eXpress: Guided Path Exploration for Regression Test Generation

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ABSTRACT

Regression test generation aims at generating a test suite that can detect behavioral differences between the original and the new versions of a program. Regression test generation can be automated by using Dynamic Symbolic Execution (DSE), a state-of-the-art test generation technique, to generate a test suite achieving high structural coverage. DSE explores paths in the program to achieve high structural coverage, and exploration of all these paths can often be expensive. However, if our aim is to detect behavioral differences between two versions of a program, we do not need to explore all these paths in the program as not all these paths are relevant for detecting behavioral differences. In this paper, we propose an approach on guided path exploration that avoids exploring irrelevant paths in terms of detecting behavioral differences such that behavioral differences are more likely to be detected earlier in path exploration. Experimental results on 27 versions of two programs show that our approach requires about 54.6% fewer runs (i.e., explored paths) on average (maximum 77.6%) to cause the execution of a changed region and 45% fewer runs on average (maximum 73.8%) to cause program-state differences after its execution than exploration without guidance.

1. INTRODUCTION

Regression test generation aims at generating a test suite that can detect behavioral differences between the original and the new versions of a program. A behavioral difference between two versions of a program can be reflected by the difference between the observable outputs produced by the execution of the same test (referred to as a difference-exposing test) on the two versions. Developers can inspect these behavioral differences to determine whether they are intended or unintended (i.e., regression faults).

Regression test generation can be automated by using Dynamic Symbolic Execution (DSE) [11, 20, 4], a state-of-the-art test generation technique, to generate a test suite achieving high structural coverage. DSE explores paths in a program to achieve high structural coverage, and exploration of all these paths can often be expensive. However, if our aim is to detect behavioral differences between two versions of a program, we do not need to explore all these paths in the program as not all these paths are relevant for detecting behavioral differences.

To formally investigate irrelevant paths for exposing behavioral differences, we adopt the Propagation, Infection, and Execution (PIE) model [25] of error propagation. According to the PIE model, a fault can be detected by a test if a faulty statement is executed (E), the execution of the faulty statement infects the state (I), and the infected state (i.e., error) propagates to an observable output (P). A change in the new version of a program can be treated as a fault and then the PIE model is applicable for effect propagation of the change. Many paths in a program often cannot help in satisfying any of the conditions P, I, or E of the PIE model.

In this paper, we present an approach[1] (and its implementation called `eXpress`) that uses DSE to detect behavioral differences based on the notion of the PIE model.

Our approach first determines all the branches (in the program under test) that cannot help in achieving any of the conditions E and I of the PIE model in terms of the changes in the program. To make test generation efficient, we develop a new search strategy for DSE to avoid exploring these irrelevant branches (including which can lead to an irrelevant path[2]). In particular, our approach guides DSE to avoid from flipping branching nodes, which on flipping execute some irrelevant branch. A branching node in the execution tree of a program is an instance of a conditional statement in the source code. A branching node consists of two sides (or more than two sides for a `switch` statement): the true branch and the false branch. Flipping a branching node is flipping the execution of the program from the true (or false) branch of the branching node to the false (or true) branch. Flipping a branching node representing a switch statement is flipping the execution of the current branch to another unexplored branch.

This paper makes the following major contributions:

- **Approach.** We propose an approach that uses DSE for efficient generation of regression unit tests. To the best of our knowledge, ours is the first approach that guides path exploration specifically for regression test generation.

- **Implementation.** We have implemented our approach in a tool `eXpress`, an extension for Pex [23], an automated struc-

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[1]An earlier version of this work [22] is described in a four-page paper that will appear in the NIER track of ICSE 2009. This version significantly extends the previous work in the following major ways. First, in this paper, we develop techniques for efficiently finding irrelevant branches that cannot execute any change. Second, we automate our approach by developing a tool called `eXpress`. Third, we conduct more extensive experiments to evaluate our approach.

[2]An irrelevant path is a path that cannot help in achieving P, I, and E of the PIE model.

```
      static public int testMe(int x, int[]  y){
1         int j=1;
2         if(x==90){
3            for(int i=0; i< y.Length; i++){
4               if(y[i] == 15)
5                  x++;
6               if(y[i] == 16)
7                  j=2;
8               if(y[i] == 25)
9                  return x;
10              if(x == 110)
11                 x = j+2; //x = 2*j+1
12              if(x>110)
13                 return x;
14           }
15        }
16        return x;
      }
```

Figure 1: An example program

tural testing tool for .NET developed at Microsoft Research. Pex has been previously used internally at Microsoft to test core components of the .NET architecture and has found serious bugs [23]. The current Pex has been downloaded by thousands of times in industry. Some parts of Pex may be integrated to Microsoft Visual Studio 2010, benefiting an enormous number of developers in industry. `eXpress` efficiently generates regression tests given an original and new version of a software program. The generated tests on execution detect behavioral differences (if any exist) between the two versions.

- **Evaluation.** We have conducted experiments on 27 versions of two programs. Experimental results show that our approach requires about 54.6% fewer runs (i.e., explored paths) on average (maximum 77.6%) to cause the execution of a changed region and 45% fewer runs on average (maximum 73.8%) to cause program-state differences after its execution than exploration without guidance.

The rest of the paper is organized as follows. Section 2 presents an example to illustrate our approach. Section 3 presents our approach and the major components involved in the approach. Section 4 presents the evaluation results. Section 5 discusses the threats to validity of the evaluation results. Section 6 discusses related work. Section 7 discusses research issues and future work, and Section 8 concludes.

2. EXAMPLE

In this section, we illustrate the `eXpress` approach with an example. `eXpress` takes as input two versions of a program and produces as output a regression test suite. The test suite on execution detects behavioral differences (if any exist) between the two versions of program under test. Although `eXpress` analyzes assembly code of C# programs, in this section, we illustrate the `eXpress` approach using program source code.

