

CONFU: Configuration Fuzzing Testing Framework for Software Vulnerability Detection

Master's Thesis

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ABSTRACT

Many software security vulnerabilities only reveal themselves under certain conditions, i.e., particular configurations and inputs together with a certain runtime environment. One approach to detecting these vulnerabilities is fuzz testing that feeds randomly generated inputs to the software and witnesses its failures. However, typical fuzz testing makes no guarantees regarding the syntactic and semantic validity of the input, or of how much of the input space will be explored. To address these problems, we present a new testing methodology called *Configuration Fuzzing*. Configuration Fuzzing is a technique whereby the configuration of the running application is mutated at certain execution points, in order to check for vulnerabilities that only arise in certain conditions. As the application runs in the deployment environment, this testing technique continuously fuzzes the configuration and checks "security invariants" that, if violated, indicate a vulnerability. We discuss the approach and introduce a prototype framework called *ConFu* (CONfiguration FUZZing testing framework) implementation. We also present the results of case studies that demonstrate the approach's feasibility and evaluate its performance.

Keywords: Vulnerability; Configuration Fuzzing; Fuzz testing; In Vivo testing; Security invariants

1 INTRODUCTION

As the Internet has grown in popularity, security testing is undoubtedly becoming a crucial part of the development process for commercial software, especially for server applications. However, it is often impossible in terms of time and cost to test all configurations or to simulate all system environments before releasing the software into the field, not to mention the fact that software distributors may later add more configuration options. The configuration of a software system is a set of options that are responsible for a user's preferences and the choice of hardware, functionality, etc. Sophisticated software systems always have a large number of possible configurations, e.g., a recent version of Firefox has more than 2^{30} possible configurations, and testing all of them is infeasible before the release. Fuzz testing as a form of black-box testing was introduced to address this problem [23], and empirical studies [14] have proven its effectiveness in revealing vulnerabilities in software systems. Yet, typical fuzz testing has been inefficient in two aspects. First, it is poor at exposing certain errors, as most generated inputs fail to satisfy syntactic or semantic constraints and therefore cannot exercise deeper code. Second, given the immensity of the input space, there are no guarantees as to how much of it will be explored [4].

To address these limitations, this thesis presents a new testing methodology called *Configuration Fuzzing*, and a prototype framework called *ConFu* (CONfiguration FUZZing framework). Instead of generating random inputs that may be semantically invalid that would not pass the syntactic checks, ConFu mutates the application configuration in a way that helps valid inputs exercise the deeper components of the software-under-test and check for violations of program-specific "security invariants" [2]. These invariants represent rules that, if broken, indicate the existence of a potential vulnerability. Examples of security invariants may include: avoiding memory leakage

that may lead to denial of service; a user should never gain access to files that do not belong to him; critical data should never be transmitted over the Internet; only certain sequences of function calls should be allowed, etc. ConFu mutates the configuration using the incremental covering array algorithm [6], a pairwise testing approach that captures the abstraction and generality of all possible configurations, therefore guaranteeing considerable coverage of the configuration space in the lifetime of a certain release of the software.

Configuration Fuzzing works as follows: Given an application to test, the testers annotate the configuration variables to be fuzzed in the configuration file and choose the functions to test. By fuzzing we mean changing a variable's value. After this, they write surveillance functions for specific security invariants they are willing to check. The framework then generates the actual code for a fuzzer that mutates the values of the chosen configuration variables, as well as the test functions for each chosen function. Next, the framework creates instrumentation such that whenever a chosen function is called, the corresponding test function is executed in a sandbox with the mutated configuration and the security invariants are checked with the surveillance functions. Violations of these security invariants are logged and sent back to the developer.

Configuration Fuzzing is based on the observation that most vulnerabilities occur under specific configurations with certain inputs [21], i.e., an application running with one configuration may prevent the user from doing something bad, while another might not. Configuration Fuzzing occurs within software as it runs in the deployment environment. This allows it to conduct tests in application states and environments that may not have been conceived in the lab. In addition, the effectiveness of ConFu is increased by using real-world user inputs rather than randomly generated ones. However, the fuzzing of the configuration occurs in an isolated "sandbox" that is created as a clone of the original process, so that it does not affect the end user of the program. When a vulnerability is detected, detailed information is collected and sent back to a server for later analysis.

The rest of this thesis is organized as follows. Section 2 formalizes the problem statement, and identifies requirements that a solution must meet. Section 3 discusses the background, proposes the Configuration Fuzzing approach, and provides the architecture of the framework-called ConFu. Section 4 looks at the results of our case studies and performance evaluation. Related work is then discussed in Section 5. The thesis ends with limitations in Section 6, and finally the conclusion in Section 7.

2 PROBLEM AND REQUIREMENTS

2.1 Definitions

This section formalizes some terms that are used throughout the thesis:

- **Configuration:** An arrangement of settings that represents a user's preferences and the choice of hardware, functionality, etc.
- **Vulnerability:** A term in computer security which refers to weaknesses that allow malicious users to break into a system or escalate their privileges.

- Behavior Bug: Functional bugs are defects that do not break a system's security in contrast to vulnerabilities.
- Configuration Fuzzing: A methodology of testing that mutates the configuration of a software system to check for vulnerabilities after the software is released.
- ConFu: Configuration Fuzzing framework for software vulnerability detection
- Security Invariant [2]: Representing rules that, if broken, indicate the existence of vulnerabilities.
- Surveillance Function: Functions that checks for violations of security invariants throughout the testing process.
- In Vivo Testing [18]: A perpetual testing [20] approach that continues the testing process of a software through the deployment stage after it is released.
- Covering Array [11]: A mathematical object that can be used for software testing purposes, which ensures that the tests can cover a degree of percentage of all possible use cases.

