An Approach to Fault Modeling and Fault Seeding Using the Program Dependence Graph

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We present a fault-classification scheme and a fault-seeding method that are based on the manifestation of faults in the program dependence graph (PDG). We enhance the domain/computation fault classification scheme developed by Howden to further characterize faults as structural and statement-level depending on the differences between the PDG for the original program and the PDG for the faulty program. We perform transformations on the PDG to produce the different types of faults described in our PDG-based fault-classification scheme. To demonstrate the usefulness of our technique, we implemented a fault seeder to embed faults in C programs. Our fault seeder makes controlled fault transformations to the PDG for a C program, and generates C code from the transformed PDG. The current version of the fault seeder creates multiple fault-seeded versions of the original program, each with one known fault. To demonstrate the operation of the fault seeder, we used it to perform a study of the effectiveness of dataflow testing and mutation testing using a set of faulty programs generated by our fault seeder. We also used the faulty programs to determine the mutation adequacy and dataflow adequacy of the fault-detecting test sets. © 1997 by Elsevier Science Inc.

1. INTRODUCTION

Software testing is an expensive component of the software development cycle (Sommerville, 1989) that exercises a program to demonstrate the presence of errors and to provide confidence in the program's correctness. Detecting program faults, which are sections of code that may result in incorrect output, is an important goal of software testing. A meaningful measure of a testing technique is its fault-detection ability or effectiveness (Weiss et al., 1991). We measure the effectiveness of a testing technique in terms of its ability to detect certain types of faults; we also measure the effectiveness of a testing technique relative to the effectiveness of other testing techniques.

Although there have been studies of fault categories (Basili and Selby, 1987; DeMillo and Mathur, 1994; Girgis and Woodward, 1986; Howden, 1976), there is no established correlation between categories of faults and testing techniques that expose those faults. Furthermore, although there have been formal and empirical studies (Basili and Selby, 1982; Frankl and Weyuker, 1993; Girgis and Woodward, 1986; Offutt and Hayes, 1996) on the relative effec-

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tiveness of testing techniques, there is no conclusive evidence that one technique is superior in fault-detection ability. Performing studies on fault detection is difficult because of the lack of fault-seeding techniques that automatically and systematically insert faults into a program. One fault-seeding method, mutation testing, inserts small syntactic changes or faults into a program (DeMillo et al., 1978; Hamlet, 1977). However, this approach is expensive and results in a large number of fault-seeded programs that must be tested. Additionally, mutation testing inserts only simple faults (simple syntactic code changes) into a program instead of complex faults (multiple syntactic changes or structural changes).

To facilitate the study of testing techniques, we developed a fault classification and fault-seeding approach that models both simple and complex program faults; we described our preliminary results in Tewary and Harrold (1994). Our program representation is a program dependence graph (PDG) that explicitly represents both data and control dependencies in a program (Ferrante et al., 1987). We enhanced the domain/computation fault-classification scheme that was developed by Howden (1976) to further characterize faults as structural or statement-level, depending on the differences between the PDG for the original program and the PDG for the faulty program. Structural faults are differences in the control dependence or data dependence information in the PDGs, whereas statement-level faults are differences in the information within PDG nodes. We developed transformations on the PDG to produce the different types of faults described in our PDG-based fault-classification scheme. Because statement-level faults that do not change the structure of the PDG are modeled by fault-based testing methods like mutation testing, we restrict our transformations to those that result in structural changes to the PDG.

To demonstrate the usefulness of our technique, we implemented a fault seeder to embed faults into C programs. Our fault seeder makes controlled fault transformations on the PDG, and generates code from the transformed PDG to create multiple fault-seeded versions of the original program, each with one known fault. To demonstrate the usefulness of our fault seeder, we used it to perform a small empirical study of the relative effectiveness of two unit testing techniques: dataflow testing and mutation testing. We used our fault seeder to seed faults into a set of programs, and tested the programs using both dataflow testing and mutation testing. We also determined mutation adequacy and dataflow adequacy of the fault-detecting test sets; these studies replicate earlier, more extensive, studies (Offutt et al., 1996; Wong and Mathur, 1995), and our results agree with theirs.

The advantage of our extended characterization of the domain/computation scheme is that we classify each fault type on the basis of its manifestation in the PDG. This fault representation is easy to apply to the implementation of a fault-seeding tool. There are several uses of our fault seeder. First, our fault seeder can be used as a research tool to measure both the effectiveness and relative effectiveness of unit testing techniques. Second, experiments can be conducted with software that contains specific types of faults to determine the testing technique that is best suited for finding certain types of faults. Finally, like mutation testing, our fault seeder can be used for fault-based testing, in which faults are seeded in a program, and a test suite is developed and used to test the faulty programs.

In the next section, we provide background information on program faults, the program dependence graph, dataflow testing, and mutation testing. Section 3 details our fault categorization method and our method of using the PDG to transform programs. Section 4 outlines the implementation of our prototype fault seeder, and Section 5 describes our case study. In Section 6, we discuss related work, and Section 7 gives conclusions and future directions.

2. BACKGROUND

This section first describes faults and fault categories and then discusses the program dependence graph, on which our fault modeling is based. Finally, the section describes dataflow testing and mutation testing, which are the two types of unit testing that we used for our case study.

2.1 Faults and Fault Categories

According to the IEEE standard definitions (IEEE, 1990), a fault or "bug" is an incorrect step, instruction, or data definition in a program. A fault may result in a failure, which is observed when the system exhibits incorrect external behavior. An error is an internal difference between the computed, observed, or measured values or conditions, and the true, specified, or theoretically correct values or conditions. Finally, a mistake is a human misconception that results in a fault.

To illustrate, suppose a programmer assumes that the upper bound of an array of size 50 is at index 50.
For an array of size 50 whose indices start at 0, this is a mistake. A fault in the program due to this mistake may be a statement such as `array[50] = value;`. The failure in this case may be a memory violation and core dump. If the incorrectly accessed location `array[50]` contains a numerical value that is used in some computation, the output will be different from the expected output, and this difference is an error.

Howden (1976) originally classified program faults, and Zeil (1989) extended Howden’s classification. There have been other fault classifications based on observed instances of faults and on the complexity of faults (DeMillo and Mathur, 1991). According to the Howden/Zeil classifications, program faults are categorized as domain faults or computation faults. A domain fault occurs when, due to an error in control flow, a program generates incorrect output. A computation fault occurs when a program takes the correct path, but generates incorrect output because of faults in the computations along that path. Domain faults are further classified into two categories. A missing path fault is caused by a missing conditional or clause and the associated statements, and a path selection fault is caused by an incorrect decision at a predicate. Path-selection faults can result from an incorrect predicate (predicate fault) or from an incorrect assignment statement that propagates to a control point, leading to an incorrect decision (assignment fault).