Consider the example in Figure 1. Suppose that the statement at Line 11 of `testMe` has been modified resulting in the one shown in the comment at Line 11. The `Difference Finder` component of `eXpress` compares the original and the new versions of the program under test to find differences between each corresponding method of the two program versions. For the program in Figure 1, `Difference Finder` detects that the statement at Line 11 is changed in the new version. The `Graph Builder` component of `eXpress` then builds a Control-Flow Graph (CFG) of the new

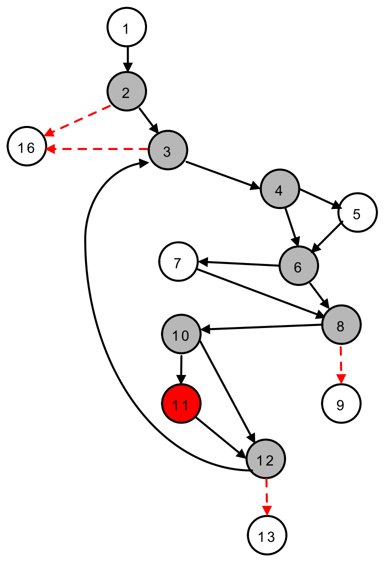

Figure 2: Control-Flow Graph for the program in Figure 1

version of the program under test and marks the changed vertices in the graph. Figure 2 shows the CFG of the example program in Figure 1. The labels of vertices in the CFG show the corresponding line numbers in Figure 1. The red (dark) vertex shows the changed statement at Line 11. The `Graph Traverser` component traverses the CFG to find all the branches[3] b in a program such that if b is taken, the program execution cannot reach the dark vertex at Line 11. On traversing the CFG in Figure 2, the `Graph Traversal` detects that taking the branches $< 2, 16 >$, $< 3, 16 >$, $< 8, 9 >$, and $< 12, 13 >$ (dotted/dark red edges in Figure 2), the program execution cannot the vertex at Line 11. Since after taking these branches, the execution cannot reach the changed statement at Line 11, the execution of these branches cannot help in executing the statement at Line 11; behavioral differences between two versions of the program cannot be detected without executing the changed statement at Line 11. Hence, these branches are not explored by the `Dynamic Test Generator` component of `eXpress` while generating regression tests for the program under test.

The `Instrumenter` component transforms the two versions of the program code such that the transformed program code is amenable to regression testing. In particular, the `Instrumenter` component instruments both versions of the program under test. The instrumentation allows us to compare the internal behavior of running the same generated test on the two versions.

Figure 3 shows the code of `testMe`'s new version after instrumentation. The `Instrumenter` component inserts a statement (Line 12 in Figure 3) just after any changed statement (Line 11 in Figure 1). The instrumented statement allows us to store the current value of `x` in a particular run (i.e., an explored path) of DSE. In particular, this statement results in an assertion `PexAssert.IsTrue("uniqueName", x == currentX)`[4] in the generated test, where `currentX` is the value of x at Line 12 in the new version of the program. One such assertion is generated by Pex each time the statement is executed in the loop. Hence, if the loop containing the changed statement executes 20 times, 20 such assertions will be added to the test generated by Pex. The generated test can be executed on the original version of `testMe` to compare program

[3]A branch is an outgoing edge of a branching node

[4]`PexAssert` is an API class provided by Pex.

```
      public boolean testMe(int x, int[]  y){
            ...
10          if(x == 110){
11              x = 2*j+1;
12              PexStore.ValueForValidation("uniqueName", x);
13          }
            ...
   }
```

Figure 3: Instrumented example program after instrumentation

states at Line 12 after the execution of the changed statement with the ones captured in the execution of the new version.

If there are multiple changed statements in the program, our approach first finds multiple regions each of which contains nearby changed statements in the program. We refer to each of such regions as a changed region in the rest of the paper. Our approach finds all the variables and fields that are identified as defined in a changed region and inserts statements (such as the statement at Line 12 of Figure 3) to log the value of each defined variable or field in the changed region. If a defined variable is a non-primitive type, such a statement enables to compare the object graphs reachable from the logged values to compare program states. The `Dynamic Test Generator` component of `eXpress` then performs DSE on the instrumented new version of the program to generate regression tests.

`eXpress` performs DSE on the instrumented new version of the program. After each run of DSE, `eXpress` executes the generated test on the instrumented original version (in the same way as instrumentation of the new version) to check whether the program state is infected after the execution of a changed region. The instrumentation enables us to perform only one instance of DSE on the new version instead of performing two instances of DSE: one on the original and the other on the new program version. Performing two instances of DSE can be technically challenging since we have to perform the two DSE instances in a controlled manner such that both versions are executed with the same input and the execution trace is monitored for both the versions by a common exploration strategy to decide which branching node to flip next in the two versions.

The `Dynamic Test Generator` component of `eXpress` uses Dynamic Symbolic Execution (DSE) to generate tests for the new version. DSE iteratively generates test inputs to cover various feasible paths in the program under test. In particular, DSE flips some branching node from a previous execution to generate a test input for covering a new path. The node to be flipped is decided by a search strategy (also called exploration starategy) such as depth-first search. `Dynamic Test Generator` implements a search strategy for Pex [23] to efficiently find behavioral differences between two versions of a program.

To cover the changed statement at Line 11, DSE needs inputs $x = 90$ and the array y of length greater than 20 where at least 20 elements of y have a value 15 and no element has a value 25. To generate the input, DSE needs to execute the loop at least 20 times. In each iteration DSE has the choice of flipping branching nodes at Lines 4, 6, 8, 10, 12, a search space of 2^{100} paths (considering a loop bound of 20).

To reduce the branch search space of DSE, the `Dynamic Test Generator` component adopts the PIE model [25] of error propagation described in Section 1. In particular, the `Dynamic Test Generator` prunes all the following branches from the search space of DSE.