2.2 Problem statement

We have observed that configuration together with user input are the major factors of vulnerability exploitation [30]. However, it is generally infeasible to test all functionality with all possible configurations, in terms of time and cost, before releasing the software into the field. For example, the Apache HTTP server has more than 50 options that generate over 2^{50} possible settings, and certain vulnerabilities^{i, ii} will only reveal themselves under specific configurations with specific user inputs. The effectiveness and efficiency of detecting such vulnerabilities in the testing process is greatly hampered due to the immensity of both the configuration and input space. Another issue of security testing resides in the difficulty of detecting vulnerabilities when the characteristics of the vulnerabilities are not deterministic and differ greatly from behavior bugs. A "test oracle" [25] alone is only sufficient in evaluating the correctness of a software with respect to its functionality but not its security. Furthermore, most configuration testing approaches such as Skoll [17] or MSET [9] provide little feedback beyond "pass/fail" and do not address security issues.

2.3 Requirements

A solution to this problem would need to address not only the issue of the immensity of the configuration and the input space, but also consider the effectiveness and efficiency of characterizing vulnerabilities and providing detailed information regarding detected vulnerabilities. Such a solution should meet the following requirements:

Guarantee a considerable degree of coverage of the configuration space. In a limited amount of time, the solution has to guarantee sufficient coverage of the configuration space. Because some options have to match the external environment such

as operating system, it might be impossible to provide full-coverage testing. However, the solution must at least have covered the most common configurations.

Support representative user inputs with which to test. The solution has to optimize the number of possible user inputs for a given configuration. The validity of the user inputs is crucial and these inputs should satisfy syntactic and semantic constraints and therefore exercise the deeper components of the software. “Maximum” coverage of the input space is desired, but with “minimum” actual test cases.

Be able to detect the most common vulnerabilities and provide an easy-to-use API to add rules for detecting other vulnerabilities. The solution should provide an effective mechanism to detect common kinds of security issues such as directory traversal, denial of service, insufficient access control, etc. Also, it must be easy to add an additional rule if a new vulnerability or exploit arises, without having to change the existing framework.

Be capable of reporting vulnerabilities back to the software developers. If a test fails and a vulnerability is discovered, the framework must allow for feedback to be sent to the software developers so that the failure can be analyzed and, ideally, fixed. In addition to sending a notification of a discovered vulnerability, the framework should also send back useful information about the system state so that the vulnerability can be reproduced.

Have low performance impact. The user of a system that is conducting tests on itself during execution should not observe any noticeable performance degradation. The tests must be unobtrusive to the end user, both in terms of functionality and any configuration or setup, in addition to performance.

3 APPROACH

3.1 Background

Configuration Fuzzing is designed as an extension to the In Vivo Testing approach [18], which was originally introduced to detect behavioral bugs that reside in software products. In Vivo Testing was principally inspired by the notion of "perpetual testing" [20] [22], which suggests that latent defects still reside in many (if not all) software products and these defects may reveal themselves when the application executes in states that were unanticipated and/or untested in the development environment. Therefore, testing of software should continue throughout the entire lifetime of the application. In Vivo Testing approaches this problem by executing tests at specified points in the context of the running program after the software is released.

In Vivo Testing conducts tests and checks properties of the software in a duplicated process of the original; this ensures that, although the tests themselves may alter the state of the application, these changes happen in the duplicated process, so that any changes to the state are not seen by the user. This duplicated process can simply be created using a "fork" system call, though this only creates a copy of the in-process memory. If the test

needs to modify any local files, In Vivo tests can use a "process domain" [19] to create a more robust "sandbox" that includes a copy-on-write view of the file system. This layered file system allows different processes to have their own view of the file system, sharing any read only files but writing into their own private copies of files and directories.

In previous research into In Vivo Testing, the approach of continuing to test these applications even after deployment was proven to be both effective and efficient in finding remaining misbehavior flaws related to functional correctness [3][18], but not necessarily security defects. In this work, we extend the In Vivo Testing approach to specifically look for security vulnerabilities.

Extending the In Vivo Testing approach to Configuration Fuzzing is motivated by three concerns.

First, many security-related bugs only reveal themselves under certain conditions, reflected in the configuration of the software together with its runtime environment. For instance, the FTP server wu-ftpd 2.4.2 assigns a particular user ID to the FTP client in certain configurations such that authentication can succeed even though no password entry is available for a user, thus allowing remote attackers to gain privilegesⁱⁱⁱ. As another example, certain versions of the FTP server vsftpd, when under heavy load, may allow attackers to cause a denial of service (crash) via a SIGCHLD signal during a malloc or free call^{iv}, depending on the software's configuration. Because In Vivo tests execute within the current environment of the program, rather than by creating a clean slate, it follows that Configuration Fuzzing increases the possibility of detecting such vulnerabilities that only appear under certain conditions.

Second, the "perpetual testing" foundation of In Vivo Testing ensures that testing can be carried out after the software is released. Continued testing improves the amount of the configuration space that can be explored through fuzzing; therefore it is more likely that an instance will find vulnerabilities under their error-prone configurations.

Third, In Vivo Testing uses real-world user inputs, which may be more likely to trigger vulnerabilities. Due to the impossibility of full coverage of the input space [27], using real-world user inputs has a higher probability of detecting vulnerabilities over contrived lab inputs.

3.2 Model

When an instrumented function is called, Configuration Fuzzing **mutates the application configuration under predefined configuration constraints of the software-under-test to look for potential vulnerabilities**. By extending the In Vivo Testing approach, **Configuration Fuzzing tests are executed in the field**, after deployment, and will provide representative real-world user inputs to test with and reveal vulnerabilities that are dependent on the application state. Furthermore, **surveillance functions using security invariants are executed throughout the test** in order to detect violations of security rules, which indicate the occurrence of potential vulnerabilities.

