AUTOMATED PENETRATION TESTING FOR PHP WEB APPLICATIONS

A Dissertation
Presented to
The Academic Faculty

By

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The task is...not so much to see what no one has yet seen; but to think what nobody has yet thought, about that which everybody sees.

Erwin Schrödinger

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ABSTRACT

Penetration Testing emerged in the mid-1960s as an approach to exploit vulnerabilities of possible attacks of a software application by nefarious users. Traditional penetration testing is done manually, which is not only inefficient but also unstable in terms of reliability. In the recent decade, multiple automated penetration testing approaches have been proposed, including automatically test inputs generation based on genetic algorithms and neural networks learning. However, these black-box testing methods only have limited accuracy, and usually require a large number of data to train the agents before they can be used to do actual tests. To address this issue, we present a novel approach in which program static analysis is exploited. The proposed penetration testing system is able to not only estimate HTTP request data more precisely, but also discover dynamic interfaces exposed by the web applications. This research is focused on PHP web applications only.

CHAPTER 1
INTRODUCTION

As the scale of enterprise web applications grows rapidly, finding an effective way for testing site reliability is becoming increasingly important. As a widely-used testing technique, penetration testing is able to exploit the vulnerabilities of a web application back-end by simulating sending HTTP requests from the client side. Since penetration testing is used to test as many parts of an application as possible, comprehensiveness is the most important factor in performing penetration testing. An ideal penetration test is the one that generates HTTP requests which cover 100% of the server-side code.

Traditionally, penetration tests are performed as black-box testing, which views the program to be tested as a ”black box” whose implementation detail is unknown to the tester. Black-box testing allows the tester to focus on only the input and the output generated by the program; however, since the inner functionality of the program is unknown, it is difficult for the tester to generate a comprehensive test suite that guarantees 100% back-end code coverage. In traditional manual penetration testing, a tester could only apply ”educated guesses” when creating test requests. Some recent research proposed automated penetration testing using AI techniques such as genetic algorithm [1] and neural network models [2]. Although these automated approaches showed promising results in some scenarios, by nature they are still black-box testing, only improving the accuracy of ”educated guess” by inferring from the statistical analysis results generated from the differences between expected outputs and actual outputs.

The lack of comprehensiveness and efficiency in black-box penetration testing prompted us to propose a new approach that performs white-box testing, during which tests are performed by looking at the implementation details in the source code of the program itself. In our implementation, both the interfaces that an application exposes and all the request data that is processed in the back-end can be inferred from static analysis results. The test suite goes through the program and checks at what positions each HTTP request variable is used. If some other variables are involved at any of the positions, then the program will use the result of data flow analysis to construct the exact value for such variables, which are also the possible values that the HTTP request variable could take. The test suite uses a library developed by Christensen, Møller, and Schwartzbach [3] to construct an automaton that represents possible string values during string variable construction.

As another major part of penetration testing, interface discovering was traditionally done by doing web crawling. However, since modern web frontend is becoming increasingly dynamic, only extracting information from the client-side HTML pages does not guarantee enough interfaces are discovered. In 2007, Halfond and Orso [4] proposed a novel approach for discovering web application interfaces using static analysis. Such technique showed promising results for finding and grouping dynamic interfaces that are not exposed directly by the front-end. In this project, the same algorithms proposed by Halfond et al. is applied for doing interfaces discovery, but is targeted for PHP web applications.

CHAPTER 2
TECHNICAL APPROACH

2.1 Background

2.1.1 Data-flow Analysis

In compiler theory, data-flow analysis is a technique for gathering information about the possible set of values calculated at various points in a computer program. The basis for performing data-flow analysis is control flow graph (CFG), which is used to determine those parts of the program to which a particular value assigned to a variable might propagate. In our particular case, we used reaching-definition for each instruction to represent the data flow information. Two techniques applied for performing reaching-definition analysis are *Liveness Analysis* and *Reaching-Def Analysis*.

Control Flow Graph (CFG) is a graph representation of all the paths that a computer program might be traversed through during its execution. In a control flow graph, each node represents a basic block - a sequential piece of a program that does not include jumps or jump targets, while the directed edges represent jumps in the program. Figure 2.1 is the complete control flow graph constructed for an example function t3f1. Each circle represents a basic block (first number in the circle denotes its line number), and the black edges represent the possible jumps that the program can take during execution. It is worth noting that the while loop in t3f1 includes a condition check at line 4, which can be reached from either line 4 (before loop starts) or from line 13 (after last instruction in the loop is finished). Therefore in the CFG there are two nodes representing line 5, with one coming from line 4 and another coming from line 13.