For fault-seeding purposes, faults should be “representative” of naturally-occurring faults; otherwise, any results obtained from the seeded faults may be inaccurate or biased. Unfortunately, to date, there is no accepted model with which to determine whether seeded faults are representative. Offutt and Hayes (1996) suggest a model for program faults that they use to identify representative collections of faults. Their model characterizes a fault syntactically as the changes needed to correct the fault, and characterizes a fault semantically by viewing the faulty program as containing a computation that produces incorrect output over some subset of the input domain. Using this characterization, they define the size of a fault: the syntactic size of a fault is the fewest number of statements or tokens that must be changed to correct the fault; the semantic size of a fault is the relative size of the input subdomain for which the program produces incorrect output. They use their semantic size model to claim that a collection of faults is “realistic” if the collection has a distribution of semantic sizes that is similar to that of real faults. However, there is little data about distributions of semantic fault sizes for naturally occurring faults.

2.2 Program Dependence Graph

The program dependence graph (PDG) explicitly represents both data dependencies and control dependencies for a program (Ferrante et al., 1987). In a PDG, nodes represent statements and predicate expressions, and edges represent either data dependencies or control dependencies. Thus, the PDG actually consists of a data-dependence subgraph (DDS) and a control-dependence subgraph (CDS).

Figure 1 gives an example procedure `Insert`, an insertion sort for a five-element array, and its PDG; for brevity, we omit declarations and procedure blocks from the figure. For our discussion, we assume that a program has a single entry and a single exit, which implies that all procedures return to their callers. Thus, we treat call sites as simple statements. These assumptions do not limit our technique, which can be generalized easily.

The PDG contains several types of nodes. Statement nodes, shown as ellipses in Figure 1, represent simple program statements such as assignment, input/output, or call. Predicate nodes, shown as squares in the figure, represent statements from which two edges may originate. An exit node, shown as a hexagon in the figure, represents the exit from the procedure. Region nodes, shown as circles in the figure, represent regions, which summarize the control-dependence conditions necessary to reach statements in the region. We distinguish several types of region nodes. In Figure 1, R1 and R3 are loop header regions, because they summarize the control dependencies for while loops. R2, R4, and R5 are true regions, because they summarize control dependence on the true branch of a predicate. Similarly, R6 is a false region, because it summarizes control dependence on the false branch of a predicate.

Two nodes in a CDS are connected with an edge if one node is control dependent on the other. In a control flow graph, if there are two nodes X and Y, X is control dependent on Y if there are two paths from Y, and taking one path will always lead to X, whereas taking the other path may not lead to X. For example, in Figure 1, S7 and S8 are control dependent on P6-T; region node R5 summarizes this control dependence.

\footnote{Howden/Zeil use the term error instead of fault in their domain/computation classification. We shall use the term fault because we are referring to sections of code that may result in failures.}
Procedure Insert
/* begin procedure Insert, declare variables */
S1. j = 1;
P2. while (j < 5)
{ 
S3. key = array[j];
S4. i = j - 1;
P5. while ((i >= 0) && (brk == 0))
{ 
P6. if (array[i] > key)
{ 
S7. array[i + 1] = array[i];
S8. i = i + 1;
} 
else
S9. brk = 1;
} 
S10. brk = 0;
S11. array[i + 1] = key;
S12. j = j + 1;
} /* end procedure Insert */

Figure 1. Procedure Insert is given on the left and its partial PDG is given on the right.

A data dependence\(^3\) exists between statements X and Y in a program if X defines a variable \(v\), Y uses \(v\), and there is a path from X to Y on which \(v\) is not defined. Dataflow analysis (Aho et al., 1986; Landi and Ryder, 1992) is used to gather dataflow information. The DDS represents the data dependencies in the program. In Figure 1, the dashed lines are data dependence edges for variable \(j\).

2.3 Dataflow Testing

Dataflow testing considers the associations between variable definitions and variable uses. A definition of a variable modifies a data item, whereas a use of a variable references a data item without modifying it. A definition of a variable reaches a use of that variable if there is a subpath in the program from the definition to the use on which the variable is not redefined. A definition-use pair is an association of a definition of a variable and a use of that variable that the definition reaches.

Dataflow testing is a family of adequacy criteria (Frankl and Weyuker, 1988) that includes all-nodes, all-edges, and all-uses. A test set satisfies the all-nodes criterion if every node in the control flow graph\(^4\) is executed by some test in the test set. A test set satisfies the all-edges criterion if each edge in the control flow graph is executed by some test in the test set. A test set satisfies the all-uses criterion if each definition-use pair in the program is executed by some test in the test set.

Figure 2 gives an example control flow graph for a partial program; only the definitions and uses for variables X and Y are shown. Definitions are shown with the variable on the left-hand side of assignments (\(X := \)) and uses are shown with the variable on the right-hand side of assignments (\( := X\)). The table to the right of the figure shows the program components and program paths that are traversed for each of the three dataflow criteria defined above, along with minimal adequate test sets for each criterion.

2.4 Mutation Testing

Mutation testing is a fault-based testing technique (DeMillo et al., 1978; Hamlet, 1977) that is based on the assumption that a program is well tested if all simple faults are predicted and removed; complex faults are coupled to simple faults and are thus

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\(^3\) Although there are several types of data dependence defined in the literature, we consider only flow dependence.

\(^4\) A control flow graph for a program consists of a node for each statement in the program and edges representing the flow of control between statements.
Fault Modeling and Fault Seeding

Figure 2. Control flow graph on the left and a table listing three dataflow testing criteria, program components to be covered, and paths that are traversed.

detected by tests that detects simple faults (DeMillo et al., 1978; Offutt, 1992; How Tai Wah, 1995). Mutation operators introduce simple faults into the program. Each change or mutation that is performed by a mutation operator produces a mutant program or simply, a mutant. A mutant is killed by a test that forces it to produce output that is different from the original program.

Figure 3 shows an example program with four mutants, in which each mutant has exactly one mutation. Equivalent mutants are mutant programs that are functionally equivalent to the original program and therefore cannot be killed by any test. In Figure 3, mutant 3 is an equivalent mutant because, if the value of X is 8, it makes no difference whether we check X > 0 or X >= 0.

Budd (1981) defined mutation analysis as a method for evaluating the degree to which a set of tests exercises a program. His suggested procedure extends the test set until all nonequivalent mutants have been killed. Because the method of test generation is not significant here, we use the terms mutation analysis and mutation testing interchangeably.

3. MODELING FAULTS USING THE PDG
We characterize the types of faults that we model using the PDG as extensions to the domain/computation classification scheme developed by Howden (1976). Our goal in extending this scheme is to establish a relationship between existing fault categories and their PDG representations—not to pro-

Figure 3. Mutation operators are applied to the the original program on the left to create mutant programs; only four mutants have been shown. The Δ marks the statement at which the mutation is applied.
vide an exhaustive fault classification. Section 3.1
details our extensions to the domain/computation
classification that are based on fault manifesta-
tions in the PDG. The relationship between our PDG-
based fault classification and the domain/computa-
tion scheme is shown in our extended fault classifi-
cation, given in Figure 4. We consider only faults
that occur within procedures; we do not consider
interface faults. In section 3.2, we describe algo-
rithms that transform the PDG to model the struc-
tural fault types detailed in Section 3.1. For these
transformation algorithms, we consider only fault
types that affect the PDG structure; we do not
consider statement-level faults because they are
modeled extensively by other methods such as muta-
tion.