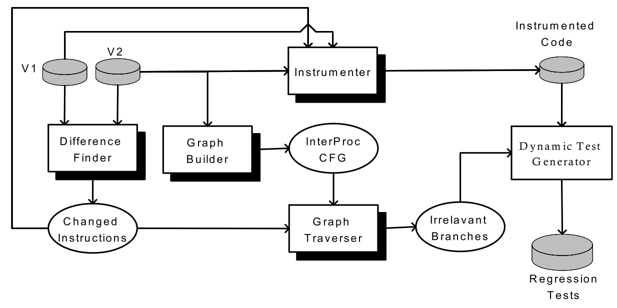

Figure 4: Overview of `eXpress`

- **Branches not satisfying E**. The branches $< 2, 16 >$, $< 3, 16 >$, $< 8, 9 >$, and $< 12, 13 >$ found to be irrelevant by the `Graph Traverser` component cannot help in executing the changed statement at Line 11. Hence, these branches are not explored by the `Dynamic Test Generator` component.

- **Branches not satisfying I**. Suppose that we cover the changed statement at Line 11 in Figure 1 using inputs $x = 90$ and the array y of length 20 where each element of y has a value 15. The execution takes a path P executing the loop 20 times, assigning the variable x to 110 and eventually covering the changed statement at Line 11 . However, the program state after the execution of changed statement is not infected since after the first execution of the changed statement, the value of x is 3 in both versions. In such situations, the branching nodes in the execution path that are after the last instance of the changed node are not explored. For the example, the branch $< 12, 3 >$ is pruned from exploration.

3. APPROACH

Figure 4 shows the overview of `eXpress`. `eXpress` takes as input the assembly code of two versions $v1$ (original) and $v2$ (new) of the program under test. In addition, `eXpress` takes as input, the name and signature of a parameterized unit test (PUT)[5] [24]; such a PUT serves as a test driver for path exploration.

The `Difference Finder` component of `eXpress` finds the set of differences between each of the corresponding method pair in the two versions of program. The `Graph Builder` component builds a partial inter-procedural graph G with the input PUT as the starting method. The `Graph Traversal` component traverses the graph to find all the branches B that need not be explored for executing the changed regions (found by the `Graph Traverser`). The `Dynamic Test Generator` then generates tests for the input PUT, pruning from its search strategy the branches B. We next discuss in detail the major components in `eXpress`.

3.1 Difference Finder

The `Difference Finder` component takes the two versions $v1$ and $v2$ as input and analyzes the two versions to find pairs $< M_{i1}, M_{i2} >$ of corresponding methods in $v1$ and $v2$, where M_{i1} is a method in $v1$ and M_{i2} is a method in $v2$. A method M is defined as a triple $< FQN, Sig, I >$, where FQN is the fully

[5]A PUT is a test method with parameters. A test generation tool (such as Pex) can generate values for the parameters to explore different feasible paths in the program under test.

qualified name[6] of the method, Sig is the signature[7] of the method, and I is the list of assembly instructions in the method body. Two methods $< M_{i1}, M_{i2} >$ form a corresponding pair if the two methods M_{i1} and M_{i2} have the same FQN and Sig. Currently our approach considers as different methods the methods that have undergone `Rename Method` or `Change Method Signature` refactoring. A refactoring detection tool [6] can be used to find such corresponding methods. For each pair $< M_{i1}, M_{i2} >$ of corresponding methods, the `Difference Finder` finds a set of differences Δ_i between the list of instructions $I_{M_{i1}}$ and $I_{M_{i2}}$ in the body of Methods M_{i1} and M_{i2}, respectively. Δ_i is a set of instructions such that each instruction ι in Δ_i is an instruction in $I_{M_{i2}}$ (or in $I_{M_{i1}}$ for a deleted instruction), and ι is added, modified, or deleted from list $I_{M_{i1}}$ to form $I_{M_{i2}}$.

In the rest of its components, `eXpress` analyzes Version $v2$ of the program while using the differences obtained from the `Difference Finder` component to efficiently generate regression tests. Note that Version $v1$ can also be used instead of $v2$ in path exploration.

3.2 Graph Builder

The `Graph Builder` component makes an inter-procedural control flow graph (CFG) of the program version v_2. The `Graph Builder` component starts the construction of the inter-procedural CFG from the PUT τ provided as input. The inter-procedural CFG is used by the `Graph Traverser` component to find branches (in the graph) via which the execution cannot reach any vertex containing a changed instruction in the graph.

Since a moderate-size software system can contain millions of method calls (including those in its dependent libraries), often the construction of inter-procedural graph is not scalable to real-world software systems. Hence, we build a minimal inter-procedural CFG for which our purpose of finding branches not reachable to some changed region in the program can be served. The pseudo code for building the inter-procedural CFG is shown in Algorithm 1. Initially, the algorithm `InterProceduralCFG` is invoked with the argument as the PUT τ. An intra-procedural CFG g is constructed for the method τ. For each method invocation vertex[8] (invoking Method c) in g, the algorithm `InterProceduralCFG` is invoked recursively with the invoked method c as the argument (Line 22 of Algorithm 1), while adding c to the call stack (Line 21). After the control returns from the recursive call, the method c is removed from the call stack (Line 23) and added to the set of visited methods (Line 24). The inter-procedural graph `cg` (with c as an entry method) resulting from the recursive call at Line 22 is merged with the graph g (Line 25). The algorithm `InterProceduralCFG` is not invoked recursively with c as argument in the following situations:

- c **is in call stack.** If c is already in the call stack, `InterProceduralCFG` is not recursively invoked with c as argument (Lines 5-6). This technique ensures that our approach is not stuck in a loop in method invocations. For example, if method A invokes method B and method B invokes A. Then the construction of inter-procedural graph stops after A is encountered the second time.

- c **is already visited.** If c is already visited, `InterProceduralCFG` is not recursively invoked with c as argument (Lines 23). This technique ensures that we do not have to build the same subgraph again.

- c **is in `ReachableToChangedRegion`.** The set `ReachableToChangedRegion` is populated whenever a changed method[9] is encountered. In particular, if a changed method is encountered, the methods currently in the call stack are added to the set `ReachableToChangedRegion` (Lines 17-19). If c is in `ReachableToChangedRegion`, `InterProceduralCFG` is not recursively invoked with c as argument, while merging CFG of some changed method with g (Line 8-11).