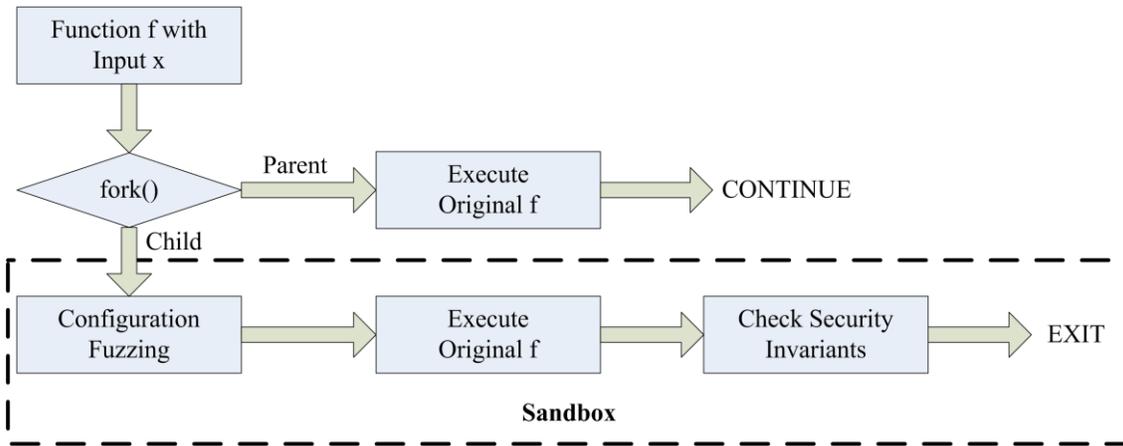


Figure 1. The model of Configuration Fuzzing Testing

The model of Configuration Fuzzing Testing is shown in Figure 1. Given a function named f with input x to test, we create a sandbox (illustrated by `fork()` in Figure 1) before f actually gets called. The sandbox is a replica of the original process with the same system state. The original function f will be executed in the original process as normal while Configuration Fuzzing tests take place in the sandbox.

Configuration Fuzzing tests are composed of three parts. First, configuration variables are mutated. However, since Configuration Fuzzing tests take place in a replica of the original process, the configuration variables stay unchanged in the original process. Second, the original function f is executed with the mutated configuration trying to exploit potential vulnerabilities. As the epilogue of the duplicated process, a surveillance function that checks for violation of security invariants is called so as to detect any vulnerability exploitation and send reports to the system administrator or developers if found. After this, the test process is terminated while the original process continues.

3.3 Architecture

Here we introduce the architecture of a framework called ConFu (Configuration Fuzzing framework for vulnerability detection). ConFu mutates the configuration of an application with a covering array algorithm [11] and checks for vulnerabilities using surveillance functions that monitor violations of security invariants. This framework allows the application to be tested as it runs in the field, using real input data. As described above, multiple invocations of the instrumented functions are run; however, the additional invocations must not affect the user and must run in a separate sandbox. The steps that software testers would take when using ConFu are as follows:

Step 1: Identifying the configuration/setting variables. Most software applications use external configuration, such as `.config` or `.ini` files, and/or internal configuration, namely global variables. Given an application to be tested, the tester first locates these configuration parameters that can be mutated. We assume that the tester can annotate or create the configuration files in such a way that each field is followed by the corresponding variable from the source code and the range of possible values of that variable. A sample annotated configuration file is shown in Figure 2, with the

corresponding variables and their values in braces. The examples listed are taken from our empirical study in Section 4 using OpenSSH^v, a secure shell server.

```
X11Forwarding yes    #[options.x11_forwarding]@{0,1}
TCPKeepAlive yes    #[options.tcp_keep_alive]@{0,1}
UseLogin          no    #[options.use_login]@{0,1}
Protocol          1    #[options.protocol]@{1,2,3}
```

Figure 2. Part of the annotated configuration file for OpenSSH

Our method mainly fuzzes those configuration variables that are responsible for changing modes or enabling options. These variables often have a binary value of 1/0 or y/n, or sometimes a sequence of numbers representing different modes. Not all configuration variables are modifiable in the sense of revealing vulnerabilities, e.g., fuzzing the host IP address of an FTP server will only lead to unable-to-connect errors. Also, configuration variables that rely on external limitations, such as hardware compatibility, should not be fuzzed. For instance, changing the variable representing the number of CPUs to four when the actual host only has two might cause vulnerabilities instead of detecting them. On the other hand, a considerable number of vulnerabilities are triggered under certain mode/option combinations in network-related applications. For example, WinFTP FTP Server 2.3.0, in passive mode, allows remote authenticated users to cause a denial of service via a sequence of FTP sessions^{vi}. Also, some early versions of Apache Tomcat allow remote authenticated users to read arbitrary files via a WebDAV write request under certain configurations^{vii}. By only fuzzing the configuration variables representing modes and options, the size of the configuration space that our approach is fuzzing decreases considerably; however, even with such a decrease, the configuration space may still be too large to test prior to deployment, and thus an In Vivo Testing approach such as Configuration Fuzzing is still useful.

```
typedef struct {
    int x11_forward;
    int tcp_keep_alive;
    ...
} result;

void fuzz_config()
{
    /* generate a set of options */
    result r=covering_array();
    options.x11_forward = r.x11_forward;
    options.tcp_keep_alive = r.tcp_keep_alive;
    ...
}
```

Figure 3. An example fuzzer for OpenSSH

Step 2: Generating fuzzing code. Given the variables to fuzz and their corresponding possible values (as specified in the configuration file), a pre-processor produces a function that is used to fuzz the configuration, as shown in Figure 3. The `fuzz_config()` function uses a covering array algorithm [11] to ensure a certain degree of coverage when exhaustive exploration of the configuration space is impossible in the lifetime of the software.