3.1 PDG-based Fault Classification

Based on the PDG, we characterize each type of fault
in the domain/computation classification
scheme as **structural** or **statement-level**. Structural
faults are "macro-level" faults, and are manifested
as differences in the structure of the PDGs of the
original program and the faulty version. If this dif-
ference in structure is due to a difference in the
control dependence successors or predecessors of
nodes in the PDGs, then the fault is a **CDS-structural fault**; if the difference in structure is due to a
difference in the data-dependence successors or pre-
decessors of nodes in the PDGs, then the fault is a
**DDS-structural fault**.

A statement-level fault is a textual difference be-
tween a faulty statement and the original statement
that is not a difference in the structure of the PDGs.
For these types of faults, the CDS and DDS struc-
ture of the faulty program are the same as the CDS
and DDS structure of the original program. How-
ever, the "micro-level" information inside some node
diffs from the information in the corresponding
node in the original PDG. We identify two types of
statement-level faults: **Incorrect Operators**, such as
'<' instead of '>', and **Incorrect Precedence of
Operation**, which occurs because of a lack of, or
misuse of, parentheses.

Our model classifies faults as either domain or
computation faults, depending on whether the fault
relates to flow of control or computations along a
particular path. In the following discussion, we de-
scribe our PDG-based fault classification, and give
some examples.

3.1.1 Domain faults. We further classify domain
faults as missing path faults and path selection faults.

3.1.1.1 Missing path faults. Missing path faults oc-
cur when the correct predicate is executed, but the

![Figure 4. PDG-based fault classification. Italicized entries are our extensions to the domain/computation classification; parenthesized entries indicate the general PDG fault class for each fault type.](image)
required path is missing. There are two manifestations of this type of fault in the PDG: (1) Omission of True/False Clause and (2) Omission of Conditional.

(1) Omission of True/False Clause Faults involve the omission of one branch of a conditional statement, and result in the omission of a true or false clause from a conditional. This fault is a CDS-structural fault represented in the PDG by the omission of a true or false region node and its successors. Figure 5, in which the false branch of P6 of Figure 1 is omitted, shows an example of this type of fault.

(2) Omission of Conditional Faults involve the omission of an entire conditional statement, such as a while statement or if statement. An omission of an error checking condition is an example of this type of fault. This fault is a CDS-structural fault represented in the PDG by the omission of a predicate or loop header region and its subgraph. Figure 6, in which the IF statement in P6 is omitted, shows an example of this type of fault.

3.1.1.2 Path selection faults. Path selection faults occur when paths originating at a predicate are correct, but an incorrect decision at the predicate results in selection of the wrong path. The fault may be in the predicate itself, or it may be in an assignment statement that affects the predicate.

(1) Predicate Faults:
(a) Incorrect Variable Used Faults (Predicate) involve the use of an incorrect variable at a predicate node. For example if the predicate expression is \((a > c)\) instead of \((a > b)\), the use of variable \(c\) is incorrect. This fault is a DDS-structural fault in which the data-dependence edges at a predicate node are violated. Figure 7, in which an extra statement, \(j = i\), alters the data-dependence between nodes S1 and P2, because it results in the incorrect value of \(j\) to be used in P2, shows an example of this type of fault.
(b) Incorrect Expression Faults (Predicate) involve the use of one or more incorrect operators. An example of an incorrect predicate expression is \((a < b)\) instead of \((a > b)\). This fault is a statement-level fault that is represented by an incorrect expression at a PDG node.

(2) Assignment Faults:
(a) Incorrect Variable Faults (Assignment) are violations of the data-dependence relations in the program. The difference may be the use of an incorrect variable (Incorrect Variable Used Faults), or the definition of an incorrect variable (Incorrect Variable Defined Faults).

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**Figure 5.** Example CDS for Insert for Omission of Clause Fault.
Procedure Insert with Omission of Conditional Fault

/* begin procedure Insert, declare variables */
S1. j = 1;
P2. while (j < 5 )
   {
S3. key = array[j];
S4. i = j - 1;
P5. while (i >= 0) && (brk == 0))
   {
S6. 
S10. brk = 0;
S11. array[i + 1] = key;
S12. j = j + 1;
   }
/* end procedure Insert */

Figure 6. Example CDS for Insert for Omission of Condition Fault.

These faults are DDS-structural faults, and are violations of data-dependence edges into an assignment node that affects a predicate node. Figure 8, in which the variable j replaces variable key (being defined) in assignment statement node S3, is an example of an Incorrect Variable Defined Fault.

(b) Incorrect Expression Faults (Assignment) involve the use of one or more incorrect operators. An example of an incorrect expression is 'a = b + c ' instead of 'a = b - c '. This fault is a statement-level fault that is represented by an incorrect expression in a PDG node.

(c) Omission of Statement Faults (Assignment) involve missing assignment statements. These faults are CDS-structural faults, and are represented by the omission of statement nodes.
Figure 8. Example DDS for Insert for Incorrect Variable Defined Fault (Assignment).

in the PDG. Figure 9 shows an example of this type of structural fault.
(d) Transposition of Statements Faults (Assignment) are of two types, depending on whether the transposition occurs within the same region, or in different regions, of control dependence.

Figure 9. Example CDS for Insert for Omission of Statement Fault.
statement $s_1$ assigns to variable $v$, statement $s_2$ uses variable $v$, and $s_1$ and $s_2$ are adjacent to each other in the code. Then there is a data-dependence edge from $s_1$ to $s_2$. A fault occurs when $s_1$ and $s_2$ are reversed in the code, so that the original data dependencies are violated. Figure 10 shows an example of this type of fault.

- **Transposition Between Regions Faults (Assignment)** occur when a statement appears in the incorrect region of control dependence. An example of this fault is omission of compound statement braces in C that causes a conditional to affect only the statement immediately after it. This fault is a CDS-structural fault, modeled by an omission of a node or branch from one point in the PDG and its appearance in another section of the PDG. An example is shown in Figure 11; nodes S4-S12, in R2 in Figure 1, are successors of E in the faulty version.

### 3.1.2 Computation faults

Computation faults occur in statements that lie on the correct control flow path in the program. We see from Figure 4 that computation faults include the same fault categories as Domain-Path-Selection-Assignment faults, because both types of faults involve assignment statements. Thus, computation faults manifest themselves in the PDG in the same way as Domain-Path-Selection-Assignment faults, which we described in Section 3.1. The important difference between these fault types is that computation faults affect program output by computing incorrect values, instead of causing an incorrect path to be selected. A fault in an assignment in which the value is used in a computation is a computation fault, whereas a fault in an assignment that affects a predicate is an assignment fault. A fault can be both a computation and an assignment fault.

#### 3.2 Fault Transformation Algorithms

We model all structural faults presented in our fault classification scheme, shown in Figure 4, by transformations on the PDG. In this section, we overview our algorithms for transforming the CDS and DDS. For simplicity, we present the handling of structured programs; the transformation techniques can also be applied to unstructured programs. In all cases, we assume that a high level driver routine traverses the PDG to determine the node to transform. The PDG

![Figure 10. Example DDS for Insert for Transposition Within Region Fault (Assignment).](image-url)
3.2.1 CDS-structural transformations. We perform CDS-structural fault transformations using two basic operations on the CDS: (1) pruning to remove nodes and branches, and (2) grafting to remove nodes and branches from one branch, and join them to another branch. Faults of omission require only pruning, whereas faults of transposition require grafting.

