AUTOMATED PENETRATION TESTING FOR PHP WEB APPLICATIONS

A Dissertation
Presented to
The Academic Faculty

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

ACKNOWLEDGEMENTS

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ABSTRACT

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 by simulating all possible request sendings from the client. Traditionally, penetration testers write web crawler programs to extract interface information from frontend HTML web-pages, and manually generate test requests to send to the server. Such process has two major draw-backs. First, a web application may not expose all of its interface

To address this issue, we present a novel approach which uses program static analysis is exploited. This new penetration testing system is not only able to estimate user inputs more precisely, but also able to determine interfaces exposed by applications. This research applicable for PHP web applications.

CHAPTER 1
INTRODUCTION AND BACKGROUND

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 and neural network models. 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 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 [1] 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 [2] 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.

CHAPTER 2
TECHNICAL APPROACH

2.1 System Requirements

1. Ubuntu 14.04
2. HHVM 3.10.0
3. Java Runtime Environment 1.7

2.2 HHVM Bytecode Processing

HHVM compiles Hack and PHP into an intermediate bytecode. The intermediate bytecode is processed to build control flow graphs.

2.2.1 Intra-Procedural Control Flow Graph Construction

Control Flow Graph (CFG) is a graph representation of a program that represents all the paths that might be traversed through during its execution, which is the basis for performing variable liveness check and building def-use/use-def chains. The procedure for building a CFG has been extensively investigated and there is a standard algorithm for building CFG from intermediate representations (Hip-Hop byte code, in this case):

Basic Block Partitioning

Identify leader statements (i.e. the first statements of basic blocks) by using the following rules:

1. Identify leader statements
    (a) The first statement is a leader

(b) Any statement that is the target of a branch statement is a leader (for most intermediate languages these are statements with an associated label)

(c) Any statement that immediately follows a branch or return statement is a leader

2. The basic block corresponding to a leader consists of the leader, plus all statements up to but not including the next leader or up to the end of the program

Control Flow Graph Construction

The basic block corresponding to a leader consists of the leader, plus all statements up to but not including the next leader or up to the end of the program

1. There is a branch from the last statement of B1 to the first statement of B2, or

2. Control flow can fall through from B1 to B2 because

   (a) B2 immediately follows B1, and

   (b) B1 does not end with an unconditional branch

2.2.2 Data Flow Analysis

In order to keep track of how each variable is used in the program, it is critical to perform data flow analysis, which outputs def-use chains and use-def chains, both of which are critical to the later stages of the project.

Def-Use Chains and Liveness Analysis

Def-use chain is used to keep information about reaching definition of a variable. Specifically, for each use of a variable x, its def-use chain is a list of the definitions of x reaching that use. Liveness Analysis is used to get def-use chains.

- At each program point:

  - Which variables contain values computed earlier and needed later – they are said to be live

- For instruction I:
  - in[I]: live variables at program point before I
  - out[i]: live variables at program point after I
- For a basic block B:
  - in[B]: live variables at beginning of B
  - out[B]: live variables at end of B
- DU[I] = out[I] – in[I]
- Note:
  - in[I] = in[B] for first instruction of B
  - out[I] = out[B] for last instruction of B

Algorithm 1 Liveness Calculation in CFG

```
for Each instruction I do
    in[I] ← ∅
    out[I] ← ∅
end for
until no change in set repeat
    for Each instruction I do
        in[I] ← (out[I] - def[I]) ∪ use[I]
    end for
    for Each basic block B do
        out[B] ← ∪ in[S] (S ∈ Successor[B])
    end for
end until
```

Use-Def Chains and Reaching-definition Analysis

To the opposite of def-use chains, use-def chain is used to keep track of reachable definitions for a use of a variable. Reaching-definition analysis is the method to get use-def chains.

- For instruction I:
  - in[I]: reaching definitions going into I
  - in[I]: reaching definitions going into I
  - in[I]: reaching definitions going into I
  - kill[I]: definition at I
- For a basic block B:
  - in[B]: reaching definitions going into B
  - out[B]: reaching definitions coming out of B
- UD[I] = in[I] – out[I]

Algorithm 2 Reaching-def Calculation in CFG

for Each instruction I **do**
  in[I] $\leftarrow \emptyset$
  out[I] $\leftarrow \emptyset$
end for
until no change in set **repeat**
  for Each instruction I **do**
    out[I] $\leftarrow$ (in[I] - kill[I]) $\cup$ gen[I]
  end for
  for Each basic block B **do**
    in[B] $\leftarrow \cup$ out[P] (P $\in$ Predecessor[B])
  end for
end until

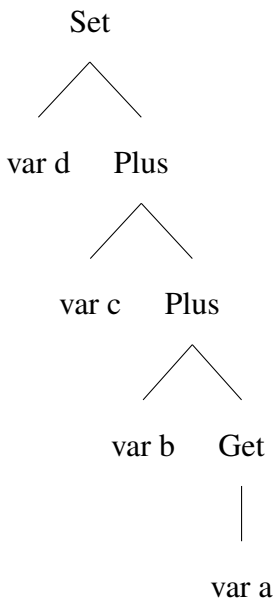
2.3 String Automaton Construction

The second step is to construct estimated input variables by using the result of data flow analysis. The Use-Def chain is particularly useful, because it allows a used variable to be traced back to where it is originally defined.

As string typed inputs are the most common interface inputs of PHP web applications, this section mainly focuses on string estimation. Christensen, Møller, and Schwartzbach [1] have proposed a promising algorithm for performing regular expression estimation for a string variable through data flow analysis. In this section a third-party package, dk.brics.automaton, is used. dk.brics.automaton is an open-source Java package implemented based on the research of Christensen, et al. It is language-independent, and supports most commonly used string operations. dk.brics.automaton is able to take flow graph composed of operators and operands (known characters), and generate a definite finite automaton (DFA), which is an estimated regular expression for the analyzed string.

In order to build a complete flow-graph for a string variable, a stack is used to mimic HHVM executions. During HHVM execution, variables and functions are pushed to top of a running stack. Each action (arithmetic operations, string operations, etc.) takes one or more elements popped from the stack, and pushes the new result to stack top. Sometimes when multiple operations are chained together, the stack actions will have a hierarchical form. For example, the stack action for d = (a + b + c) is:

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



2.4 Interface Discovery and Grouping

In the last 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 Orso and Halfond [2].

CHAPTER 3

EMPIRICAL EVALUATION

3.1 Experiment Setup

3.2 Results

CHAPTER 4

DISCUSSION

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CHAPTER 5
CONCLUSION

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Appendices

APPENDIX A

EXPERIMENTAL EQUIPMENT

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APPENDIX B

DATA PROCESSING

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[1] B. W. Kernighan and D. M. Ritchie, The C Programming Language Second Edition. Prentice-Hall, Inc., 1988.

[2] G. P. Burdell, Myths and Their Origins. Real Books, Inc., 2016.

[3] A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" Phys. Rev., vol. 47, pp. 777–780, 10 1935.

VITA

Vita may be provided by doctoral students only. The length of the vita is preferably one page. It may include the place of birth and should be written in third person. This vita is similar to the author biography found on book jackets.