Consider k as the number of variables a configuration needs to specify and v as the number of possible values each of the k variables can be. We define the level of coverage in terms of a parameter t , which if equal to k will produce full coverage, and produce no coverage when equal to zero. The set of configurations generated is called a t -way covering array. Take a simple program that uses three ($k=3$) binary ($v=2$) variables as an example. A 3-way covering array will include all 2^3 configurations, therefore guaranteeing full coverage. A 2-way covering array will look like Figure 3-2; we notice that whichever two columns out of the three columns are chosen, all possible pairs of values appear. Specifically, the pairs 00, 01, 10 and 11 all appear in the rows when we look at the columns of AB only, AC only and BC only. This property is called "2-coverage", and corresponds to $t=2$. A notion called $CAN(t, k, v)$ represents the number of configurations in the smallest (optimal) set that holds the " t -coverage" property for a configuration space of size k^v . When using the covering array algorithm, our approach will start mutating the configuration variables with a $CAN(2, k, v)$ covering array and increase t afterwards if time permits. Ideally it would be possible to take $t=k$, but that might lead to too many configurations to test. National Institution of Standards and Technology has empirically demonstrated that for most software t need not be more than 6 to find all errors [12]. The `covering_array()` function is implemented using Jenny^{viii}, an open sourced covering array generator.

	A	B	C
	0	0	0
	0	1	1
	1	0	1
	1	1	0

Figure 3-2. A 2-way covering array

Step3: Identifying functions to test. The tester then chooses the functions that are to be the instrumentation points for Configuration Fuzzing. These can conceivably be all of the functions in the program, but would generally be the points at which vulnerabilities would most likely be revealed, or the functions that are related to the configuration variables being fuzzed. Future work could investigate a general approach to determine which functions to test. The chosen functions are annotated with a special tag in the source code. Figure 4 shows an annotated function `do_child()`.

```

/#CONFU#/
void do_child(...)
{
    ...
    ...
}

```

Figure 4. Annotated function `do_child()`

Step4: Generating test code. As an example, given an original function named `do_child()` in the program `OpenSSH`, a pre-processor first renames it to `ConFu_do_child()`, then generates a skeleton for a test function named `ConFu_test_do_child()`, which is an instance of a Configuration Fuzzing test. In the test function, the configuration fuzzer (as described above) is first called, and then the original function `ConFu_do_child()` is invoked.

```

void ConFu_test_do_child(...)
{
    fuzz_config(); /*Fuzz configuration*/
    ConFu_do_child(...); /*Call the
                           original function*/
    check_invariants();
}

```

Figure 5. Test function for `do_child()`

Based on the properties of the program being tested, different security invariants are predefined by the tester in order to check for violations. The tester writes a surveillance function called `check_invariants()` according to these security invariants. For example, the function could use the substring function `strstr(current_directory, legal_directory)` to check that the user's current directory has a specified legal directory as its root; if this function indicates otherwise, it may imply that the user has performed an illegal directory traversal. As another example, the `check_invariants()` function may simply wait to see if the original function `ConFu_do_child()` returns at all; if it does not, the process may have been killed or be hanging as a result of a potential vulnerability. These surveillance functions run throughout the testing process, and record every security invariant violation with the fault-revealing configuration into a log file that could be sent to a server for later analysis. Figure 5 shows the test function for function `do_child()`. By default, `ConFu` has three built-in security invariants that check for denial of service, unauthorized directory traversal and insufficient privilege control.

Step 5: Executing tests. In the last step, a wrapper function with the name `do_child()` is created. As in the In Vivo Testing approach, when the function `do_child()` is called, it first forks to create a new process that is a replica of the original. The child process (or the "test process") calls the `ConFu_test_do_child()` function, which performs the

Configuration Fuzzing and then exits. Because the Configuration Fuzzing occurs in a separate process from the original, the user will not see its output. Meanwhile, the original function `ConFu_do_child()` is invoked in the original process (as seen by the user) and continues as normal. The wrapper function for function `do_child()` is shown in Figure 6.

```
void do_child(...)
{
    int pid = fork(); /*Create new process*/
    if(pid == 0) { /*Test function*/
        ConFu_test_do_child(...);
        exit(0);
    }
    return ConFu_do_child(); /*Originalfunction*/
}
```

Figure 6. Wrapper function for do_child()

4 EVALUATION

4.1 Setup

In order to demonstrate the feasibility of using Configuration Fuzzing to detect vulnerabilities, we reproduced certain known vulnerabilities and used ConFu to find them. The vulnerability we chose is that early versions of OpenSSH do not properly drop privileges when the `UseLogin` option is enabled, which allows local users to execute arbitrary commands by providing the command to the `ssh` daemon^{ix}. The *CVSS Severity*^x of this vulnerability was 10 (the highest) and we believe it was mainly caused by insufficient testing of the configurations of OpenSSH. We chose this vulnerability not only because of its high severity but also because insufficient privilege control is one of the most common vulnerabilities besides denial of service and unauthorized directory traversal. The following lists the details of each step in using ConFu to detect the vulnerability.

- Identifying the configuration variables

The `sshd` server OpenSSH 2.1.0 was used as the program-under-test in our feasibility study. From the configuration file (`sshd_config`) we found that there are a total of 15 modifiable (fuzzable) configuration variables: `permit_root_login`, `ignore_rhosts`, `ignore_user_known_hosts`, `strict_modes`, `x11_forwarding`, `print_motd`, `keepalives`, `rhosts_authentication`, `password_authentication`, `permit_empty_passwd`, `kerberos_authentication`, `kerberos_or_local_passwd`, `kerberos_ticket_cleanup`, `use_login`, and `check_mail`. We annotated these variables with the possible values in the configuration file.

- Generating fuzzing code

After recognizing these configuration variables, ConFu generated the `fuzz_config()` function which mutates the configuration.

- Identifying functions to test

We picked the `do_child()` function as the function to test. The reason we picked this function in the role of software testers is that `do_child()` is responsible for creating a session and authenticating the user's identity when a ssh client tries to access the sshd server, and it is one of the functions most vulnerable to insufficient privilege control. Note that a wider range of functions can also be tested, including the `main()` function.