Pruning algorithm OmitPath, shown in Figure 12, is used to model Omission of Clause, Omission of Conditional, and Omission of Statements faults. OmitPath seeds faults by pruning statement nodes, or region or predicate branches. OmitPath calls GetNode to return node_ptr, a pointer to the region or predicate that is to be deleted. Delete-List removes this region or predicate node and its successor nodes. OmitPath deletes the node referenced by node_ptr from the successor list of its parent; this deletion also causes all nodes in the subgraph rooted at this node to be deleted. Next, the algorithm decrements the PDG node count, node_count, by the number of nodes in the deleted subgraph; the subgraph node count is part of the node structure. Finally, OmitPath returns node_count. For example, to model the fault in Figure 5, given the PDG in Figure 1, OmitPath prunes region node R6 and decrements the PDG node count, node_count, by 2. OmitPath has runtime that is linear in the number of nodes in the PDG.

Our technique seeds Omission of Conditional faults by pruning all conditional branches. This transformation is similar to the Omission of Clause transformation except that, while the PDG is being traversed, conditional and iterative regions are removed. Algorithm OmitConditional performs this transformation; we omit OmitConditional because it is similar to algorithm OmitPath, which is given in Figure 12.

Algorithm TransposeBetweenRegions, shown in Figure 13, is a grafting algorithm that seeds
Algorithm OmitPath

input node.id
globals cd.info
output modified cd.info and reduced node.count
declare node.ptr
getNode(node.id)
DeleteList(list, node.id)

begin OmitPath
node.ptr = getNode(node.id)
DeleteList(node.ptr.pred.list, successor.list, node.id)
remove node referenced by node.ptr from successor list of parent
node.count = node.count - node.ptr.subgraph.count
return node.count
end OmitPath

Figure 12. Fault transformation algorithm OmitPath.

**Transpose Between Regions (Assignment)** faults. This transformation results in the transposition of nodes from one point in the PDG to another. Procedure getNode returns a pointer, node.ptr, to the region node from which nodes must be transposed. A new parent is found for the transposable nodes (nodes that will be moved out of the region) by GetViableParent, which searches and returns a new parent region node to which new control-dependence successors will be grafted.getNode returns a pointer, parent.ptr, to the new parent. For each transposable successor n in transpose._list, the region node's successor count is decremented and the new parent's successor count is incremented. After getNode returns a pointer to n, InsertList updates the successor and predecessor lists of the new parent and the transposed node, to form the new control-dependence edge. Finally, DeleteList severs the link between region node and transposed node. After grafting, the transformed PDG has the same number of nodes as the original PDG. Figure 11 gives an example of this transformation; R2 is the region node from which nodes S4 to S12 are transposed onto the new parent.

Algorithm TransposeBetweenRegions

input node.id : id of region node for transformation
transpose.list : list of node ids to transpose
globals cd.info : CDS
output transformed cd.info
declare node.ptr, n.ptr, parent.ptr : pointers to nodes
new.parent.id, n : node ids
getNode(node.id) : returns pointer to node
GetViableParent(node.id) : returns new parent id
InsertList(list, node.id) : deletes/inserts node(s)

begin TransposeBetweenRegions
node.ptr = getNode(node.id)
new.parent.id = GetViableParent(node.id)
parent.ptr = getNode(new.parent.id)
foreach(n ∈ transpose.list) do
node.ptr.succ.count--
parent.ptr.succ.count++
n.ptr = getNode(n)
InsertList(n.ptr.pred.list, new.parent.id); InsertList(parent.ptr.cd.succ.list, n.ptr)
DeleteList(n.ptr.cd.pred.list, node.ptr); DeleteList(node.ptr.cd.succ.list, n)
end TransposeBetweenRegions

Figure 13. Fault transformation algorithm TransposeBetweenRegions.
3.2.2 DDS-structural transformations. The DDS-structural transformations involve a violation of one or more edges in the DDS, in conjunction with the addition of new edges. We assume that the required dataflow information is available at each node. The algorithms have runtime that is linear in the number of nodes in the PDG.

Figure 14 shows our first DDS-structural transformation algorithm that we use to seed Incorrect Variable Used Faults (Predicate/Assignment/Computation). In algorithm IncorrectVarUse, after GetNode returns a pointer to the node being transformed, procedure DeleteEndList deletes a DDS predecessor of this node. This violation of an incoming DDS edge represents the removal of a variable used in the node. GetReachingDefs selects another node (def_ptr) containing a variable definition reaching this node. Using InsertList, the algorithm constructs a new DDS edge from the new variable definition node def_ptr. PrefixString modifies the current node source string, by attaching the required assignment statement (new variable used is assigned to old variable used). Figure 7 shows the result of applying IncorrectVarUse to the PDG in Figure 1. Node P2 is transformed by violating the DDS edge from S1 (definition of j), and adding the DDS edge from S8 (definition of i); the assignment ‘j = i’ is prefixed to the source string at node P2.

The second DDS transformation is more complex. Figure 15 shows algorithm IncorrectVarDef that models Incorrect Variable Defined Faults (Assignment/Computation). First, GetNode returns a pointer to the statement node. DeleteList removes all outgoing DDS edges at this node because the definition will change. GetReachingDefs returns a node pointer (def_ptr) to another variable definition. Next, the algorithm replaces the original variable defined (in the def field) by the new variable in def_ptr. The source string at (src) is changed by ChangeValue. GetReachableUses returns all reachable uses of the new definition, and for each of these uses, InsertList constructs new DDS edges. Finally, because the new definition may “kill” some other definitions of the variable, all DDS edges from the “killed” definition must be removed. Removal of these edges is done in the foreach loop at the end of IncorrectVarDef. If any DDS successors of the node def_ptr are now successors of the new definition at node_ptr, they are deleted from the successor list of def_ptr, because that definition no longer reaches. Figure 8 shows an example of this transformation, where the PDG in Figure 1 has an Incorrect Variable Defined Fault (Assignment). Node S3 is transformed, and the variable key is changed to j. This change results in the omission of DDS edges to P6 and S11 because S3 no longer defines key. New edges to S4 and S12 are added, as these nodes have uses of j. Also, edges (S1, S4) and (S1, S12) are removed, because the definition at S1 no longer reaches S4 and S12.