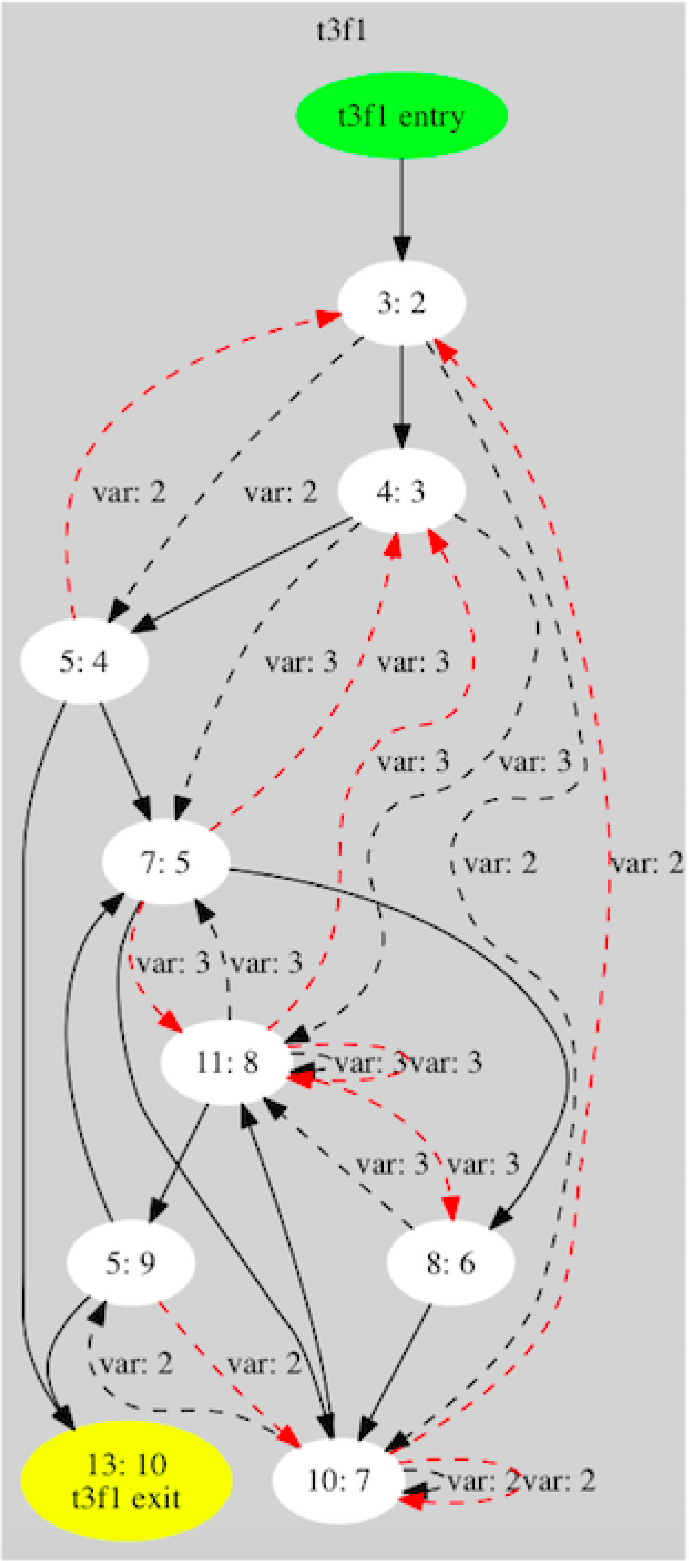


Figure 2.1: Control Flow Graph for Function t3f1

```
 1 <?php
 2 function t3f1($c, $d) {
 3    $a = 0;
 4    $b = 0;
 5    while($a <= 5)
 6    {
 7       if ($b > 5) {
 8          $b = 5;
 9       }
10       $a = $a + 1;
11       $b = $b + 2;
12    }
13 }
14 ?>
```

As one of the two techniques used for performing reaching-definition analysis, liveness analysis is to calculate, at instruction level, the variables that may be potentially read before their next write, that is, the variables that are live at the exit from each program point. In the given example, variable b is first defined at line 4; it is also defined at line 8 and 11 in the main loop. Therefore, var b is said to be ”alive” from line 4 to line 8, and from line 11 back to line 8. Given liveness analysis output, def-use chains can be constructed for each variable. The DU chain represents the exact places where a variable definition is later used in other instructions. The DU chains in t3f1 are shown as black dotted edges in Figure 2.1.

To the contrary of liveness analysis, reaching-def analysis calculates the possible definition instructions for a given use variable. Reaching-def analysis helps generate use-def chains for each variable used in a program. The UD chains for variables in t3f1 are shown as red dotted edges in Figure 2.1.

2.1.2 HipHop VM and HipHop Bytecode

HipHop Virtual Machine (HHVM) is an open-source virtual machine based on just-in-time (JIT) compilation that serves as an execution engine for the PHP and Hack programming languages. During HHVM execution, PHP or Hack code is first transformed into an intermediate code format, HipHip bytecode (HHBC), for the consumption by JIT compilers [5]. We found HHBC an ideal code representation for PHP programs, because unlike PHP native statements, which only describes *what* actions to perform, HHBC is consisted by instructions, which tell the machine *how* those actions should be performed. Specifically, declare, load and set operations for variables are explicitly stated in HHBC, which makes it easy to build CFGs and perform data analysis. Moreover, HHBC introduces the concept of ”execution stack”, a stack space upon which data are processed by pushing and popping according to different operations. Such concept could greatly help with the string analysis that we use for testcase generation, which will be discussed in 2.3.1.

2.2 Inter-procedural CFG Construction

Usually during static analysis, an intra-procedural CFG is constructed for each individual function before all intra-procedural CFGs are combined into one inter-procedural CFG (ICFG) that represents the control flow for the entire program. ICFG is a combination of all individual functions and a function call graph (CG), which is a graph representation of function dependencies in a program, in which functions are represented as nodes and function invocations are represented as directed edges. Since one variable defined/used in any function can be used/defined in other functions, extra work needs to be done in order to expand a variable's DU and UD chains in ICFG. Algorithm 1 shows the construction of DU and UD chains in ICFG given individual CFGs and CG.