Algorithm 1 $InterProceduralCFG(\tau)$

Input: A test method τ.
Output: The inter-procedural Control Flow Graph (CFG) of the program under test.

```
1:  Graph $g \leftarrow GenerateIntraProceduralCFG(\tau)$
2:  for all Vertex $v \in g.Vertices$ do
3:      if v.Instruction = MethodInvocation then
4:          $c \leftarrow getMethod(v.Instruction)$
5:          if $c \in MethodCallStack$ then
6:              goto Line 2 To avoid loops
7:          end if
8:          if $c \in ReachableToChangedRegion$ then
9:              $g \leftarrow GraphUnion(ChangedMethod, g, v)$
10:             goto Line 2
11:         end if
12:         if $c \in Visited$ then
13:             goto Line 2
14:         end if
15:         if $c \in ChangedMethods$ then
16:             $ChangedMethod \leftarrow c$
17:             for all Method $m \in MethodCallStack$ do
18:                 $ReachableToChangedRegion.Add(m)$
19:             end for
20:         end if
21:         $MethodCallStack.Add(c)$
22:         $cg \leftarrow InterProceduralCFG(c)$
23:         $MethodCallStack.Remove(c)$
24:         $Visited.Add(c)$
25:         $g \leftarrow GraphUnion(cg, g, v)$
26:     end if
27: end for
28: return $g$
```

Since our aim of building the intra-procedural CFG is to find irrelevant branches, those in the graph via which the execution cannot reach any changed instruction, the preceding three techniques help in achieving the aim while reducing the cost of building the inter-procedural CFG. In addition, the size of the inter-procedural CFG is also reduced resulting in reduction in the cost of finding irrelevant branches.

3.3 Graph Traverser

The `Graph Traverser` component takes as input the inter-procedural CFG g constructed by the `Graph Builder` component and a set V of changed vertices in the CFG g. `Graph Traverser` traverses the graph to find a set of branches B, being those via which the execution cannot reach any of the branch in V. A branch b in CFG g is

[6]The fully qualified name of a method m is a combination of the method's name, the name of the class c declaring m, and the name of the namespace containing c.

[7]Signature of a method m is the combination of parameter types of m and the return type of m.

[8]A `method invocation vertex` is a vertex representing a call instruction.

[9]A changed method M_i is a method for which the set $\Delta_i \neq \phi$.

an edge $e =< v_i, v_j >$: $e \in g$, where v_i is a vertex in g with a degree of more that one. The vertex v is referred to as a branching node. The pseudo code for finding the set of branches B is shown in Algorithm 2.

Algorithm 2 $FindUnreachableBranches(g, V)$

```
Input: A Graph $g$ and a set $V$ of vertices in Graph $g$.
Output: A set of branches $B$ in Graph $g$ that do not have a path to
    any vertex $v \in V$.
 1: $Reachable \leftarrow Reachable \cup V$
 2: for all Vertex $v \in g.Vertices$ such that $v.degree > 1$ do
 3:     if $Reachable.Contains(v)$ then
 4:         goto Line 2
 5:     end if
 6:     $\rho \leftarrow FindPathUsingDFS(v, V, Reachable)$
 7:     if $\rho$ is empty then
 8:         for all Vertex $n \in v.OutVertices$ do
 9:             $B \leftarrow B \cup < v, n >$
10:         end for
11:         goto Line 2
12:     end if
13:     for all Vertex $pv \in \rho$ such that $v.degree > 1$ do
14:         $Reachable \leftarrow Reachable \cup pv$
15:     end for
16:     for all Vertex $n \in v.OutVertices$ do
17:         $R \leftarrow R \cup < v, v_j >: v_j \in \rho$
18:         $g \leftarrow g.RemoveEdge(e)$
19:         $\rho \leftarrow FindPathUsingDFS(v, V, Reachable)$
20:         if $\rho$ is empty then
21:             for all Vertex $n \in v.OutVertices$ do
22:                 $B \leftarrow B \cup < v, n >$
23:             end for
24:             $g \leftarrow g.AddEdges(R)$
25:             goto Line 2
26:         end if
27:     end for
28:     $g \leftarrow g.AddEdges(R)$
29: end for
30: return $B$
```

For each Vertex v in g such that $degree(v) > 1$, the `Graph Traverser` performs a depth first search (DFS) from Vertex v (Line 6) to finds a path between v and some vertex $c \in V$ (the pseudo code of DFS is shown in Algorithm 3). If no path is found, all branches $b_i =< v, v_i >$ are added to the set B (Lines 7-10) since none of these branches have a path to any of the vertices in V. If a path ρ is discovered (Lines 16-27 in Algorithm 2) by the DFS, there may still be a branch $b_i =< v, v_i >$ that is not reachable to any vertex $c \in V$. To find such branch, we remove the edge $e_j =< v, v_j >$: $e_j \in \rho$ from the graph and perform DFS again starting from v. We repeat the preceding steps until we either find no path ρ or all the edges from v are removed from the graph. If no path is found, the branches from v containing the remaining vertices are added to the set B (Lines 21-23).

To make the traversal efficient, whenever a path ρ is found, all the vertices $r : degree(r) > 1$ are added to the set of $Reachable$. This technique can help in making the future runs of DFS efficient. Whenever a vertex in the set $Reachable$ is encountered, the DFS is stopped; returning the current path (Lines 3-4 of Algorithm 3).