- Generating test code

The original function `do_child()` was renamed by a preprocessor to `ConFu_do_child()` and the test function `ConFu_test_do_child()` was generated with the `fuzz_config()` function and the `check_invariants()` function. Several security invariants were checked in our experiment, including the security invariant for privilege control, which is that a user should never be able to use other users' identities. An initial surveillance function that checks this security invariant is shown in Figure 7, which checks whether the user identification has changed.

```
void check_invariants(Session *s)
{
    if(geteuid() != s.uid || getuid() != s.uid)
        /* Log the detection */
        log("Insufficient privilege control");
    /* Check for other security invariants */
    ...
}
```

Figure 7. Surveillance function for `ConFu_test_do_child()`

- Executing tests

Last, ConFu generated a wrapper function with the name `do_child()` that forks a child process to execute the `ConFu_test_do_child()` function and runs the original function `ConFu_do_child()` in the parent process, as shown in Figure 6. Whenever `do_child()` gets called, the wrapper function gets executed that checks for violation of security invariants under the mutated configuration with user input in the duplicated process.

4.2 Results

To facilitate the exploitation, we simulated both valid and invalid combinations of username and password as user inputs in the real-world for the instrumented sshd server. If the vulnerability is exploited, the server program records the exploitation with its corresponding configuration in a log file¹. We ran the program 10,000 times, which took roughly ten minutes. A fragment of the log file is shown in Figure 8. By analyzing the log file, we were able to find the mapping between the `UseLogin` option and insufficient privilege control. It is also worth pointing out that the number of detections in the log file was identical to the number of tests where `UseLogin` was enabled (with valid input). We have not yet managed to detect new vulnerabilities, however, this study demonstrates the

¹ Might need to raise an alert when an exploitation is detected.

functional feasibility of the Configuration Fuzzing approach. Performance feasibility is discussed below.

```

permit_root_login option is:0
...
...
UseLogin option is:1
Check_mail option is: 0
Insufficient privilege control

permit_root_login option is:1
...
...
UseLogin option is:1
Check_mail option is: 0
Insufficient privilege control

```

Figure 8. Log file of the OpenSSH server

4.3 Performance

The performance impact of ConFu is crucial because Configuration Fuzzing tests are executed while the program-under-test is running. We evaluated our approach's performance by applying it to the OpenSSH server with the steps stated above. `do_child()` is chosen as the function to test and 15 configuration variables are fuzzed. All experiments were conducted on an Intel Core2Quad Q6600 server with a 2.40GHz CPU and 2GB of RAM running Ubuntu 8.04.3.

# of tests	Overhead introduced by <code>fuzz_config()</code>	Overhead introduced by <code>ConFu_do_child()</code>	Overhead introduced by <code>check_invariants()</code>	Total Avg. additional time per test
100	3.446	0.271	0.001	0.037
1000	42.23	2.434	0.014	0.045
10000	378.2	29.92	0.157	0.041
100000	3694	236.8	1.628	0.039

Figure 9. Overhead of instrumented `do_child()`(in seconds) with varying number of tests

For both the original code (without instrumentation) and the instrumented code, we simulated user inputs (both valid and invalid) for the `do_child()` function and recorded the function's execution time. The OpenSSH service was provided on the test machine, and the `do_child()` function sent requests to IP address 127.0.0.1 rather than to other servers to eliminate any overhead from network traffic. We ran tests in which the function was called 100, 1000, 10000 and 100000 times in order to estimate the overhead caused by our approach.

Figure 9 shows the results we collected from the experiments. The first column shows

the number of tests that were carried out, i.e., the number of times the `do_child()` function was called. The second and third columns are the overhead in seconds for the `fuzz_config()` function and the `ConFu_do_child()` function, respectively. The total average additional time (in seconds) per instrumented test is listed in the last column. From the results we can see that the average additional cost per test stayed around 45ms and did not increase when the number of tests grew. Thus, a single client of a server running OpenSSH with ConFu is unlikely to notice any performance slowdown. It is worth mentioning that most of the performance overhead comes from the cost of generating the covering arrays in `fuzz_config()`, and this cost is only affected by the number of variables being fuzzed.

To obtain better performance, software testers could, in principle, pre-calculate the covering arrays for the chosen configuration variables before the software is shipped. However, since many configuration options are enabled or disabled at build time and later hotfixes might add more configuration options, it is more secure to calculate the covering array during the runtime of the software.

5 RELATED WORK

5.1 Security testing

One approach to detecting security vulnerabilities is environment permutation with fault injection [13], which perturbs the application external environment during the test and checks for symptoms of security violations. Most implementations of this approach view the security testing problem as the problem of testing the fault-tolerance properties of a software system [5] [24]. They consider each environment perturbation as a fault and the resulting security compromise a failure in the toleration of such faults. However, as the errors being injected are independent of the software, most of these errors might not occur in real-world usage. Therefore, fault injection testing may raise false positives.

Instead of injecting faults, ConFu mutates the configuration under predefined configuration constraints of the software-under-test to produce potential vulnerabilities, which relies on the internal properties of the software. Hence it would decrease the occurrence of false positives considerably. The two approaches, however, could certainly be used in conjunction with each other; we leave this as future work.

Another security testing approach used to detect vulnerabilities is anomaly detection [10] [15]. Anomaly detection first establishes a model of normal behavior then detects data sets that cause the program to not conform to the model. Anomaly detection is potentially capable of detecting zero day attacks; however, it is always difficult to define normal behavior. Thus, these approaches depend on the validity of the normal behavior model being used. Anomaly detection may suffer severely from false positives.

ConFu treats the violations of security invariants as vulnerability exploits, and these security invariants are defined based on the consequences of known abnormal behaviors. In a sense, ConFu uses a model of abnormal behaviors that is much easier to obtain than a model of normal behaviors. Hence ConFu would be expected to have fewer false

positives; however, further empirical studies are needed to compare the effectiveness and efficiency between these two approaches.

