that p is D-free.

Lemma 2: If P is a (normal or pseudo) predicate, and there is a control-dependence edge $P \rightarrow S$ in the PPDG, then S is controlled by P.

Proof of Lemma 2: The fact that the control-dependence edge $P \rightarrow S$ is in the PPDG means that S postdominates one but not all of P's ACFG successors in the CFG. Without loss of generality, assume that S postdominates P's successor n_1 but does not postdominate P's successor n_2. This means that there is a path p from n_1 to S such that S postdominates all nodes in p. To show that S is controlled by P, we must show that p is D-free (where D is the IPD of P's ACFG successors). This must be true: the fact that S postdominates all nodes in path p means that if path p included D, then S would postdominate D, and would also postdominate all of P's ACFG successors including n_2, which violates the assumption that S does not postdominate n_2.

Lemma 3: If S is controlled by a normal predicate P, and P is controlled by a pseudo or normal predicate Q, then S is controlled by Q.

Proof of Lemma 3: Let Q's ACFG successors be $q_1 ... q_j$, and let P's ACFG successors be $n_1 ... n_k$. Note that since P is a normal predicate, IPD($n_1 ... n_k$) = IPD(P).

P controlled by Q means there is a path $p1$ from one of Q's ACFG successors to P that does not include IPD($q_1 ... q_j$). Without loss of generality, assume that this path starts from node q_2.

S controlled by P means there is a path $p2$ from one of P's CFG successors to S that does not include IPD(P). Without loss of generality, assume that this path starts from node n_1.

This situation is illustrated in Figure 13.

Claim : IPD($q_1 ... q_j$) also postdominates P.

Proof : Suppose not: then there is a path $p3$ from P to *exit* that does not include IPD($q_1 ... q_j$). But then the path $p1 \parallel p3$ is a path from q_2 to *exit* that does not include IPD($q_1 ... q_j$), which cannot happen.

Since path $p2$ does not include IPD(P), it cannot include any postdominator of P, and thus cannot include IPD($q_1 ... q_j$). Therefore, the path $p1 \parallel p2$ is a path from one of Q's ACFG successors to S that does not include IPD($q_1 ... q_j$), and thus S is controlled by Q.

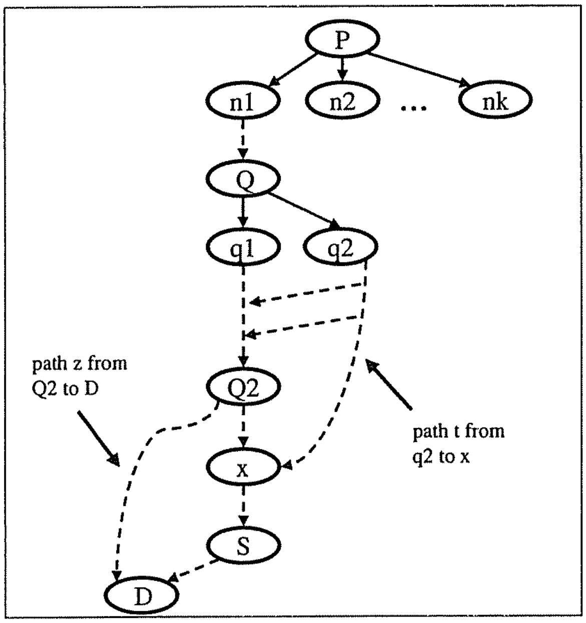


Figure 13: Illustration of Lemma 3.

PROOF OF THEOREM:

Proof part 1 (Theorem (A) $\Rightarrow$ Theorem (B)):

Recall that node S is controlled by predicate P iff there is a D-free path p from one of P's ACFG successors to S (where D is the IPD of P's ACFG successors). In what follows, we will assume (without loss of generality) that path p starts from node y_1.

Case 1: *S **postdominates** y_1.* By Lemma 1, there is some y_j that is not postdominated by S. Therefore, the control-dependence edge $P \rightarrow S$ will be in the PPDG, which satisfies the conditions of part (B) of the Theorem.

Case 2: *S **does not post-dominate** y_1.* This means that there is some set of (normal) predicate nodes M on path p that S does not post-dominate in the CFG.

We will now proceed by induction on the size of set M.

Base case: *size(M) = 1.* In this case, $M = \{N\}$. N must be followed by one of its successors $N1$ in path p, and S must postdominate $N1$ in the CFG (since by assumption S postdominates all predicates in path p other than N), but not some other successor $N2$ of N (or else S would also postdominate N). Therefore S is control dependent on N, and the control-dependence edge $N \rightarrow S$ is in the PPDG.

Furthermore, since S postdominates all other predicates in path p, there can be no predicates at all in the path from y_1 to N (since S does not postdominate any of the nodes in that path), so it must be the case that N postdominates y_1. Since path p is D-free, and the path from y_1 to N is a prefix of p, that path must also be D-free. Therefore, by Lemma 1, there is some y_i that is not postdominated by N, and thus N is control dependent on P, and the control-dependence edge $P \rightarrow N$ is in the PPDG. In this case, the PPDG path $P \rightarrow N \rightarrow S$ satisfies the conditions of part (B) of the Theorem.

Induction step: *Assume that the proof (Theorem (A) $\Rightarrow$ Theorem (B)) holds for all M of size 1 to n. We must now show that it holds for M of size n+1.*

Consider the node N in M that occurs last in path p. As in the base case, N must be followed by one of its successors $N1$ in path p, and S must postdominate $N1$ in the CFG, but there must be some other successor $N2$ of N that S does not postdominate. Therefore S is control dependent on N, and the control-dependence edge $N \rightarrow S$ is in the PPDG.

Furthermore, N must be controlled by P (because the path from y_1 to N is a prefix of the D-free path from y_1 to s), and the number of (normal) predicate nodes in the prefix of path p from y_1 to N must be n (since S does not postdominate any node in that prefix, and since N itself was the n+1^{st} predicate in p that S did not postdominate). Therefore, either N postdominates y_1 (in which case it is control dependent on P, and the control-dependence edge $P \rightarrow N$ will be in the PPDG), or the induction hypothesis holds for nodes N and P (the size of set M for node N is between 1 and n), so we can conclude that there is a control-dependence path from P to N in the PPDG. That path plus the edge $N \rightarrow S$ provides a path that satisfies the conditions of part (B) of the Theorem.

Proof part 2 (Theorem (B) $\Rightarrow$ Theorem (A)):

The proof is by induction on the length of the path from P to S in the PPDG.

Base Case: *There is a control-dependence edge $P \rightarrow S$ in the PPDG.*

By Lemma 2 above, this means that S is controlled by P.

Induction step: *Assume that if there is a control-dependence path of length $n \geq 1$ from P to S in the PPDG (where all nodes other than P and S are normal predicates), then S is controlled by P. We must now show this is true for paths of length n+1.*

If there is a control-dependence path $P \rightarrow M_1 \rightarrow \ldots \rightarrow S$ in the PPDG of length n+1, then the control-dependence path $M_1 \rightarrow \ldots \rightarrow S$ is of length n, and so by the induction hypothesis, S is controlled by M_1. Lemma 2 says that the presence of the control-dependence edge $P \rightarrow M_1$ means that M_1 is in turn controlled by P; Lemma 3 says that if S is controlled by M_1 (a normal predicate), and M_1 is controlled by P, then S is controlled by P.

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