3.4 Instrumenter

The `Instrumenter` component transforms the two versions of

Algorithm 3 $FindPathUsingDFS(g, v, R)$

```
Input: A Graph $g$, a vertex $v$ in the graph $g$, a set of vertices $R$.
Output: A path $\rho$ in Graph $g$ from Vertex $v$ to Vertex $c \in V$.
 1: $v.Visited \leftarrow true$;
 2: $\rho$.Append(v)
 3: if $v \in R$ then
 4:     return $\rho$
 5: end if
 6: for all Vertex $n$ in v.OutVertices do
 7:     if $n.Visited \neq true$ then
 8:         goto Line 6
 9:     end if
10:     $\rho$.Append(n);
11:     if $n \in R$ then
12:         return $\rho$
13:     end if
14:     $\varrho \leftarrow FindPathUsingDFS(g, n, R)$
15:     if $\varrho$ is not empty then
16:         return $\varrho$
17:     end if
18:     $\rho.Remove(n)$
19: end for
20: $\rho$.Remove(v)
21: return $\phi$
```

the program code such that the transformed program code is amenable to regression testing. In particular, our approach instruments both versions of the program under test. The instrumentation allows us to compare the internal behavior of running the same generated test on the two versions.

The `Instrumenter` component uses Sets Δ_i (differences between method M_{i1} and M_{i2}) produced by the `Difference Finder`. For each changed method pair $< M_{i1}, M_{i2} >$ for which $\Delta_i \neq \phi$, the `Instrumenter` component finds a region δ_i containing all the changed instructions in the program. δ_i is a minimal list of continuous instructions such that all the changed instructions in the method M_i are in the region δ_i. Hence, there can be a maximum of one changed region in one method. At the end of each changed region δ_i, the `Instrumenter` component inserts instructions to save the program state. In particular, the `Instrumenter` inserts the corresponding instructions for `PexStore` statements for each variable (and field) defined in the changed region. The `PexStore` statement for a variable x results in an assertion statement `PexAssert.IsTrue( "uniqueName", x == currentX)` in the generated test, where `currentX` is the value of x at Line 12 in the new version of the example program in Figure 1. The `Dynamic Test Generator` component generates tests for the new version $v2$. Once a test is generated that executes a changed region, the test is executed on Version $v1$ to compare program states after the execution of the changed region with the ones captured in the execution of Version $v2$.

3.5 Dynamic Test Generator

The `Dynamic Test Generator` component performs Dynamic Symbolic Execution (DSE) [5, 13, 11, 20, 4] to generate regression tests for the two given versions of a program. DSE iteratively generates test inputs to cover various feasible paths in the program under test (the new version in our approach). In particular, DSE flips some branching node from a previous execution to generate a test input for covering a new path. The node to be flipped is decided by a search strategy such as depth-first search. The exploration is quite expensive since there are an exponential number of paths with respect to the number of branches in a program. However, the execution of many branches often cannot help in detecting behavioral differences. In other words, covering these branches does not help in satisfying any of the condition E or I in the PIE model described in Section 1. Therefore, we do not flip such branching nodes in our new search strategy for generating test inputs that detect behavioral differences between the two given versions of a program. Recall that, we refer to such branches as irrelevant branches. These branches are found using the `Graph Traversal` component. We next describe the two categories of paths that our approach avoids exploring, and then describe their corresponding branches.

3.5.1 Paths being Pruned

Our approach avoids exploring the following categories of paths:

- **Rationale E: Paths not leading to any changed region.** Paths that cannot reach any changed region (denoted as δ) need not be explored. For example, consider the `testMe` program in Figure 1. The changed statement is at Line 11 (δ). While searching for a path to cover δ, we do not need explore paths containing the `true` branch of the condition at Line 8.

- **Rationale I: Paths not causing any state infection.** Suppose that we cover δ at Line 11 in Figure 1 using inputs `x=90` and the array `y` of length 20 where each element of `y` has a value 15. The execution takes a path P executing the loop 20 times, assigning the variable `x` to 110 and eventually covering δ at Line 11 . However, the program state after the execution of δ is not infected since after the first execution of δ, the value of `x` is 3 in both versions. We need not explore the subpaths after the execution of a changed region that does not cause any state infection if these subpaths do not lead to any other changed region.

3.5.2 Branching Nodes being Pruned

In DSE, path exploration is realized by flipping branching nodes. We next describe two categories of branching nodes that we avoid flipping corresponding to the preceding two categories of paths that we intend to avoid exploring.

- **Category E.** This category contains all the branching nodes whose the other unexplored branch cannot lead to any changed region. These branches are obtained from the `Graph Traversal` component, which traverses the inter-procedural CFG constructed by the `Graph Builder` component.

- **Category I.** If a changed region is executed but the program state is not infected after the execution of the changed region, all the branching nodes after the changed region δ in the current execution path are included in this category. These branches are obtained by inspecting the path P followed in the previous DSE run. Let $P =< b_1, b_2, .., b_c ... b_n >$, where b_i are the branching nodes in the Path P, while b_c is the last instance of branching node containing δ. We do not flip the branching nodes from b_c to b_n in P if the program state is not infected.

4. EVALUATION

We conducted experiments on two programs and their 34 versions (in total) collected from two different sources to assess the effectiveness of `eXpress`. In our evaluation, we try to answer the following research questions:

Table 1: Experimental subjects

Project	Classes	Versions	LOC	Branches
replace	1	32	625	181
Silverlight String-To-PathGeometry Converter	1	2	684	274

- **RQ1.** Can `eXpress` more efficiently execute the changed regions between the two versions of a program than without using `eXpress`?

- **RQ2.** Can `eXpress` more efficiently infect the program states after the execution of changed regions than without using `eXpress`?

- **RQ3.** Can the optimizations used in `Graph Builder` and `Graph Traverser` components of `eXpress` efficiently reduce the time to find irrelevant branches that cannot help in satisfying E of the PIE model?

4.1 Subjects

To answer the research questions, we conducted experiments on two subjects: `replace` and Silverlight String-To-PathGeometry Converter (STPG). `replace` is a program available from the Subject Infrastructure Repository (SIR) [7], while STPG[10] is an open source program hosted by the codeplex website, Microsoft's open source project hosting website[11]. We converted the `replace` program to C# (since the original `replace` is written in C). We then seeded all the 32 faults available at SIR one by one to generate 32 new versions of `replace`. The codeplex website contains snapshots of check-ins in the code repositories for STPG. We collect three different versions of the subject STPG from the three most recent check-ins. We use the main method in `replace` as a PUT [24] for generating tests. For STPG, we use the `Convert(string path)` method as the PUT for generating tests. The method `Convert` is the main conversion method that converts a string path data definition to a `PathGeometry` object.