Algorithm 1 Dataflow Expansion in ICFG

```
Require:
$CG$: call graph of the application program;
$CFGS$: CFGs for all functions in the program
                                                              ▷ main
procedure DATAFLOW EXPANSION
    $visited \leftarrow \emptyset$
    for Each $CFG$ in $CFGS$ do
        for Each instruction $I$ in $CFG$ do
            if $I$ has KILL variable $kv$ then
                COMPLETEDEFUSE($CFG$, $I$, $kv$, $visited$)
            end if
        end for
    end for
    $visited \leftarrow \emptyset$
    for Each $CFG$ in $CFGS$ do
        for Each instruction $I$ in $CFG$ do
            if $I$ has GEN variable $gv$ then
                COMPLETEUSEDEF($CFG$, $I$, $gv$, $visited$)
            end if
        end for
    end for
end procedure
```

```
function COMPLETEDEFUSE($cfg$, $instr$, $var$, $visited$)
    if $instr$ in $visited$ then
        return $instr.duchain$
    end if
    for Each Use $use$ in $instr.duchain$ do
        if $use$ is a function call site then
            Get the callee function $targetfunction$
            Get the function parameter $targetvar$ in $targetfunction$ that corresponds to $use.var$
            Get the instruction $targetInstr$ that initiates $targetvar$ in $targetfunction$
            $newuses \leftarrow$ COMPLETEDEFUSE($targetfunction.CFG$, $targetInstr$, $targetvar$, $visited$)
            $instr.duchain \leftarrow$ ($instr.duchain$ - $use$) $\cup$ $newuses$
        end if
    end for
    $visited \leftarrow visited \cup instr$
    return $instr.duchain$
end function
```

```
function COMPLETEUSEDEF(cfg, instr, var, visited)
    if $instr$ in $visited$ then
        return $instr.udchain$
    end if
    for Each Def $def$ in $instr.udchain$ do
        if $def$ is a function entry site then
            Get all the functions $callerfuncs$ that calls current function
            for Each function $callerfunc$ in $callerfuncs$ do
                Get the function parameter $sourcevar$ in $callerfunc$ that corresponds to $def.var$
                Get the instruction $sourceInstr$ in $callerfunc$ that passes $sourcevar$ to callee stack
                $newdefs \leftarrow$ COMPLETEUSEDEF($callerfunc.CFG$, $sourceInstr$, $sourcevar$, $visited$)
                $instr.udchain \leftarrow$ ($instr.udchain$ - $def$) $\cup$ $newdefs$
            end for
        end if
    end for
    $visited \leftarrow visited \cup instr$
    return $instr.duchain$
end function
```

2.3 Testcase Generation Algorithm

2.3.1 Precise String Analysis for Input Generation

Typically, users interact with a web application through a user interface (e.g., web page) that allows them to enter input data (e.g., into a form) and submit such data to the web application via HTTP request. The data that users enter are mostly in string literal forms (e.g., name, address, email, etc). Therefore, generating appropriate string inputs automatically during penetration testing is of our particular interest.

The most direct and effective approach for generating test string literal inputs is to check what values the input variable is compared with during input validation in the application back-end. Usually after the application receives a request from the client side, it will compare each input field against some specific values or regular expressions, in order to check if the value is valid, or to process data differently according to the given value. For string literal fields, the checker strings/regex are particularly useful, because they provide a good reference for generating our test inputs (the testcase generator only needs to make the input value either match the given value or differ from it). Therefore, in order to generate our test inputs, the fundamental step is to construct the string literals or regular expressions that the inputs are compared with in the application.

Conventional static analysis does not try to get the information of what the value of a variable exactly is. However, in order for our testcase generation tool to construct more plausible input string literals, it is important to estimate the exact value of string literals used to compare with inputs passed into the application. Fortunately, the structure of HipHop Bytecode makes it possible to perform such action. The compiled HHBC for a PHP program models the flow of program execution by using a stack of frames referred to as the ”call stack”. Each call stack maintains an ”evaluation stack”, on which data is pushed or popped based on type of HHBC instruction. By using a stack data structure to model this evaluation stack, along with the data flow analysis results that the earlier phase generates, we can partially simulate the actual program's behavior during execution, which is sufficient for us to construct exact string literal values.

Listing 2.1 shows a simple PHP program that uses a $create\_name$ function to build full names from first and last names. In line 3, first name is first concatenated with a space and then concatenated with last name. Listing 2.2 is the HHBC generated for line 3 after compilation, which shows how the act of concatenation in line 3 is performed by HHVM. HHVM starts the series of actions by declaring a String (a space) (line 152), which is pushed to the evaluation stack; next, HHVM looks for the variable with ID 0 (CGetL2 0 in line 157), and pushes it onto the stack; then, when it comes to the ”Concat” instruction, HHVM takes the top two elements from the stack, append the topmost value (which is the space) to the back of the second topmost value (the variable with ID 0), and pushes the result onto the stack, thus completing the first concatenation. The rest of the HHVM actions are similar to what have happened: HHVM pushes the variable with ID 1 to the stack, pops the top two elements, concatenates them, and finally pushes the result to the stack.