Figure 16 shows our third DDS transformation algorithm. This transformation models the Transposition Within Region Fault (Assignment). The algorithm TransposeWithinRegion accepts as input the statement node to be transposed; GetNode re-

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```plaintext
Algorithm IncorrectVarUse
input node_id : id of statement node for transformation
globals cd.info, dd.info : CDS and DDS
output modified dd.info
declare node_ptr, succ_ptr, def_ptr : pointers to nodes
    GetNode(node_id) : returns pointer to node
    DeleteEndList(list), InsertList : deletes/inserts node(s)
    GetReachingDefs(node_ptr) : returns pointer to each node with reaching def
    PrefixString(string pointer) : prefixes string to source string

begin IncorrectVarUse
    node_ptr = GetNode(node_id)
    succ_ptr = DeleteEndList(node_ptr.dd.pred_list)
    def_ptr = GetReachingDefs(node_ptr)
    InsertList(def_ptr.dd.succ_list, node_ptr); InsertList(node_ptr.dd.pred_list, def_ptr)
    PrefixString('succ_ptr.def = def_ptr.def',node_ptr.src)
end IncorrectVarUse

Figure 14. Fault transformation algorithm IncorrectVarUse.
```
Algorithm IncorrectVarDef
input node.id : id of statement node for transformation
globals cd.info, dd.info : CDS, DDS
output modified dd.info
declare node.ptr, succ.ptr, n.ptr : pointers to node
n : id of node
use.ptr, def.ptr : pointer to node with reachable use/new def
getNode(node.id) : returns pointer to node
DeleteList(list, node.id), InsertList(list, node.ptr) : deletes/inserts node(s)
GetReachingDefs(node.ptr) : returns pointer to each node with reaching def
GetReachableUses(node.ptr) : returns pointer to each node with reachable uses
ChangelValue(string pointer, lhs) : substitutes lhs in string

begin IncorrectVarDef
  node.ptr = getNode(node.id)
  DeleteList(node.ptr.dd.succ_list, all-nodes)
  def.ptr = GetReachingDefs(node.ptr)
  node.ptr.def = def.ptr.def
  ChangelValue(node.ptr.src, node.ptr.def)
  while (use.ptr = GetReachableUses(node.ptr) is valid node) do
    InsertList(node.ptr.dd.succ_list, use.ptr); InsertList(use.ptr.dd.pred_list, node.ptr)
    foreach (n ∈ def.ptr.dd.succ_list) do
      if (n ∈ node.ptr.dd.succ_list) then
        DeleteList(def.ptr.dd.succ_list, n)
        n.ptr = getNode(n)
        DeleteList(n.ptr.dd.pred_list, def.ptr.id)
    end foreach
end IncorrectVarDef

Figure 15. Fault transformation algorithm IncorrectVarDef.

Algorithm TransposeWithinRegion
input node.id : id of statement node for transformation
globals cd.info, dd.info : CDS, DDS
output modified dd.info
declare node.ptr, sibling.ptr : pointers to node
getNode(node.id) : returns pointer to node
GetSibling(list, node.id), InsertList(list, node.ptr) : deletes/inserts node(s)
GetSibling(node.id) : returns pointer to sibling node
ExchangeInfo(node.ptr, node.ptr) : swaps node info

begin TransposeWithinRegion
  node.ptr = getNode(node.id)
  while (sibling.ptr = GetSibling(node.id) != invalid pointer) do
    if (sibling.ptr.id ∈ node.ptr.dd.succ_list)
      DeleteList(node.ptr.dd.succ_list, sibling.ptr.id);
      DeleteList(sibling.ptr.dd.pred_list, node.ptr.id)
      InsertList(node.ptr.dd.pred_list, sibling.ptr);
      InsertList(sibling.ptr.dd.succ_list, node.ptr)
      ExchangeInfo(node.ptr, sibling.ptr)
  end while
end TransposeWithinRegion

Figure 16. Fault transformation algorithm TransposeWithinRegion.
turns a pointer to this statement node. GetSibling obtains each sibling node of node_id, and checks to see if the sibling node is the DDS successor of node_id. If the sibling node is the DDS successor of node_id, the direction of the edge is reversed using DeleteList and InsertList routines. Also, the information within the two nodes is exchanged using the ExchangeInfo routine. For example in the PDG in Figure 1, there is a data-dependence edge (S8, S7) (not shown). Thus, exchanging the information in these nodes results in a fault. The DDS edge (S8, S7) is removed, and a new edge (S7, S8) is created. Reachable uses and reaching definitions information for these nodes is also exchanged.

4. PROTOTYPE FAULT SEEDER

To demonstrate the usefulness of our transformation algorithms that model program faults, we built a prototype fault seeder that inserts structural faults into C programs. We developed our fault seeder in C on Sun SPARC machines, using our analysis system, Aristotle (Harrold et al., 1995), to gather program information and generate the faulty programs. Figure 17 shows a dataflow diagram representing our fault seeder, and illustrates its use of some of Aristotle's components. Aristotle's parser/analyser, CParse, takes the C program, pgm.c, as the input to be seeded with faults. CParse parses the program, and produces various types of analysis information including the PDG, which is used by our fault seeder. The fault-transformation component of our prototype, FSeed, inputs the PDG for pgm.c, along with the fault type that the user desires. FSeed seeds as many faults as possible of this fault type, and produces a new PDG for each fault it seeds. The transformed PDGs are then input to CGen, which is a source code generator and instrumenter available in Aristotle. For each transformed PDG, CGen generates a C program, and stores it in a file. The result is a set of n fault-seeded program versions, pgm.fseed.0.c ... pgm.fseed.n.c, each with exactly one fault of the user specified fault type.

FSeed implements the fault-transformation algorithms presented in Section 3.2, each of which requires information about the portion of the PDG to transform. To provide this information, FSeed has a

---

5 SPARCstation is a trademark of Sun Microsystems, Inc.
6 We used this design for our prototype fault seeder. A tool for general distribution might let the user determine, for each fault classification, the percentage of faults to be generated.

---

The goal of our prototype fault seeder is to produce multiple fault-seeded versions of pgm.c each with one fault of the fault type. Thus, each case in algorithm FaultSeederDriver corresponds to a structural fault in our classification scheme in Figure 4; each case label represents a concatenation of nodes in the classification tree. The user inputs the fault type value, and FaultSeederDriver traverses the PDG to find as many places as possible to perform the fault transformation fault_type. Hence, in each case, FaultSeederDriver iterates over all the nodes in the PDG.

For each node in the PDG, FaultSeederDriver checks for certain conditions to determine the appropriate transformation position. For example, to seed the domain fault Omission of Clause, FaultSeederDriver finds all conditional predicate nodes, and calls the OmitPath routine to omit true and false regions. Because the fault categories for computation faults and assignment faults are the same, the only difference in the action taken by FaultSeederDriver is to set the selection type variable to C_USE or P_USE. The driver performs some additional analysis to determine the uses (c-uses or p-uses) of the definition in the node.

---

7 A c-use occurs on the right-hand side of an assignment or in an output statement, whereas a p-use occurs in a predicate expression.
Algorithm FaultSeederDriver
input fault_type, node_count, program_file
globals cd_info, dd_info : CDS, DDS
output fault-seeded programs of type specified
declare Transformation algorithms from section ??
node_id : node id being processed
node_ptr : pointer to node
GetNode(node_id) : returns pointer to node
RightRegion(node_ptr), LeftRegion(node_ptr) : return left/right region node id for predicate
GetUse(node_ptr) : returns list of c-use/p-uses
CGen : source code generator

begin FaultSeederDriver
switch(fault_type)
case Domain.MissingPath.OmissionOfClause :
    foreach(node_id ∈ 1..node_count)do node_ptr = GetNode(node_id)
    if(node_ptr.type ==if-predicate)then
        OmitPath(RightRegion(node_ptr)) CGen
        OmitPath(LeftRegion(node_ptr)) CGen
    elseif(node_ptr.type ==while/do/for predicate)then
        OmitPath(node_id) CGen
    return

case Computation.IncorrectVariable: selection_type = C.USE
    foreach(node_id ∈ 1..node_count)do node_ptr = GetNode(node_id)
    if(node_ptr.type ==statement)and(selection_type ∈ GetUse(node_ptr))then
        IncorrectVarUse(node_id) CGen
        IncorrectVarDef(node_id) CGen
    return

case Computation.OmissionOfStatements: selection_type = C.USE (omitted)

end FaultSeederDriver

Figure 18. Driver routine for FSeed; only two cases are detailed.