Table 1 shows the details about the subjects. Column 1 shows the subject name. Column 2 shows the number of classes in the subject. Column 3 shows the number of versions (not including the original version) used in our experiments. Column 4 column shows the number of lines of code in the subject. Column 5 shows the number of branches in the subject program. The experimental subjects and results can be downloaded from our our project web[12].

4.2 Experimental Setup

For `replace`, we find behavioral differences between the original version and each version $v2$ available from the SIR, using `eXpress` and the default search strategy in Pex [23, 30]. For STPG, we find behavioral differences between two successive pairs of the three versions that we collected from the codeplex website. In our experiments, we set max number of runs as 1000 for both Pex and `eXpress`.

To answer RQ1, we compare the number of runs of DSE required by the default search strategy in Pex with the number of runs required by `eXpress` to execute a changed region. To answer RQ2, we compare the number of runs required by the default search strategy in Pex with the number of runs required by `eXpress` to infect

[10]`http://stringtopathgeometry.codeplex.com/`
[11]`http://www.codeplex.com`
[12]`http://ase.csc.ncsu.edu/projects/express`

the program states after the execution of a changed region. To answer RQ3, we compare the time required to find irrelevant branches using eXpress with and and without optimizations.

Currently, we have not automated the steps to prune branches that cannot help in achieving I of PIE model. To simulate the pruning of branches to achieve I, in our experiments, we manually instrument the new version to throw an exception just after the changed regions, if the program state is not infected after the execution of the changed region. If the changed region is located inside a loop, we throw the exception just after the loop. In future work, we plan to automate the pruning of branches that cannot help in satisfying I. The rest of the approach is fully automated and is implemented in a tool called eXpress. We developed eXpress as an extension[13] to Pex [23]. We developed its components to statically find irrelevant branches as a .NET Reflector[14] AddIn.

4.3 Experimental Results

Table 2 shows the experimental results. Column 1 shows the name of the subject. Column 2 shows the version number. For the replace subject, the version number indicates the version in the SIR, while an STPG version is just a serial number assigned by us. Column 3 shows the total number of DSE runs required by the default search strategy in Pex for satisfying E. Column 4 shows the total number of DSE runs required by eXpress for satisfying E. Column 5 shows the percentage reduction in the number of DSE runs by eXpress for achieving E. Column 6 shows the total number of DSE runs required by the default search strategy in Pex for satisfying I. Column 7 shows the total number of DSE runs required by eXpress for satisfying I. Column 8 shows the percentage reduction in the number of DSE runs by eXpress for achieving I. Column 9 shows the time required for eXpress to find irrelevant branches. Here the time includes the elapsed time for finding differences, building inter-procedural CFGs, and traversing the CFGs. Column 10 shows the time required to find irrelevant branches without using optimizations in the Graph Builder and Graph Traverser components. Finally, Column 11 shows the number of irrelevant branches found by eXpress that cannot help in satisfying E of the PIE model.

For the replace subject, among the 32 pairs of versions, the changed regions cannot be executed for 4 of theses versions (Versions 14, 18, 27, and 31) by the default strategy in Pex or by eXpress in 1000 DSE runs. We do not include these versions while calculating the sum of DSE runs for satisfying I and E of the PIE model (in the last row of Table 2). For 3 of the versions (Versions 3, 22 and 32), the changed region was executed but the program state is not infected in 1000 DSE runs. We do not include these versions while calculating the sum of DSE runs for satisfying I of the PIE model (in the last row of Table 2). For 3 of the versions (Versions 12, 13, and 21), the changes are in the fields due to which there are no benefits of using eXpress. We exclude these three versions from the experimental results shown in Table 2. The Version 19 could not be translated to C# due to an invocation of native method in C. We also exclude this version from the experimental results shown in Table 2

As shown in Table 2, eXpress finds around 95 irrelevant branches on average for replace, which is around 61% of the total branches in replace. eXpress find 16 irrelevant branches on average for STPG which is about 6% of the total branches in the program. In general, irrelevant branches are more if changes are towards the beginning of the PUT since there are likely to be more branches in the program that do not have a path to any changed regions. These branches also include the branches whose branching condition is not dependent on the inputs of the program and therefore do not lead to branching conditions during path exploration. Hence, pruning these branches is not helpful in making the DSE efficient.

For all the version pairs of both versions, eXpress takes 1039 DSE runs in total (38.3 on average) to execute the changes in contrast to 2287 DSE runs in total (82.5 on average) taken by the default strategy in Pex to execute the changes. In total, eXpress took 54.6% fewer runs in executing the changes with a maximum of 77.6% for Versions 23 and 24 available in the SIR. For these versions eXpress takes 95 DSE runs in contrast to 425 runs taken by Pex to execute the changed locations.

eXpress takes 1971 DSE runs in total (78.8 on average) to infect program states after executing the changes in contrast to 3581 DSE runs in total (154 on average) taken by the default strategy in Pex to execute the changes. In total, eXpress took 45% fewer runs in executing the changes with a maximum of 73.8% for Version 6 of replace available in the SIR. For this version, eXpress takes 83 DSE runs in contrast to 317 runs taken by Pex to infect the program state after the execution of changed locations.

eXpress takes around 5.7 seconds (on average) to find the irrelevant branches for each version of replace using optimizations. We also observe that the time varies for different versions (between 0.3 to 21.4 seconds) as our optimizations depend on the location of a change. Without using optimizations, eXpress takes 21.8 seconds to find irrelevant branches. For STPG, eXpress takes only 0.7 seconds to find irrelevant branches with optimizations. Without optimizations, eXpress was not able to find irrelevant branches in 30 minutes. We suspect the reason for such a big difference to be that a large number of method invocations are present in the subject as the subject uses a parser to parse the input string. While using optimizations, we do not build redundant parts of the inter procedural graph, making the process of building CFG efficient.