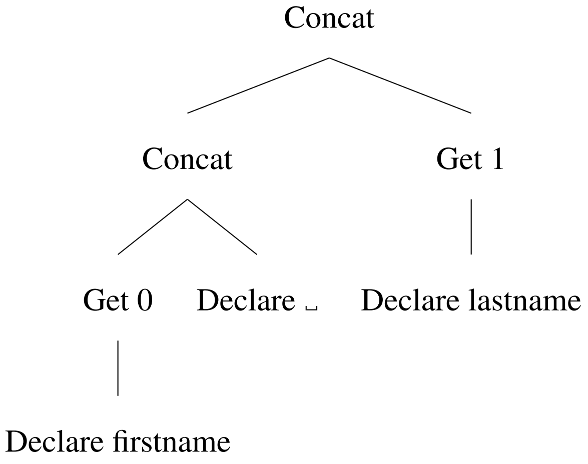
Listing 2.1: Sample PHP Code and Compiled HHBC Snippet

```
1  <?php
2  function create_name($a, $b) {
3    return $a.”␣”.$b;
4  }
5  $firstname1 = ”John”;
6  $lastname1 = ”Doe”;
7  $firstname2 = ”George”;
8  $lastname2 = ”Burdell”;
9  $name1 = ceate_name($firstname1, $lastname1);
10 $name2 = create_name($firstname2, $lastname2);
11 $n = $_POST[”name”];
12 if($n == $name1) {
13   echo ”You␣are␣a␣UGA␣student”;
14 } else if($n == $name2) {
15   echo ”You␣are␣a␣Georgia␣Tech␣student”;
16 } else {
17   echo ”Failed”;
18 }
19 ?>
```

Listing 2.2: HHBC Snippet for line 3

```
  152: String ”␣”
  157: CGetL2 0
  159: Concat
  160: CGetL 1
  162: Concat
  163: RetC
```

Given the fact that HHBC instructions also represent stack operations, we can take advantage of such property to build the string literal by mocking HHVM stack operations. In our implementation, a global stack data structure is maintained by the static analyzer. After each basic block is created, all the instructions in the basic block are simulated to work on the stack. The result is an ActionNode tree. ActionNode is a data structure that represents the specific HHVM ”Action” performed by the given instruction. For example, ”Concat” and ”String” instructions represent ”Concatenation” and ”Declaration” actions respectively. Different type of ActionNode. Essentially each instruction should correspond to an action node and different instruction operators should be represented by distinct action nodes. However, given the large number of PHP string operations, we only implemented ActionNodes for certain commonly used operations (Table 2.2). ActionTree is a hierarchical representation of ActionNode actions upon each other. In the HHBC sample given by Listing 2.2, the ActionNode tree looks like the following:



As shown in the tree diagram above, Concat ActionNode always has two children, while Get ActionNode has one child, and Declare ActionNode has zero. Different ActionNodes have different number of children, depending on their specific actions.

In the last step, static analyzer uses the action trees and a modified Java String Analyzer (JSA) library to construct string literal values. Java String Analyzer (JSA) [4] is a tool that uses static analysis information to predict the possible values of string expressions in Java programs. JSA is consisted of several phases, each transforming the program into a different form. The phases are separated into two parts: The front-end and the back-end. At the front-end, JSA performs Java language specific static analysis and generates a Flow Graph for each string expression; at the back-end, JSA takes Flow Graphs as its input and converts them in to finite-state automata.

Flow Graph is language-independent, and can be constructed directly from data flow analysis(liveness and reaching-def analysis). Therefore, in our implementation, the static analyzer uses Def-Use chains and Use-Def chains along with the action trees to build flow graph for each string expression; the flow graph is then fed into the back-end of JSA library, which will take care the rest of string analysis and generate a finite-state automaton to represent the string expression.

Algorithm 2 Flow Graph Construction Algorithm

```
Require:
  $CG$: Call graph of the application program
  $ICFGS$: Inter-procedural CFG with complete Def-Use and Use-Def chains
                                                                  ▷ main
procedure FLOW GRAPH CONSTRUCTION
    Group functions in $CG$ into Strongly Connected Components $sccGraph$
    Get the topological ordering of SCCs, $sccList$ , in $sccGraph$
    $continue \leftarrow true$
    until continue is $false$ repeat
        for Each SCC $scc$ in $sccList$ do
            for Each Function $function$ in $scc$ do
                $cfg \leftarrow function.cfg$
                for Each BasicBlock $block$ in $cfg.getTopologicalSortedBlocks$ do
                    $success \leftarrow$ STRINGANALYSIS($block$, $ICFG$)
                    if $success$ is $true$ then
                        $continue \leftarrow false$
                    end if
                end for
            end for
        end for
    end until
end procedure
```

```
function stringAnalysis($basicblock$, $ICFG$)
    Build ActionTrees $trees$ from $basicblock$.instructions
    for Each ActionTree $tree$ in $trees$ do
        $success \leftarrow$ buildFlowGraph($tree$.root, $ICFG$)
        if not $success$ then
            return $false$
        end if
    end for
    return $true$
end function
```

```
function buildFlowGraph($ActionNode$, $ICFG$)
    Initialize FlowGraph $flowgraph$
    Initialize FlowGraphNode $fgnode$
    for Each child node $childnode$ of $ActionNode$.children do
        $success \leftarrow$ buildFlowGraph($childnode$, $ICFG$)
        if not $success$ then
            return $false$
        end if
        $flowgraph \leftarrow childenode$.flowgraph
        Add all nodes in $childnoded$.flowgraph to $flowgraph$
    end for
    switch $ActionNode.type$ do
        case $Declare$
            $v \leftarrow ActionNode$.value
            $at \leftarrow v$.getAutomaton
            $fgnode \leftarrow flowgraph$.addInitializationNode($at$)
        case $Get$
            $instr \leftarrow ActionNode$.instr
            $fgnode \leftarrow flowgraph$.addAssignmentNode;
            for Each Definition $def$ in $instr$.usedefchain do
                Get the ActionNode $setNode$ corresponding to $def$
                $setFlowGraph \leftarrow setNode$.flowgraph
                Add all nodes in $setFlowGraph$ to $flowgraph$
                Set Def-Use relationship between $setNode$.fgnode and $fgnode$
            end for
        case $Set$
            ActionNode $toSet \leftarrow ActionNode$.child
            $fgnode \leftarrow flowgraph$.addAssignmentNode($toSet$)
            Set Def-Use relationship between $toSet$ and $fgnode$
        case $Load$                                  ▷ Explained in section 2.3.2
        case $Function$
            $fgnode \leftarrow flowgraph$.ADDASSIGNMENTNODE
            Get called function name $funcName$
            $retCFG \leftarrow ICFG$.GETCFG($funcName$)
            $retBlocks \leftarrow retCFG$.GETRETBLOCKS
            $vars \leftarrow ActionNode$.children
            $varMap \leftarrow$ Associate each variable in $vars$ with its formal parameter in function pointed by $funcName$
            for Each BasicBlock $retBlock$ in $retBlocks$ do
                $retActionNode \leftarrow retBlock$.GETLASTACTIONNODE
                $fg\_copy \leftarrow$ COPYFLOWGRAPH($retActionNode$.flowgraph, $varMap$)
                Add all nodes in $fg\_copy$ to $flowgraph$
                Set Def-Use relationship between the last node in $fg\_copy$ and $fgnode$
            end for
                                                        ▷ change type to Default
            $ActionNode$.type $\leftarrow Default$
            Clear $ActionNode$.children
        case $Default$
            do nothing
                                        ▷ For string specific actions, refer to Appendix B
```