to differentiate between computation and assignment faults. For example, if the input fault_type is Computation.IncorrectVariable, FaultSeederDriver sets the selection_type to C.USE, and the algorithm iterates over all nodes and selects a statement node with c-uses for transformation. The algorithm calls IncorrectVarUse and IncorrectVarDef to perform DDS-structural transformations. The output of FSeed consists of the transformed PDGs for pgm.c, which are shown in Figure 17 as PDG0, PDG1, ..., PDGn.

The transformed PDGs are then input to CGen, which generates C programs pgm.fseed.0.c, pgm.fseed.1.c, ..., pgm.fseed.n.c. CGen consists of two main components: a CDS walk routine and a node-level code generator. The CDS walk routine traverses the CDS to generate a walk sequence, which is a sequence of nodes obtained using a graph traversal algorithm such that a correct program is generated from this sequence. Using the walk sequence, the node-level code generator produces code for each node in the CDS, based on the node type and the statements associated with the node. At this point, the fault-seeder tool becomes language dependent; CGen is written for C.

5. FAULT SEEDING CASE STUDY
We performed a case study with our prototype fault seeder to demonstrate its operation. In the first part of our study, we compared the fault-detection abilities of dataflow testing and mutation testing; in particular, we compared the all-uses dataflow criterion to mutation testing. Several previous studies (Mathur and Wong, 1994; Offutt et al., 1996) have compared the relative effectiveness of dataflow testing and mutation testing. However, none of these studies used an automatic fault-seeding tool to insert faults into the subject programs. In the second part of our case study, we evaluated the dataflow adequacy and mutation adequacy of the test suite created by our fault seeder.
5.1 Case Study Procedure

We applied our fault seeder to a set of subject C programs that are listed in Table 1. We then used Combat (Harrold and Kolte, 1992) to dataflow test each C program, and we used Mothra (DeMillo et al., 1988) to mutation test equivalent Fortran-77 versions of the subject programs. We now describe the steps involved in the case study.

5.1.1 Step 1. In the first step of the case study, we prepared the subject programs. Because Mothra required Fortran-77 programs as input and Combat required C programs, we first translated the subject programs so that both language versions would be available. We started with Fortran-77 versions of the programs, and first made sure that the programs did not use any features of Fortran-77 that would not translate directly into C. Then, we hand translated the programs into C taking care to use as direct a translation as possible so as not to introduce any bias into our results because we used different programs. We attempted to preserve the control structure of the programs during translation; however, we had to introduce some differences in the programs due to the requirements of Mothra and Combat. For example, Combat requires input and output statements as part of the procedure being tested. Thus, for a program using arrays, the result was two extra loops to read and print the arrays, and hence extra faults. However, these faults in the input and output loops were trivial and easy to detect and therefore do not affect the results of our study. We tested our translations by running both versions on a set of functional tests, and comparing the outputs of the two versions.

In this first step of the case study, we manually determined the equivalent-mutant and infeasible-path information for the subject programs. Although this process was time consuming, it was essential in the computation of the adequacy scores. For the subject programs, Table 1 shows the number of PDG nodes and edges, the number of definition-use (DU) pairs, the number of mutants, the number of infeasible DU pairs, and the number of equivalent mutants.

5.1.2 Step 2. We performed the fault seeding in the second step of our procedure. We ran our fault-seeder system on each subject C program, and created several fault-seeded versions of the program. We selected four structural faults from our classification (Figure 4) to be seeded: Omission of Clause, Omission of Conditional, Transposition Between Regions, and Transposition Within Region. The second column in Table 2, labeled Total Faults, gives the total number of faults seeded. The next four columns give the numbers of faults of each type that were seeded.

5.1.3 Step 3. In Step 3, we hand translated each of the faulty C programs into its Fortran-77 counterpart. We used a procedure similar to that used in Step 1 to guarantee equivalence of the faulty Fortran-77 and C versions.

5.1.4 Step 4. In this step, we tested each set of faulty versions using Combat for dataflow testing and Mothra for mutation testing. Figure 19 shows the flow chart for the procedure we used. For each faulty version of a subject program, we generated tests to satisfy the adequacy criterion (dataflow or mutation). We generated the tests manually by considering DU pairs to be satisfied or mutants to be killed; we made no attempt to minimize the test sets.

### Table 1. Details of Subject Programs

<table>
<thead>
<tr>
<th>Program</th>
<th>PDG Nodes</th>
<th>PDG Edges</th>
<th>DU Pairs</th>
<th>Mutants</th>
<th>Infeasible DU Pairs</th>
<th>Equivalent Mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>bisect</td>
<td>13</td>
<td>17</td>
<td>46</td>
<td>511</td>
<td>0</td>
<td>62</td>
</tr>
<tr>
<td>bub</td>
<td>15</td>
<td>19</td>
<td>37</td>
<td>338</td>
<td>1</td>
<td>35</td>
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<tr>
<td>cal</td>
<td>19</td>
<td>28</td>
<td>59</td>
<td>3010</td>
<td>0</td>
<td>266</td>
</tr>
<tr>
<td>euclid</td>
<td>4</td>
<td>4</td>
<td>13</td>
<td>196</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>find</td>
<td>28</td>
<td>38</td>
<td>148</td>
<td>1022</td>
<td>13</td>
<td>75</td>
</tr>
<tr>
<td>insert</td>
<td>16</td>
<td>21</td>
<td>44</td>
<td>437</td>
<td>1</td>
<td>46</td>
</tr>
<tr>
<td>mid</td>
<td>10</td>
<td>14</td>
<td>31</td>
<td>183</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>newton</td>
<td>9</td>
<td>12</td>
<td>33</td>
<td>394</td>
<td>0</td>
<td>48</td>
</tr>
<tr>
<td>quad</td>
<td>4</td>
<td>4</td>
<td>359</td>
<td>0</td>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td>search</td>
<td>14</td>
<td>18</td>
<td>37</td>
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</tr>
<tr>
<td>secant</td>
<td>9</td>
<td>12</td>
<td>30</td>
<td>694</td>
<td>0</td>
<td>84</td>
</tr>
<tr>
<td>tritype</td>
<td>19</td>
<td>45</td>
<td>112</td>
<td>951</td>
<td>14</td>
<td>109</td>
</tr>
</tbody>
</table>
Table 2. Faults Detected by Mutation and Dataflow Testing

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Omission of Clause</th>
<th>Omission of Conditional</th>
<th>Transposition Between Regions</th>
<th>Transposition Within Region</th>
<th>Dataflow</th>
<th>Mutation</th>
</tr>
</thead>
<tbody>
<tr>
<td>bisect</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>bub</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>cal</td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>euclid</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>find</td>
<td>8</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>insert</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>mid</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>newton</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>quad</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>search</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>secant</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>tritype</td>
<td>10</td>
<td>1</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>74</td>
<td>10</td>
<td>42</td>
<td>14</td>
<td>8</td>
<td>72</td>
</tr>
</tbody>
</table>

If some test in the adequate test set caused a program failure, we isolated the test as a fault-detecting test, and declared the fault detectable by the adequate test set. This one-to-one correspondence between test, fault, and failure was a natural outcome of the fact that each program version has exactly one fault, and that fault must be failure causing. It is important to note that when we generated the tests, we used no information about the current fault in the program version being tested; this avoided a bias in the generation of tests. The ideal way to remove any such bias would be to fully automate the test generation procedure. For Mothra, a tool such as Godzilla generates a large number of tests to attempt to satisfy the mutation adequacy criterion; however, a number of tests must be hand picked.

Figure 19. Procedure used for case study.
For Combat such a tool does not currently exist. Therefore, for this study, we manually generated all tests for both Mothra and Combat. The last two columns in Table 2 give the total number of faults detected by dataflow testing and mutation testing.