Another popular approach is fuzz testing [23]. It simply feeds randomly generated inputs to a software application and monitors its failures. Typical fuzz testing is scalable, automatable and does not require access to the source code. The notion behind this technique is that the randomly generated inputs often exercise overlooked corner cases in the parsing component and error checking code. This technique has been shown to be effective in uncovering errors [14], and is used heavily by security researchers [4]. Yet it also suffers from several problems: a single unsigned int value can vary from 0 to 65535; adding another int value to the input domain causes the input space to grow exponentially, which can hardly be covered with limited time and cost. Furthermore, by only changing the input, a fuzzer may not put the application into a state in which the vulnerability will appear. White-box fuzzing [7] was introduced to help generate well formed inputs instead of random ones and therefore increases their probability of exercising code deep within the semantic core of the computation. It analyzes the source code for semantic constraints and then produces inputs based on them or modifies valid inputs. White-box fuzzing improves the effectiveness of fuzz testing; however, it overlooks the enormous size of the input space and also suffers from severe overhead [8].

ConFu deals with this problem by mutating the configuration rather than randomly generating inputs of the program-under-test. The space of the former is considerably smaller than the latter and is more relevant in triggering potential illegal states. In addition, extending the testing phase into deployed environments ensures representative real-world user inputs with which to test.

5.2 Configuration testing

Researchers and testers have done lots of work in testing software configuration. The importance of configuration testing has increased as more and more vulnerabilities are discovered to be caused by inappropriate configuration. However, most of these popular configuration testing approaches were not designed to reveal security defects. One approach named Ratchet [26], is designed to test the compatibility of a software by mutating configuration in the development process. Ratchet models the entire configuration space for software systems and uses the model to generate test plans to sample a portion of the space, and later uses these test plans to test the compatibility between the software and other software during its compile time.

Another approach called Skoll [17] is composed of software quality assurance (QA) processes that leverage the extensive computing resources of volunteer communities to improve software quality. Skoll takes a QA process' configuration space to build a formal model that captures all valid configurations for QA subtasks, and uses this model to generate test cases for each machine in the community. The idea is to reduce duplication and spread testing burden across the community. Skoll collects the pass/fail results of all the tests to provide feedback to the developers.

Both of these approaches are able to detect functionality errors when the program-under-test fails. However, vulnerabilities such as security defects are more difficult to

find since most of them will not lead the program to failure. ConFu deals with this problem by checking the violations of security invariants with surveillance functions. Whereas vulnerabilities such as directory traversal and insufficient privilege control can easily hide themselves from being detected by Ratchet or Skoll, ConFu can still catch these vulnerabilities when they alter the values of the security invariants.

6 LIMITATIONS

The most critical limitation of the current implementation is that testers' intervention is required to identify the functions to test. In principal, one can always choose the main() function, but it might be less efficient and increase the overhead. A better way to determine the function-under-test might be picking the most frequently called functions according to real world usage, or choosing the currently running function with a run-time injection approach such as the one proposed by Antoni et al. [1], or. We leave this as future work.

ConFu relies on surveillance functions that check for violations of security invariants to detect vulnerabilities. Therefore, software testers need a priori knowledge of the potential exploitation behavior in order to design specific surveillance functions. ConFu's built-in surveillance functions check for common security invariants and are capable of detecting most well-known exploits, e.g. denial of service, directory traversal, etc. However, they might not be as effective in detecting zero day vulnerabilities.

Because each configuration is only tested with relatively few inputs, the chance of detecting a vulnerability that would only be revealed under one specific configuration with one particular input is relatively low using the current ConFu implementation. A distributed version of ConFu would increase the efficiency of detecting such vulnerabilities, in which the testing assignments are split amongst applications running in a homogenous "application community" [16]. We have developed a distributed In Vivo Testing framework [3] and we leave it as future work to develop a global coordinator that is in charge of allocating test cases for each deployed configuration across the user community, and collecting and analyzing the results for ConFu.

7 CONCLUSION

In this thesis, we explored an approach for software vulnerability detection in the domain of security testing [28] and developed a framework called ConFu based on our approach [29]. Vulnerability detection is difficult to achieve not only because the characteristics of vulnerabilities are hard to define but also because of the immensity of the input and configuration space. Our proposed approach, Configuration Fuzzing, deals with these problems by extending the testing phase into the deployment environment while ensuring a considerable degree of coverage configuration space and representative samples of the input space. Surveillance functions that check for violations of security invariants are executed during Configuration Fuzzing in order to detect vulnerabilities. Configuration Fuzzing tests happen in a duplicated copy of the original process, so that they do not affect the state of the running application. As future work, we are planning to develop a distributed version of ConFu with a full-fledged sandbox, which will significantly further its potential in detecting software vulnerabilities. We believe that ConFu can help

developers build more secure software and improve the security of existing software systems.

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ⁱⁱ <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-2007-1742>