Supported PHP Core Operations
Function
Declare
ArrayDeclare
Set
Get
Load

Table 2.1: Supported PHP Core operations

Supported PHP String Operations
Concat
StrComp
Substr
ToUpperCase
ToLowerCase
Reverse
Trim
Split
Replace
StrToTime

Table 2.2: Supported PHP string operations

2.3.2 Array Content Propagation

In addition to being initialized directly, it is common that string literals are also declared in arrays and maps, therefore it is important to capture all possible string literal values in such data structures. Suppose arr is an array with n string literals in a program, and at some point in the program, a variable a is assigned to an element in arr at a particular position i. The actual value of a depends on index i, but in our case, what we care is all the *possible* string literal values a could be assigned, and therefore index is no longer relevant. Instead, we assume that *all* the n elements in arr can be assigned to a. The same idea applies for maps as well.

Nested array and map is another consideration when extracting string literals. If an element is retrieved by indexing into the first level of a two-dimensional array, then only the elements at the first level are extracted. Similarly, if the array is indexed at its second level, then only those elements at the second level are retrieved. In our implementation, each LOAD ActionNode represents going one more level into an array/map. Therefore a recursive array unpacking procedure is applied at LOAD ActionNodes on flow graph construction, by which the action node can get to the correct level of an array/map and copy all the string literals at that level into its own data structure.

2.4 Interface Discovery Algorithm

In this step, variables exposed by the application interface(input variables) are identified and grouped logically. This part of the program implements two interface discovery algorithms proposed by Halfond and Orso [4].

CHAPTER 3
EMPIRICAL EVALUATION

3.1 Experiment Setup

3.1.1 Experimental Subjects

The experimental subjects used in the study is consisted of three student-developed projects that use PHP as their back-end language.

3.1.2 Tools Used in Evaluation

We evaluate the effectiveness of our interface discovery mechanism by comparing the number and quality of interfaces that it generates with the interfaces extracted by web crawlers. The web crawler tool that we used is OpenWebSpider, an open-sourced framework for crawling/spidering websites. For each interface output, we check if any of the HTTP requests in this output is processed in the back-end program.

We evaluate the effectiveness of our test request generation mechanism by comparing it against naive random test case generation. For each HTTP request, a set of possible values is generated for all of the fields in this request, creating a set of test HTTP requests, which are then sent to the server. The final code coverage of the back-end PHP code is recorded.

3.2 Results

3.2.1 Email Sender

A simple PHP program that processes a form which contains 4 input fields and sends an email according to the information supplied in the form.

Form Inputs

- first_name (required)
- last_name (required)
- email (required)
- telephone (optional)

All required fields are checked against a regular expression. The only optional field (telephone) is not checked against any regex or string variables.

Our penetration testing tool successfully identified all the fields (required and optional). It generated test cases for all the required variables from the given regex expression. For the ”telephone” field, which is optional, our testing tool did not infer any information from static analysis, therefore would be producing random strings for this field during testing.

Code coverage achieved: 82.92%

Code coverage by random generator: 60.98%

3.2.2 Fancy Hotel (CS4400 Class Project)

A web application powered by PHP and MySQL that serves as an online room reservation system for a non-existing hotel.

User Login

Form Inputs

- username (string)
- password (string)

Our penetration testing tool successfully identified both username and password fields in the interface. Since the application does not compare username and password to specific patterns or values, our static analysis did not infer possible value information for these fields.

However, the analyzer identified session information created during login, which could potentially make subsequent penetration testing more thorough by exploiting user sessions.