5.1.5 Step 5. Having determined the number of faults found using mutation and dataflow testing, we wanted to determine how close the fault-detecting test sets came to satisfying the dataflow adequacy criteria and the mutation adequacy criterion. That is, we wanted to compute the dataflow adequacy and the mutation adequacy of the test sets that were, by construction, 100% effective. For this purpose, we tested the original programs using the isolated fault-detecting test sets, and determined mutation and dataflow adequacy scores. For additional information we noted the all-nodes and all-edges as well as the all-uses adequacy of the fault detecting test sets. Table 3 shows the results of this study for dataflow adequacy and Table 4 shows the results of the study for mutation adequacy. We computed the adequacy scores as \( N_e/N_r - N_u \), where \( N_e \) is the number of nodes, edges or DU pair satisfied, or the number of mutants killed; \( N_r \) is the total number of nodes, edges, DU pairs or mutants, and \( N_u \) is the number of unsatisfiable entities: nodes, edges or DU pairs that lie on infeasible paths, or equivalent mutants.

The second through fourth columns of Table 3 show the adequacy scores of the fault detecting test sets that were obtained using three dataflow criteria. The last two columns compare test set sizes. The fifth column gives the test set size for an all-uses adequate test set and the sixth column gives the size of the structural fault-detecting test set obtained by fault seeding, for which the adequacy scores in this table were recorded. The dataflow adequate test sets were not minimized.

The second column of Table 4 gives the overall number of mutants generated and the third column gives the overall mutation adequacy scores. The fourth through ninth columns give the numbers and adequacy scores for each of the three mutation superclasses. The last two columns compare the test sets sizes for mutation adequate test sets (tenth column), and fault-detecting test sets obtained by fault seeding, for which the adequacy scores in this table have been recorded (eleventh column). The mutation adequate test sets have not been minimized.

5.2 Analysis of Results

Table 2 shows that dataflow testing detected 72 of the 74 faults seeded, whereas mutation testing detected all faults seeded. The two faults that were not detected by dataflow testing were, somewhat surprisingly, trivial faults. Both were Omission of Conditional type of faults, and both resulted in the control flow graph of the program being reduced to a single basic block. In practice, such faults are not persistent in that they do not remain undetected for long. It appears from our results that both dataflow and mutation testing are nearly 100% effective in detecting most types of PDG structural faults. For mutation testing, our results indicate that the coupling effect, which was suggested and empirically investigated by mutation testing researchers (DeMillo et al., 1978; Offutt, 1992), may hold for structural faults as well. Thus, although mutation operators have been designed to find simple syntactic faults, the coupling effect results in complex faults being linked to simple ones, and hence in their being discovered.

The results of finding the dataflow and mutation adequacy of the fault-detecting test sets reveal some interesting facts. The second through fourth columns in Table 3 show the all-nodes, all-edges, and all-uses

<table>
<thead>
<tr>
<th>Program</th>
<th>All-Nodes</th>
<th>All-Edges</th>
<th>All-Uses</th>
<th>Adeq Set</th>
<th>Fseed Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>bisect</td>
<td>92.31</td>
<td>82.35</td>
<td>93.48</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>bub</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>cal</td>
<td>100.00</td>
<td>80.00</td>
<td>90.56</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>euclid</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
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<td>97.36</td>
<td>97.30</td>
<td>1</td>
<td>5</td>
</tr>
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<td>100.00</td>
<td>100.00</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
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<td>64.28</td>
<td>74.93</td>
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<td>7</td>
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<tr>
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<td>66.67</td>
<td>78.78</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
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<td>100.00</td>
<td>100.00</td>
<td>2</td>
<td>3</td>
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<td>search</td>
<td>92.85</td>
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<td>90.91</td>
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<td>4</td>
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<td>53.84</td>
<td>68.42</td>
<td>56.81</td>
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<td>10</td>
</tr>
</tbody>
</table>
### Table 4. Mutation Adequacy Scores of Fault Detecting Test Sets

<table>
<thead>
<tr>
<th>Program</th>
<th>All</th>
<th>Score</th>
<th>cca</th>
<th>Score</th>
<th>pda</th>
<th>Score</th>
<th>sal</th>
<th>Score</th>
<th>Adeq Set</th>
<th>Fseed Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>bisect</td>
<td>511</td>
<td>89.4</td>
<td>203</td>
<td>95.4</td>
<td>195</td>
<td>75.9</td>
<td>23</td>
<td>100.0</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>bub</td>
<td>338</td>
<td>23.4</td>
<td>189</td>
<td>30.4</td>
<td>119</td>
<td>7.7</td>
<td>30</td>
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<td>8</td>
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<td>89.4</td>
<td>272</td>
<td>86.1</td>
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<td>91.8</td>
<td>47</td>
<td>7</td>
</tr>
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<td>euclid</td>
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<td>97.7</td>
<td>98</td>
<td>96.8</td>
<td>72</td>
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The adequacy of the fault-detecting test sets. For nine out of 12 subject programs, the fault-detecting test sets were more than 90% dataflow adequate. For four of these nine programs, the fault-detecting test sets were 100% dataflow adequate. The two subject programs for which the fault-detecting test sets were poorly dataflow adequate were mid and tritype. An inspection of the fault types seeded in the third through sixth columns of Table 2 reveals that the faults seeded for mid and tritype are not well distributed: there are no Transposition Between Regions or Transposition Within Region type of faults. Thus, there may be a relation between types of faults seeded and dataflow adequacy of test sets that expose these faults. The dataflow adequacy scores for newton show that the fault-detecting test set was only about 80% all-uses adequate, although Table 2 shows that newton had a good distribution of seeded faults. This anomaly might be due to the specific test sets that were selected for newton. Such anomalies can be resolved by increasing the number of subject programs and the size of the programs seeded with faults. Columns 5 and 6 in Table 3 show that the fault-detecting test sets do not provide an improvement in test set size, because the adequate test sets satisfying the all-uses dataflow criterion are small.

The third column of Table 4 (Score) shows the overall mutation adequacy scores for the fault-detecting test sets. For half of the subject programs, the fault-detecting test sets at least 89% mutation adequate. These subject programs were euclid, search, insert, bisect, cal, and find. These programs cover a range of sizes and numbers of mutants; thus, the adequacy results for the fault-detecting test sets are important because they show that we can construct nearly mutation adequate test sets that are also 100% structural fault-detecting, using a small number of tests. For comparison, Table 4 shows the sizes of the (100%) mutation adequate test sets (in column Adeq Set) and the sizes of the fault-detecting test sets (in column Fseed Set). Comparing these two test sets indicates that it may be possible to get a good mutation adequacy with small test sets. For program find, the fault detecting test set consisting of eight tests is nearly 100% mutation adequate, compared to a 100% mutation adequate test set with 13 tests. More interesting, is program cal for which the mutation-adequate test set is very large (47 tests), yet the fault-detecting 90% mutation adequate test set is small (seven tests). The results for bisect are similar. This raises the issue of whether it is acceptable to have small (and hence cheap) nearly-mutation-adequate test sets, that are 100% effective in finding structural faults. We can also consider building small fault-detecting test sets and adding tests to kill certain classes of mutants, thus streamlining the process of selecting mutation adequate test sets.