ⁱⁱⁱ <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-2008-1668>

^{iv} <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-2004-2259>

^v <http://www.openssh.com/>

^{vi} <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-2008-5666>

^{vii} <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-2007-5461>

^{viii} <http://burtleburtle.net/bob/math/jenny.html>

^{ix} <http://web.nvd.nist.gov/view/vuln/detail?vulnId=CVE-CVE-2000-0525>

^x <http://www.oracle.com/technology/deploy/security/cpu/cvssscoringsystem.htm>

Appendix A Annotated OpenSSH Configuration File

```
# This is ssh server systemwide configuration file.

Port 22
#Protocol 2,1
ListenAddress 0.0.0.0
#ListenAddress ::
HostKey /etc/ssh_host_key
ServerKeyBits 768
LoginGraceTime 600
KeyRegenerationInterval 3600
PermitRootLogin yes #[options.permit_root_login]@{0,1}
#
# Don't read ~/.rhosts and ~/.shosts files
IgnoreRhosts yes #[options.ignore_rhosts]@{0,1}
# Uncomment if you don't trust ~/.ssh/known_hosts for
RhostsRSAAuthentication
#IgnoreUserKnownHosts yes
StrictModes yes #[options.strict_modes]@{0,1}
X11Forwarding no #[options.x11_forwarding]@{0,1}
X11DisplayOffset 10
PrintMotd yes #[options.print_mod]@{0,1}
KeepAlive yes #[options.keepalives]@{0,1}

# Logging
SyslogFacility AUTH
LogLevel INFO
#obsoletes QuietMode and FascistLogging

RhostsAuthentication no #[options.rhosts_authenticaiton]@{0,1}
#
# For this to work you will also need host keys in
/etc/ssh_known_hosts
RhostsRSAAuthentication no #[options.rhosts_rsa_authenticaiton]@{0,1}
#
RSAAuthentication yes #[options.rsa_authenticaiton]@{0,1}

# To disable tunneled clear text passwords, change to no here!
PasswordAuthentication yes #[options.password_authenticaiton]@{0,1}
PermitEmptyPasswords no #[options.permit_empty_passwd]@{0,1}
# Uncomment to disable s/key passwords
#SkeyAuthentication no

# To change Kerberos options
KerberosAuthentication no #[options.kerberos_authentication]@{0,1}
KerberosOrLocalPasswd yes #[options.kerberos_or_local_passwd]@{0,1}
AFSTokenPassing no
KerberosTicketCleanup no #[options.kerberos_ticket_cleanup]@{0,1}

# Kerberos TGT Passing does only work with the AFS kaserver
#KerberosTgtPassing yes
```

```
CheckMail no #[options.check_mail]@{0,1}
UseLogin no #[options.use_login]@{0,1}
```

Appendix B Fuzzer Code Using Jenny

```
/* a fuzzer which generates covering array. */
int fuzz(int* cnt,...)
{
    static int way = 0; /* specify which way we are in */
    FILE *test2 = fopen("2way.carray", "r");
    FILE *test3 = fopen("3way.carray", "r");
    FILE *test4 = fopen("4way.carray", "r");
    FILE *test5 = fopen("5way.carray", "r");
    FILE *test6 = fopen("6way.carray", "r");
    if(test2){
        fclose(test2);
        way = 2;
    }
    else if(test3){
        fclose(test3);
        way = 3;
    }
    else if(test4){
        fclose(test4);
        way = 4;
    }
    else if(test5){
        fclose(test5);
        way = 5;
    }
    else if(test6){
        fclose(test6);
        way = 6;
    }
    int count =*cnt;
    int i,j;
    int *tmp;
    char jenny[512] = "jenny -n2"; /* Put jenny in /bin on the
host */
    char content[256] = "\0";
    char out[256] = " > 2way.carray";
    char cmd1[256] = "2way.carray"; /*cmd[0]*/
    char cmd2[256] = "sed '1d' 2way.carray > array.tmp";
/*cmd[9]*/
    char cmd3[256] = "cp array.tmp 2way.carray";/*cmd[13]*/
    char cmd4[256] = "rm -f 2way.carray";/*cmd[6]*/
    char cmd5[256] = "3way.carray";/*cmd[0]*/
    char cmd6[256] = "sed '1d' 3way.carray > array.tmp";/*cmd[9]*/
    char cmd7[256] = "cp array.tmp 3way.carray";/*cmd[13]*/
    int nposition = 8 + count * 2 + 4;
    va_list ap;
    va_start(ap, *cnt);
```

```

for(; count>0; count--){
    strcat(content, " 2");
}
strcat(jenny, content);
strcat(jenny, out);
/*The cnt -9 field is for digits bigger than 9*/
int x = (*cnt) * 3 + 1;
if(*cnt > 9) x+=(*cnt) - 9;
char buf[x];
switch (way) {
    case 0:
        //printf("full command is: %s\n", jenny);
        system(jenny);
        char filename[100] = "2way.carray";
        FILE *file = fopen(filename,"r");
        if (fgets( buf, x, file)){
            buf[x-1]='\0';
            //printf("the buf is %s\n",buf);
            fclose(file);
            system("sed '1d' 2way.carray > array.tmp");
            system("cp array.tmp 2way.carray");
            system("rm -f array.tmp");
            /* assign values to global variables */
            for(i=0,j=0;i<strlen(buf);i++){
                if(buf[i]=='a'){
                    tmp = va_arg(ap, int*);
                    *tmp=0;
                    j++;
                }
                if(buf[i]=='b'){
                    tmp = va_arg(ap, int*);
                    *tmp=1;
                    j++;
                }
            }
        }
        return 0;
    case 2:
        printf("!!!!in case 2 now\n");
        jenny[8] = '3';
        jenny[nposition] = '3';
        break;
    case 3:
        printf("!!!!in case 3 now\n");
        cmd1[0] = '3';
        cmd2[9] = '3';
        cmd3[13] = '3';
        cmd4[6] = '3';
        if(*cnt >= 4){
            cmd5[0] = '4';
            cmd6[9] = '4';
            cmd7[13] = '4';
            jenny[8] = '4';
        }
}