In addition, the user login program can be redirected to three different URLs once login information is validated. Since these URLs are not exposed to the front-end HTML, they were not identified by web crawler. However, by performing static analysis on the source code, our penetration testing tool was able to discover all three of them.

User Registration

Form Inputs

- username (string)
- password (string)
- confirmed_password (string)
- email (string)

Our penetration tool successfully identified all request (or interface) parameters and their names (usn, psw, con_pwd, email). It identified the regular expression that was used to check valid email and username in the program and used this information to construct test cases for the email and username fields.

Code coverage achieved: 91.67%

Code coverage by random generator: 66.67%

Room Search

Form Inputs

- start_date (string)
- end_date (string)

- location (string)

Note

- start_date must be greater than 2015-08-01;
- start_date cannot be greater than end_date;
- start_date cannot be smaller than today's date (2015-08-31);
- end_date must be smaller than 2016-01-31;

Our penetration tester successfully identified all the required fields as well as the session information not exposed by the interface itself. Furthermore, static analysis has inferred key information about both start_date and end_date. For start_date, output test cases include ”20150831” and ”20150801”; for end_date, output test cases include ”20160131”.

Code coverage achieved: 95.23%

Code coverage by random generator: 85.71%

3.2.3 Paycheck Calculator

A basic PHP web application that takes in one input (salary) and shows how much tax should be deduced.

Form Inputs

- salary (integer)

Our penetration tool successfully identified the interface. Static analysis generated all possible numeric values that are used, either directly or indirectly, to compare with the interface input variable in the program.

Code coverage achieved: 85.37%

Code coverage by random generator: 82.92%

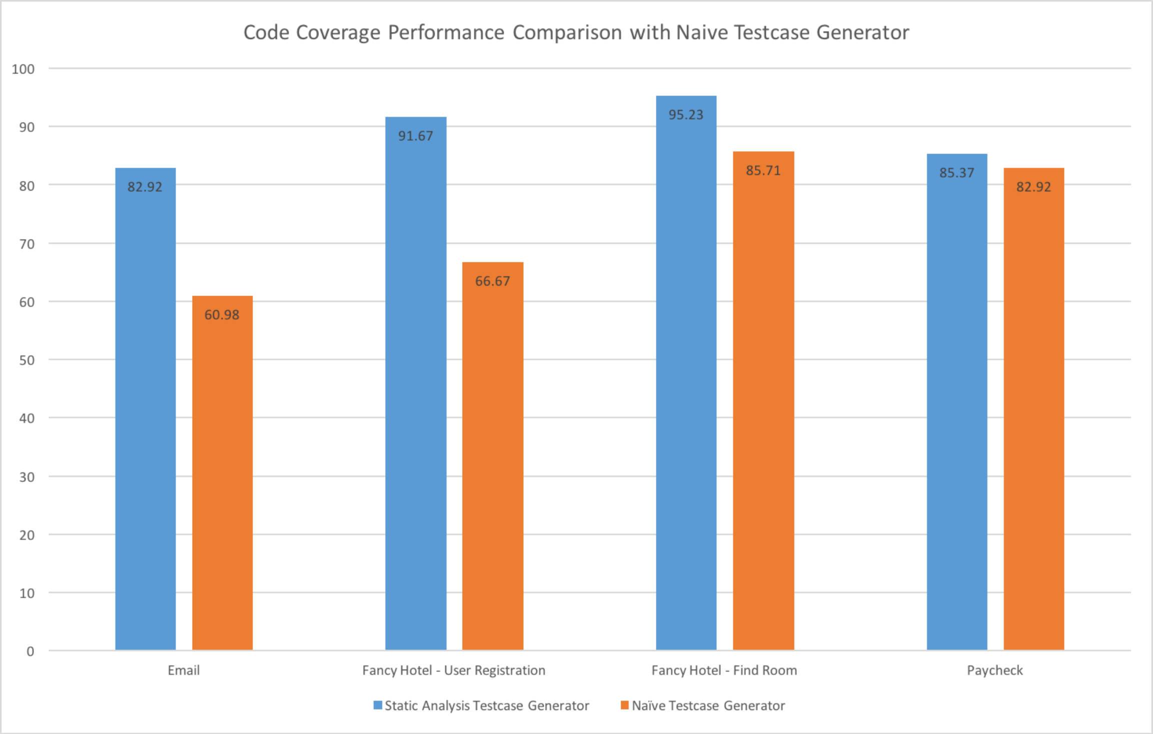


Figure 3.1: Code Coverage Performance Comparison with Naive Testcase Generator

CHAPTER 4
DISCUSSION

The comparison against OpenWebSpider for interface discovery performance and naive random string construction for test case generation shows that our penetration tool, which is based on static analysis, could identify more web interfaces than traditional web spider and achieve higher code coverage than traditional penetration testing tool. In our study, we found that in the case that application hides its some of its URLs from the front-end, web crawler is unable to discover those URLs and would fail to visit their pages. However, there is no such problem for our penetration testing tool. Since our implementation does not rely on front-end information when identifying interfacing but rather directly inspects all the source codes, our interface discovery mechanism will eventually visit all the files in the application code base and get interface information from them. Moreover, the static analysis mechanism also helps us identify hidden URLs in the application, from which a complete site map could be generated. However, the limitation for our penetration testing tool is that it has to have read access of all the PHP files in use, which is sometimes difficult to accomplish.

