AUTOMATED PENETRATION TESTING FOR PHP WEB APPLICATIONS

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By

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Tests are stories we tell the next generation of programmers on a project.

Roy Osherove, The Art of Unit Testing: With Examples in .NET

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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 backend 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 gurantees 100% backend 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 backend 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 frontend. 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 sequencial 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.

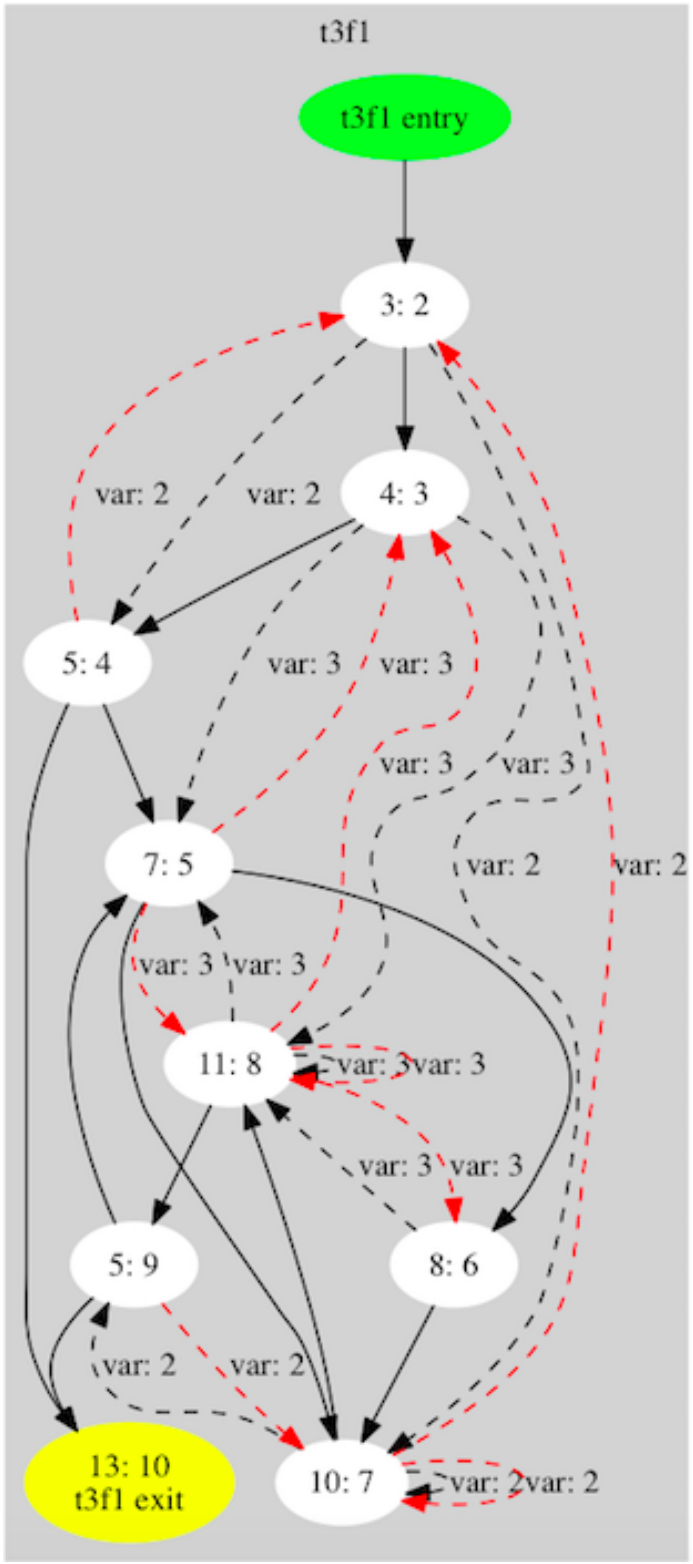

Figure 2.1: Control Flow Graph for Function t3f1

```
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 Bytecode

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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 invokations 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.

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 ap-

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

```
37: function COMPLETEUSEDEF(cfg, instr, var, visited)
38:     if instr in visited then
39:         return instr.udchain
40:     end if
41:     for Each Def def in instr.udchain do
42:         if def is a function entry site then
43:             Get all the functions callerfuncs that calls current function
44:             for Each function callerfunc in callerfuncs do
45:                 Get the function parameter sourcevar in callerfunc that corresponds
    to def.var
46:                 Get the instruction sourceInstr in callerfunc that passes sourcevar
    to callee stack
47:                 newdefs ← COMPLETEUSEDEF(callerfunc.CFG, sourceInstr,
    sourcevar, visited)
48:                 instr.udchain ← (instr.udchain - def) ∪ newdefs
49:             end for
50:         end if
51:     end for
52:     visited ← visited ∪ instr
53:     return instr.duchain
54: end function
```

plication 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 backend. 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 happend: 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

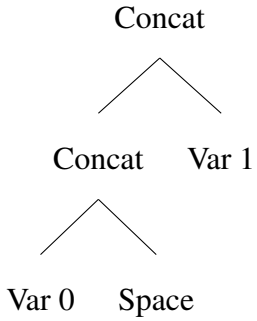
```
1   152: String " "
2   157: CGetL2 0
3   159: Concat
4   160: CGetL 1
5   162: Concat
6   163: RetC
```

Given the fact that HHBC instructions also represent stack operations, we can take ad-

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

Table 2.1: Supported PHP string operations

vantage 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. 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 2.1). 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:



Supported PHP Core Operations
Function
Declare
ArrayDeclare
Set
Get
Load

Table 2.2: Supported PHP Core operations

2.3.2 Array Content Propagation

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

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 backend 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 PHPCrawl, an open-sourced framework for crawling/spidering websites written in PHP. For each interface output, we check if any of the HTTP requests in this output is processed in the backend program.

We evaluate the effectiveness of our test request generation mechanism by comparing it against another PHP test case generation tool, PHPUnit. 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. Then the final code coverage in the backend is recorded.

3.2 Results

Table 3.1: Interface Discovery Results

	# Identified Interfaces		
Project Name	PHPCrawl	Current	Improvement
CS4400	#	#	#
Email	3	3	0 (0%)
STP	12	16	4 (33%)
TodoList	#	#	#

CHAPTER 4
DISCUSSION

4.1 Interface Discovery

As Table 3.1 shows, the number of interfaces identified by our automated penetration testing tool is always greater than or equal to what are identified by traditional web crawling.

Such result is in accordance with what is reported by Halford et al. [4], which demonstrates the correctness of our implementation of the interface discovery algorithms. We manually inspected the interfaces exposed by each of the applications and analyzed the procedure that our tool took during interface discovery phase. We identified that there are some cases in which the the web application does not use all the information sent from the client side. PHPCrawler does not have any knowledge of what request is actually processed, so it could generate more request than necessary; however, our interface discovery mechanism is able to send the HTTP requests with only the fields that are known to be handled in the backend, which improves the overall efficiency of penetration testing by reducing the number of unnecessary requests.

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 also generate fewer test cases in order to cover 100% of the backend code.

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