```

```
        jenny[nposition] = '4';
    }else {
        cmd5[0] = '2';
        cmd6[9] = '2';
        cmd7[13] = '2';
        jenny[8] = '2';
        jenny[nposition] = '2';
    }
    break;
case 4:
    printf("!!!!in case 4 now\n");
    cmd1[0] = '4';
    cmd2[9] = '4';
    cmd3[13] = '4';
    cmd4[6] = '4';
    if(*cnt >= 5){
        cmd5[0] = '5';
        cmd6[9] = '5';
        cmd7[13] = '5';
        jenny[8] = '5';
        jenny[nposition] = '5';
    }else {
        cmd5[0] = '2';
        cmd6[9] = '2';
        cmd7[13] = '2';
        jenny[8] = '2';
        jenny[nposition] = '2';
    }
    break;
case 5:
    printf("!!!!in case 5 now\n");
    cmd1[0] = '5';
    cmd2[9] = '5';
    cmd3[13] = '5';
    cmd4[6] = '5';
    if(*cnt >= 6){
        cmd5[0] = '6';
        cmd6[9] = '6';
        cmd7[13] = '6';
        jenny[8] = '6';
        jenny[nposition] = '6';
    }else {
        cmd5[0] = '2';
        cmd6[9] = '2';
        cmd7[13] = '2';
        jenny[8] = '2';
        jenny[nposition] = '2';
    }
    break;
case 6:
    printf("!!!!in case 6 now\n");
    cmd1[0] = '6';
    cmd2[9] = '6';
```

```

        cmd3[13] = '6';
        cmd4[6] = '6';
        cmd5[0] = '2';
        cmd6[9] = '2';
        cmd7[13] = '2';
        jenny[8] = '2';
        jenny[nposition] = '2';
        break;
    }
    FILE *old = fopen(cmd1, "r");
    if (fgets(buf, x, old)){
        buf[x-1]='\0';
        //printf("line: %s, x=%d\n",buf,x);
        fclose(old);
        system(cmd2);
        system(cmd3);
        system("rm -f array.tmp");
        for(i=0,j=0; i<strlen(buf); i++){
            if(buf[i]=='a'){
                tmp = va_arg(ap, int*);
                *tmp = 0;
                j++;
            }
            if(buf[i]=='b'){
                tmp = va_arg(ap, int*);
                *tmp = 1;
                j++;
            }
        }
    } else {
        system(jenny);
        system(cmd4);
        FILE *new = fopen(cmd5, "r");
        if (fgets(buf, x, new)){
            buf[x-1]='\0';
            //printf("line: %s, x=%d\n",buf,x);
            fclose(new);
            system(cmd6);
            system(cmd7);
            system("rm -f array.tmp");
            for(i=0,j=0; i<strlen(buf); i++){
                if(buf[i]=='a'){
                    tmp = va_arg(ap, int*);
                    *tmp = 0;
                    j++;
                }
                if(buf[i]=='b'){
                    tmp = va_arg(ap, int*);
                    *tmp = 1;
                    j++;
                }
            }
        }
    }
}

```

```
    }
  }
  return 0;
}
```

Appendix C Preprocessor of CONFU

```
#!/usr/bin/perl5.10.1
#Usage: ./preprocessor <Config file> <source file> <check_invariant
file>
use 5.010;
use strict;

my $count = @ARGV;
my $readable = 1;
my @configuration;
foreach(@ARGV){
    if(not -f $_){
        $readable = 0;
        last;
    }
}
if( $count < 3 or not $readable){
    say "Usage: ./preprocessor <Config file> <source file>
<check_invariant file>";
    exit(0);
}

open CONFIG, "<", $ARGV[0] || die "Cannot open the configuration
file. $/";
while(<CONFIG>){
    if( $_ =~ /\#\[(.*)\]@\{(.*)\}/){
        push(@configuration, $1);
    }
}

#foreach (keys %configuration){
#    say "$_ ==> $configuration{$_}";
#}

my $c_count = scalar @configuration;
my $keys = "";
foreach (@configuration){
    $keys.="&$_,";
}
$keys =~ s/,,$//;
my $fuzz_func = "void fuzz_config()\n{\n\tint cnt =
$c_count;\n\tfuzz(&cnt,$keys);";
foreach (@configuration){
    state $i = 1;
    $fuzz_func .= "\n\tchar log$i\[100\] = \"$_ is:\n\t";
    $fuzz_func .= "sprintf(log$i+strlen(log$i), \"%d\", $_);\n\t";
}
```

```

        $fuzz_func .= "writelog(log$i);\n\t";
        $fuzz_func .= "writelog(\"\\n\\n\");";
        $i++;
    }
    $fuzz_func .=
    "\n\twritelog(\"//////////////////////////////////////\\n\");\n}";

my $fuzzcode;
{
    local @ARGV = ("fuzzer.c");
    while(<>){
        $fuzzcode.= $_;
    }
}
$fuzzcode .= "\n$fuzz_func";

my $line;
my $func_name;
my $type;
my $argv;
my $insert_line;
#say $fuzzcode;

{
    local @ARGV = ($ARGV[1]);
    local $^I = '.bak';
    while(<>){
        if(/\/\/*\#CONFU#\*\/){
            $line = $.;
        }elseif($. == $line + 1){
            /^s*(\w+\**)\s*(\w+)\((.*)\)/;
            $type = $1;
            $func_name = $2;
            $argv = $3;
            s/$2/CONFU_$func_name/;
            print;
        }else{
            print;
        }
    }
}

my $check_func;
my $check_code;
open CHECK, "<", $ARGV[2];
while(<CHECK>){
    $check_code .= $_;
    if(/^w+\s*(\w+)\s*\(/){
        $check_func = $1;
    }
}

#Hard coded arguments, need to change#
my $testcode;

```

```
$testcode = "\n$type
CONFU_TEST_$func_name($argv){\n\tfuzz_config();\n\tCONFU_$func_name(
home, file, real);\n\treturn $check_func(home, real);\n}";
$fuzzcode .= "\n$check_code";
$fuzzcode .= "\n$testcode";

my $wrapper;
$wrapper = "$type $func_name($argv){\n\tint pid = fork();\n\tif(pid
== 0){\n\tCONFU_TEST_$func_name(home, file,
real);\n\texit(0);\n}return CONFU_$func_name(home, file, real);\n}";
$fuzzcode .= "\n$wrapper";

#say $fuzzcode;
{
    local @ARGV = ($ARGV[1]);
    local $^I = '.bak2';
    while(<>){
        if(/s*\w+s*main\s*\(/){
            print $fuzzcode;
            print $_;
        }else{
            print;
        }
    }
}
```