Another potential advantage for using our penetration testing tool is that its interface discovery mechanism can identify which input variable is not going to be processed, thus saving time to generate test case for it. If an input variable is never used in the back-end, then it is not going to be identified during static analysis; however, a web crawler may simply look at the input fields in the front end and assume that all input fields are going to be processed.

Figure 3.1 shows our implementation for testcase generation achieves more code coverage than the naive testcase generation method. The improvement is relatively big for the first three sample programs while it is only minute for the last one. The reason is that the first three programs are mainly dealing with string typed inputs, as opposed to the last program, Paycheck Calculator, which only processes integer data input. It is clear that static analysis along with string literal value estimation makes our penetration testing tool more capable of getting to the ”edge cases” where the program may branch out, thus is able to achieve high code coverage by using relatively fewer test cases. Further investigation into the implementation details of sample programs leads to the finding that the performance of our testcase generator is higher if input variables are checked against const string literals or regular expression patterns (program 1 and 2), and is lower if input variables are checked with each other(program 3).

CHAPTER 5

CONCLUSION

In this paper we presented a novel approach for performing automated penetration testing for PHP web applications. It uses static analysis to identify the application program's behavior on each variable and function, and then construct the possible interfaces exposed by the application as well as the possible values that each request field can take. We compared the effectiveness of this new test system with traditional penetration testing tools, in terms of interface discovery and test case generation. The result shows our proposed testing tool can not only identify more interfaces for dynamic web applications, but is able to achieve higher code coverage by using fewer test cases.

Appendices

APPENDIX A

EXPERIMENT EQUIPMENT

1. Ubuntu 14.04

2. Java Runtime Environment 1.7

3. PHP 5.5

4. HHVM 3.10.0

5. OpenWebSpider

APPENDIX B

FUNCTION *BUILDFLOWGRAPH* CONTINUED

```
case $Concat$
    ActionNode $toConcat1$ ← $ActionNode$.children[0]
    ActionNode $toConcat2$ ← $ActionNode$.children[1]
    $fgnode$ ← $flowgraph$.ADDCONCATENATIONNODE
    Set Def-Use relationship between $toConcat1$ and $fgnode$
    Set Def-Use relationship between $toConcat2$ and $fgnode$
case $Comp$
    ActionNode $toCmp1$ ← $ActionNode$.children[0]
    ActionNode $toCmp2$ ← $ActionNode$.children[1]
    $fgnode$ ← $flowgraph$.ADDBINARYNODE(AssertEqualsOperation)
    Set Def-Use relationship between $toCmp1$ and $fgnode$
    Set Def-Use relationship between $toComp2$ and $fgnode$
case $Substr$
    ActionNode $substrNode$ ← $ActionNode$.children[0]
    $fgnode$ ← $flowgraph$.ADDUNARYNODE(SubstringOperation)
    Set Def-Use relationship between $substrNode$ and $fgnode$
case $ToUppserCase$
    ActionNode $upperNode$ ← $ActionNode$.children[0]
    $fgnode$ ← $flowgraph$.ADDUNARYNODE(ToUpperOperation)
    Set Def-Use relationship between $upperNode$ and $fgnode$
case $ToLowerCase$
    ActionNode $lowerNode$ ← $ActionNode$.children[0]
    $fgnode$ ← $flowgraph$.ADDUNARYNODE(ToLowerOperation)
    Set Def-Use relationship between $lowerNode$ and $fgnode$
case $Reverse$
    ActionNode $reverseNode$ ← $ActionNode$.children[0]
    $fgnode$ ← $flowgraph$.ADDUNARYNODE(ReverseOperation)
    Set Def-Use relationship between $reverseNode$ and $fgnode$
```

```
        case $Trim$
            ActionNode $trimNode \leftarrow ActionNode$.children[0]
            $fgnode \leftarrow flowgraph.$ADDUNARYNODE(TrimOperation)
            Set Def-Use relationship between $trimNode$ and $fgnode$
        case $Split$
            ActionNode $splitNode \leftarrow ActionNode$.children[0]
            $fgnode \leftarrow flowgraph.$ADDUNARYNODE(SplitOperation)
            Set Def-Use relationship between $splitNode$ and $fgnode$
        case $StringToTime$
            ActionNode $timeNode \leftarrow ActionNode$.children[0]
            $fgnode \leftarrow flowgraph.$ADDUNARYNODE(ToTimeFormatOperation)
            Set Def-Use relationship between $timeNode$ and $fgnode$
    return $true$
end function
```

APPENDIX C

EXPERIMENT INTERFACE OUTPUT

C.1 Email Sender

```
Found URLs:
=========================================
Interface 1
=========================================
Request 1
**************************************
_POST{last_name}
———————— Domain Info —————————
Types    []
Values: []

String values:

digraph FlowGraph {
  N122 [label=””,shape=circle]
  N124 –> N122
  N123 [label=”<???>”]
  N124 [label=””,shape=circle]
  N123 –> N124
}
```

```
——————————— Test Cases ————————————
[]   .C–z N.


************************************
Request 2
************************************
_POST{telephone}
—————————— Domain Info ————————————
Types    []
Values: []


String values:


——————————— Test Cases ————————————
[]
************************************
Request 3
************************************
_POST{first_name}
—————————— Domain Info ————————————
Types    []
Values: []


String values:


digraph FlowGraph {
  N76 [label="",shape=circle]
  N124 –> N76
  N123 [label=”<???>”]
  N124 [label=””,shape=circle]
  N123 –> N124
}

————————— Test Cases ——————————
[]  SIT


***********************************
Request 4
***********************************
_POST{email}
———————— Domain Info ——————————
Types    []
Values: []


String values:


digraph FlowGraph {
  N45 [label=””,shape=circle]
  N47 –> N45
  N46 [label=”<???>”]
  N47 [label=””,shape=circle]
  N46 –> N47
}
```

```
——————— Test Cases ———————
[]  –S.YTh@A22.I–P8P4G7nY0LIB.84––––.Mvw

***********************************
```