In summary, our evaluation of eXpress answers the following questions that we mentioned at the beginning of this section:

- **RQ1.** On average, eXpress requires 54.6% fewer runs (i.e., explored paths) on average (maximum 77.6%) than the existing search strategy in Pex to execute the changed regions of the 34 versions of our two subjects.
- **RQ2.** On average, eXpress requires *45% fewer runs on average (maximum 73.8%) than the existing search strategy in Pex to infect the program states after the execution of changed regions.
- **RQ3.** Our optimizations in the Graph Builder and Code Traverser components of eXpress reduce the time to find irrelevant branches (that cannot help in satisfying E of the PIE model) by 3.75 times for replace.

5. THREATS TO VALIDITY

The threats to external validity primarily include the degree to which the subject programs, faults, or program changes are representative of true practice. One of our subject replace is taken from the SIR [7]. Most of the faulty versions available for replace at the SIR involve manually seeded faults including one or two lines. The subject has also been used for experiments by evaluating various approaches [3, 26]). The other subject STPG is an open source software program taken codeplex website. The three versions used in our experiments are the three most recent snapshots in the code repository for STPG. The two versions contain changes on regions involving 10 and 15 lines, respectively. These

[13]http://pex.codeplex.com/

[14]http://www.red-gate.com/products/reflector/

Table 2: Experimental Results

		Execution			Infection			Optimization for Finding Irrelevant Branches		
Subject	Version	$E_{\texttt{Pex}}$	$E_{\texttt{eXpress}}$	$E_{Reduction}(\%)$	$I_{\texttt{Pex}}$	$I_{\texttt{eXpress}}$	$I_{Reduction}(\%)$	$T_{optimized}(s)$	$T_{unoptimized}(s)$	Irrelevant
replace	1	7	7	0	16	14	12.5	4	21.2	137
replace	2	7	7	0	79	65	17.7	4	23.5	137
replace	3	28	28	0	-	-	-	0.3	25.6	15
replace	4	28	28	0	133	133	0	0.3	24.3	15
replace	5	240	150	37.5	240	158	34.2	12.9	18.6	137
replace	6	317	83	73.8	317	83	73.8	0.3	21.3	17
replace	7	60	32	46.7	128	58	54.7	11.7	25.6	137
replace	8	60	32	46.7	133	133	0	6.4	25.5	137
replace	9	13	13	0	243	102	58	7	22.2	140
replace	10	13	13	0	152	111	27	7	22.2	140
replace	11	13	13	0	224	138	38.4	7.5	23.5	140
replace	14	-	-	-	-	-	-	-	-	-
replace	15	4	4	0	4	4	0	3.4	18.9	15
replace	16	60	32	46.7	126	123	2.4	3.6	19.9	137
replace	17	15	15	0	15	15	0	6.3	26.3	137
replace	18	-	-	-	-	-	-	-	-	-
replace	20	15	15	0	15	15	0	6.3	26.5	137
replace	22	6	6	0	-	-	-	21.3	29.4	138
replace	23	6	6	0	6	6	0	21.4	29.5	112
replace	24	6	6	0	15	15	0	21.4	29.5	112
replace	25	425	95	77.6	465	132	71.6	0.5	19.1	18
replace	26	425	95	77.6	469	133	71.6	0.5	19.1	18
replace	27	-	-	-	-	-	-	-	-	-
replace	28	60	32	46.7	182	123	32.42	3.6	27.3	137
replace	29	60	32	46.7	182	123	32.42	3.6	27.3	137
replace	30	60	32	46.7	60	32	46.7	3.6	27.1	137
replace	31	-	-	-	-	-	-	-	-	-
replace	32	13	13	0	-	-	-	6.5	20.5	140
STPG	1	141	178	125	127	11.3	28.7	0.7	-	16
STPG	2	200	200	125	128	37.5	36	0.7	-	16
Total		2287	3581	1039	1971	54.6	45	164.8	-	2559

threats could be further reduced by experiments on more subjects. The main threats to internal validity include faults in our tool implementation, faults in Pex that we use to generate tests, and the instrumentation effects that can bias our results. To reduce these threats, we have manually inspected the artifacts (such as control flow graphs, irrelevant branches, and generated tests) for some versions.

6. RELATED WORK

Previous approaches [9, 21] generate regression unit tests achieving high structural coverage on both versions of the class under test. However, these approaches explore all the irrelevant paths, which cannot help in achieving any of the conditions P, I, or E in the PIE model. In contrast, we have developed a new search strategy for DSE to avoid exploring these irrelevant paths.

Santelices et al. [2, 19] use data and control dependence information along with state information gathered through symbolic execution, and provide guidelines for testers to augment an existing regression test suite. Unlike our approach, their approach does not automatically generate tests but provides guidelines for testers to augment an existing test suite. Some existing search strategies [3, 30] guide DSE to effectively achieve high structural coverage in a software system under test. However, these techniques do not specifically target to cover a changed region. In contrast, our approach guides DSE to avoid exploring paths that cannot help in executing a changed region. In addition, our approach avoids exploring paths that cannot help in P or I of the PIE model [25].

Differential symbolic execution [16] determines behavioral differences between two versions of a method (or a program) by comparing their symbolic summaries [10]. Summaries can be computed only for methods amenable to symbolic execution. However, summaries cannot be computed for methods whose behavior is defined in external libraries not amenable to symbolic execution. Our approach still works in practice when these external library methods are present as our approach does not require summaries. In addition, both approaches can be combined using demand-driven-computed summaries [1], which we plan to investigate in future work.

Our previous Orstra approach [27] automatically augments an automatically generated test suite with extra assertions for guarding against regression faults. Orstra first runs the given test suite and collects the return values and receiver-object states after the execution of the methods under test. Based on the collected information, Orstra synthesizes and inserts new assertions in the test suite for asserting against the collected method-return values and receiver object states. However, this approach observes the behavior of the original version to insert assertions in the test suite generated for only the original version. Therefore, the test suite might not include test inputs for which the behavior of a new version differs from the original version.