For information on the mutation adequacy with respect to mutant superclasses, of the fault-detecting test sets, consider the fourth through ninth columns in Table 4. The distribution of mutants in the three mutant superclasses is shown here, along with the percentage of mutants of each class that are killed. It appears that our fault-detecting test sets target the sal type mutants, as in most cases, the fault-detecting test sets are more than 90% adequate for the sal mutant class. The pda class of mutants is least affected by the fault-detecting test sets. For the programs: quad, secant, and newton, the fault-detecting test sets were only between 75% and 80% mutation adequate; the sixth column shows that the percentage of pda mutants in this class was high, which is logical because these programs consist primarily of numerical computation statements. Fault-detecting test sets for the programs tritype and mid are poorly mutation adequate, which might be due to the fact that these programs had a very large number of branches and
hence pda type mutants. The fault-detecting test set for bub had the least mutation adequacy: only 23%. Table 4 indicates that there is nothing exceptional about the mutant distribution for bub. The low mutation score might be due to the specific test set selected.

Despite this variation in dataflow and mutation adequacy scores, and the recognized need for extended experimentation, the results of the conducted experiments clearly show that it is feasible to use the structural fault seeder in conjunction with established testing methods, for many applications.

6. RELATED WORK

Howden (1976) categorized faults as domain and computation faults. In his classification, domain faults were further categorized as missing path or path selection faults, and path selection faults were categorized as predicate faults or assignment faults. Zeil (1989) later detailed Howden's categorization. We have extended the domain/computation fault categorization so that it can be easily translated to a well-defined program representation and hence, automated. Basili and Selby (1987) classified faults according to two schemes. The first scheme separates faults of commission from faults of omission, and the second scheme partitions faults into six classes: initialization, computation, control, interface, data, and cosmetic. This scheme does not characterize faults according to a program representation that can be used to automate the process of fault classification and fault seeding. The authors state that the fault categorization for their experimental programs was based on a "consistent interpretation" of the faults and that it is possible for another analyst to categorize the faults in a given program differently.

DeMillo and Mathur (1991) presented a fault categorization scheme based on their investigation of Knuth's Tex error log. According to their categorization, faults are "simple" or "complex." They defined simple faults as those that are modeled by mutation operators. Complex faults, under this classification, consist of the following types: missing code, incorrect placement, incorrect algorithm, and miscellaneous. Simple faults are, by definition, easy to model and reproduce (by mutation operators), but the modeling of complex faults was not dealt with in this work. Our fault categorization method provides a clear distinction between statement and structural faults, where statement faults are modeled as first-order or multi-order mutations, or are interface faults.

Mutation analysis has been applied to several languages, and several tools have been developed to implement mutation analysis systems. The Mothra system (DeMillo et al., 1988; DeMillo and Offutt, 1991), was developed for Fortran-77. Mothra uses a set of mutant operators, described by King and Offutt (1991), that were based on earlier mutation systems (St. Andre, 1979; Budd et al., 1980).

More recent efforts have focused on mutation systems for the C language. Agrawal (1989) describes a set of mutant operators for C, which we henceforth call the Purdue C operators. To date, there are two publicized systems that use these operators. Delamaro et al. developed teletype (Delamaro, 1995; Delamaro et al., 1993), and Untch developed TUMS (Untch, 1995; Untch et al., 1993) to implement the schema-based execution model (Untch et al., 1993). The Pisces system (Voas et al., 1991) also uses mutation to assess testability and to perform weak mutation (Howden, 1982). The Pisces system is partially based on the Purdue operators, and it is, to date, the only commercial tool that is based on mutation.

Offutt et al. (1996) defined a set of mutant operators for the Ada language. These operators are loosely based on the Purdue C operators, but differ in terms of the language feature and the modifications made to the C operators to fix several problems and inconsistencies with the C operators.\(^8\)

There is some overlap between our fault classification and the C operators. Our missing path fault category is similar to the Fortran-77 operator Statement Deletion (SDL), the C operator Statement deletion (SSDL), and the Ada operator Statement-Replace with NULL (SRN), except that ours removes the entire subpath, whereas the mutation operators delete one statement at a time. Our incorrect variable used fault is modeled by the various variable replacement operators in the mutation operators. Our incorrect expression faults are similar to the mutation operators that mutate expressions, except that ours can introduce more than one incorrect operator. Some of the transposition between regions faults will be modeled by the C operator Move brace up or down (SMVB), and the Ada operator END shift (SES), which moves end markers of compound statements up or down. However, most of the transposition between regions faults transformations will create more complicated faults. Finally, the transposition within region fault is not related to any operator for Fortran-77, C, or Ada.

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\(^8\) Untch suggested some of these inconsistencies.
Perhaps the biggest difference between our fault seeder and mutation systems is based on the semantic fault model summarized earlier. Offutt and Hayes (1996) point out a key difference between fault seeding and mutation analysis. When fault seeding, we want faults that approximate natural faults as closely as possible; by exhibiting a distribution of semantic fault sizes that matches the distribution of natural faults. Mutation, however, may not want a similar distribution of semantic fault size. Using faults that have smaller semantic size may lead to stronger tests.

7. CONCLUSIONS AND FUTURE WORK

In this project we used the PDG as the basis for a fault-classification scheme, and applied this scheme in building an automated fault-seeding tool. Our classification categorized faults on the basis of transformations made on the CDS and the DDS to create the PDG for the faulty program. The two broad categories of faults identified are structural (macro-level) faults and statement (micro-level) faults. Structural faults can be DDS-structural faults or CDS-structural faults. We used our fault-seeder tool to perform structural fault transformations on the PDG to create faulty versions of a given program.

We conducted a case study using the fault-seeder system, and our results indicate the possibility of various applications. The primary application of such a fault seeder is to help investigate effectiveness of testing methods, and address issues related to cost and efficiency of testing methods. We can use the fault seeder to predict the fault distribution of software: instead of making actual fault transformations, we can output the number of faults of each type that are possible, and use the appropriate testing technique to test the software. Also, we could use the fault seeder to make mutation testing more cost-efficient in the number of tests. We can do this by constructing structural fault-detecting test sets that are almost mutation adequate, and adding test cases to kill certain classes of mutants. Finally, we can build a test-case generator that generates structural fault detecting tests, using information at the point of transformation in the PDG.

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REFERENCES