C.2 Fancy Hotel - User Login

```
Found URLs:
Location: /user_registration.php
Location: /functionality_customer.php
Location: /functionality_manager.php
====================================
Interface 1
====================================
====================================
Interface 2
====================================
Request 1
 ....................................
_POST{password}
Test Cases:
 ....................................
Request 2
 ....................................
_POST{username}
Test Cases:
 ....................................
====================================
Interface 3
========================================
Request 1
........................................
_SESSION{identity}
Test Cases:
........................................
========================================
Interface 4
========================================
Request 1
........................................
_POST{password}
Test Cases:
........................................
Request 2
........................................
_POST{username}
Test Cases:
........................................
Request 3
........................................
_SESSION{identity}
Test Cases:
........................................
```

C.3 Fancy Hotel - User Registration

```
Found URLs:
==========================================
Interface 1
==========================================
==========================================
Interface 2
==========================================
Request 1
************************************
_POST{usn}
———————— Domain Info ————————
Types    [String]
Values: []

String values:

digraph FlowGraph {
  N38 [label="<???>"]
}

———————— Test Cases ————————
[]   6Ew

************************************
Request 2
************************************
_POST{con_pwd}
```

```
—————— Domain Info ——————
Types    []
Values: []

String values:

digraph FlowGraph {
  N54 [label=””,shape=circle]
  N168 –> N54
  N167 [label=”<???>”]
  N168 [label=””,shape=circle]
  N167 –> N168
}

——————— Test Cases ——————
[]

*************************************
Request 3
*************************************
_POST{pwd}
—————— Domain Info ——————
Types    []
Values: []

String values:
```

```
digraph FlowGraph {
  N60 [label=””,shape=circle]
  N62 –> N60
  N61 [label=”<???>”]
  N62 [label=””,shape=circle]
  N61 –> N62
}

—————— Test Cases ——————
[]

************************************
Request 4
************************************
_POST{email}
————— Domain Info ——————
Types    [String]
Values: []

String values:

digraph FlowGraph {
  N74 [label=”<???>”]
}

—————— Test Cases ——————
[]   o7Muhy1@Ph.com
```

```
************************************
```

C.4 Fancy Hotel - Room Search

```
Found URLs:
========================================
Interface 1
========================================
========================================
Interface 2
========================================
Request 1
************************************
_POST{usn}
——————— Domain Info ————————
Types    [String]
Values: []

String values:

digraph FlowGraph {
  N38 [label=”<???>”]
}

———————— Test Cases ————————
[]   6Ew
```

```
***********************************
Request 2
***********************************
_POST{con_pwd}
———————— Domain Info —————————
Types    []
Values: []


String values:


digraph FlowGraph {
  N54 [label=””,shape=circle]
  N168 –> N54
  N167 [label=”<???>”]
  N168 [label=””,shape=circle]
  N167 –> N168
}

————————— Test Cases ——————————
[]


***********************************
Request 3
***********************************
_POST{pwd}
———————— Domain Info —————————
Types    []
```

```
Values: []

String values:

digraph FlowGraph {
  N60 [label=””,shape=circle]
  N62 –> N60
  N61 [label=”<???>”]
  N62 [label=””,shape=circle]
  N61 –> N62
}

———————— Test Cases ————————
[]

***************************************
Request 4
***************************************
_POST{email}
——————— Domain Info ————————
Types    [String]
Values: []

String values:

digraph FlowGraph {
  N74 [label=”<???>”]
}

————— Test Cases —————
[]   o7Muhy1@Ph.com

************************************
```

C.5 Paycheck Calculator

```
========================================
Interface 1
========================================
Request 1
************************************
_POST{salary}
———— Domain Info —————
Types    [Number]
Values: [2331.89, 4663.75, 1399.13, 3751.05,
   3751.06, 2826.66, 2331.88, 1903.99, 4664.68]

String values:

————— Test Cases —————
[2331.89, 4663.75, 1399.13, 3751.05, 3751.06,
   2826.66, 2331.88, 1903.99, 4664.68]

************************************
```

REFERENCES

[1] P. S. Srivastava and T. Kim, “Application of genetic algorithm in software testing,” International Journal of Software Engineering and Its Applications, vol. 3, no. 4, Nov. 2009.

[2] R. Zhao and S. Lv, “Neural-network based test cases generation using genetic algorithm,” in 13th Pacific Rim International Symposium, Dec. 2007, pp. 97–100.

[3] A. S. Christensen, A. Møller, and M. I. Schwartzbach, “Precise analysis of string expressions,” in The 10th International Conference on Static Analysis, 2003.

[4] W. G. J. Halfond and A. Orso, “Improving test case generation for web applications using automated interface discovery,” in The the 6th Joint Meeting of the European Software Engineering Conference, ser. ESEC–FSE ’07, Dubrovnik, Croatia: ACM, 2007, pp. 145–154, ISBN: 9781595938114.

[5] Facebook, Hiphop bytecode specification v1 revision 18, 2014.