Li [14] prioritizes source code portions for testing based on dominator analysis. In particular, her approach finds a minimal set of blocks in the program source code, which, if executed, would ensure the execution of all of the blocks in the program. Howritz [12] prioritizes portions of source code for testing based on control and flow dependencies. These two approaches focus on testing in general. In contrast, our approach focuses specifically on regression testing.

Ren et al. develop a change impact analysis tool called Chianti [17]. Chianti uses a test suite to produce an execution trace for two versions of a software system, and then categorizes and decomposes the changes between two versions of a program into different atomic types. Chianti uses only an existing test suite and does not aim to exercise behavioral differences between the two versions of the software system under test. In contrast, the goal of our approach is specifically to expose behavioral differences across versions.

Some existing capture and replay techniques [8, 15, 18] capture the inputs and outputs of the unit under test during system-test execution. These techniques then replay the captured inputs for the unit as less expensive unit tests, and can also check the outputs of the unit against the captured outputs. However, the existing system tests do not necessarily exercise the changed behavior of the program under test. In contrast, our approach generates new tests to specifically find behavioral differences.

7. DISCUSSION

Added/Deleted and Refactored Methods. If a method M is added or deleted from the original program version, `eXpress` does not detect M as a changed region. The change is detected if a method call site is added or deleted from the original program version. If the added or deleted method is never invoked, the behavior of the two versions is the same unless M is an overriding method. We plan to incorporate support for such overriding methods that are added or deleted. Similarly, if a method M is refactored between the two versions, `eXpress` does not detect M as a changed region. However, when a method is refactored, its call sites are changed accordingly (unless the method undergoes `Pull Up` or `Push Down` refactoring). Hence, `eXpress` detects the method containing call sites of M as changed. In our experiments, we considered versions of `replace` in which method signature was changed along with other changes.

Granularity of Changed Region. In our current approach, a changed region is the list of continuous instructions that include all the changed instructions in a method. One method can have only a single changed region. Hence, a changed region can be as big as a method and as small as a single instruction. The granularity of a changed region can be increased to a single method or reduced to single instruction. Changing the granularity to single method M can affect the efficiency of our approach in reducing DSE runs since some of the branches in M that should be considered irrelevant would not be considered irrelevant. In contrast, reducing the granularity to a single instruction makes our approach more efficient in reducing DSE runs. However, the overhead cost of our approach is increased due to state checking at multiple points in the program. In future work, we plan to enhance `eXpress` to allow users to choosse from different levels of granularity.

Original/Modified Program Version. In our current approach, we perform DSE on the new version of a program. We then execute the test (generated after each run) on the new version. We can also perform DSE on the original version instead of the new version. One approach may be effective than the other depending on the types of changes made to the program. In future work, we plan to conduct experiments to compare the effectiveness of the two approaches with respect to the types of changes.

Branch Prioritization. `eXpress` currently prunes branches that cannot help in detecting behavioral differences between the two versions. However, some branches in the program code can be more promising in detecting behavioral differences than others. Branching nodes can be prioritized based on the distance of the branching node to a changed region in the CFG. The distance $d(n1, n2)$ between any two nodes $n1$ and $n2$ in a CFG g is the number of nodes with degree > 1 between $n1$ and $n2$ in the shortest path between $n1$ and $n2$. Hence, the distance between a node b and a changed region Δ is the number of nodes with degree of more than one between b and the node representing the first instruction in Δ. The intuition behind this prioritization is that shorter the distance between the branching node and δ, it is likely to be easier to generate inputs to cause the execution of the changed region δ. This kind of branch prioritization is used by Burnim and Sen [3]. We can also prioritize branching nodes based on the probability to cause infection and to propagate the infection to an observable output. Moreover, we can prioritize branches based on data dependence from a changed region.

Pruning of Branches for Propagation. Currently, `eXpress` prunes branches that cannot help satisfy E or I of the PIE model for change propagation. In future work, we plan to prune more categories of branches that cannot help in Propagation (P). Consider that a changed region is executed and the program state is infected after the execution of the changed region; however, the infection is not propagated to any observable output. Let χ be the last location in the execution path such that the program state is infected before the execution of χ but not infected after its execution. χ can be determined by comparing the value spectra [28, 29] obtained by executing the test on both versions of the program. This category contains all the branching nodes after the execution of χ. These branches can be obtained by inspecting the path P followed in the previous DSE run. Let $P =< b_1, b_2, .., b_\chi ... b_n >$, where b_i are the branching nodes in the Path P, while b_χ is the last instance of branching node containing χ. We do not flip the branching nodes from b_χ to b_n in P until if the program state is not propagated after the execution of χ.

Changes in Fields. Currently, `eXpress` does not detect changes in program code that is outside method bodies. For example, if the declaration of a field f is modified, `eXpress` cannot help in reducing DSE runs to detect behavioral differences that may be introduced in the program due to the change. In such situations, the source code can be searched to find the references of f. The corresponding instructions for all these statements referring to f can be considered as changed. If a field is added or deleted, `eXpress` can still be helpful in reducing DSE runs as in the case of added or deleted methods as discussed earlier in this section.

8. CONCLUSION

Regression testing aims at generating tests that detect behavioral differences between two versions of a software program. Dynamic symbolic execution (DSE) can be used to generate such difference exposing tests. DSE explores paths in the program to achieve high structural coverage, and exploration of all these paths can often be expensive. However, many of these paths in the program cannot help in detecting behavioral differences in any way. In this paper, we presented an approach and its implementation called `eXpress` for regression test generation using DSE. `eXpress` prunes paths or branches that cannot help in detecting behavioral differences such that behavioral differences are more likely to be detected earlier in path exploration. Experimental results on various versions of programs showed that our approach can efficiently detect behavioral differences than without using our approach.

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