Waffle

by

Behnam Bojnordi Arbab

Previous Degrees (i.e. Degree, University, Year)
Bachelor of Computer Engineering, Ferdowsi University of Mashhad, 2015

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Computer Science

In the Graduate Academic Unit of Computer Science

Supervisor(s):	Ali Ghorbani, Faculty of Computer Science
Examining Board:	N/A
External Examiner:	N/A

This thesis is accepted by the
Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

.

Abstract

Start writing from here. (not more than 350 words for the doctoral degree and not more than 150 words for the masters degree).

Dedication

Dedicated to knowledge.

Acknowledgements (if any)

Start writing here. This is optional.

Table of Contents

List of Tables

List of Figures

List of Symbols, Nomenclature or Abbreviations

Start writing here. This is optional.

$\sum$ \sum
$\bigcap$ \bigcap

Chapter 1

Introduction

1.1 Introduction

1.2 Summary of contributions

The fundamental goal of this thesis is to suggest a technique developed on AFL to identify the vulnerabilities related to excessive resource usages. The summary of our contributions follows:

- For **instrumentations**, we have proposed a technique of instrumenting a program to log the usage of resources in runtime. To collect the information, we leverage the *visitor* functions that LLVM project provides. We have empirically proved that the new instrumentation does not bring a noticeable overhead.
- We have changed the fuzzing procedure to consider the new instrumentations and enhance the generations of inputs with a higher number of executions of the specified visited instructions.

- We integerate the instrumentations and fuzzing procedure on top of AFL. Our experiments have shown an improvement in the code coverage of AFL. As the current version of our fuzz testing has introduced new bottlenecks, we may improve the code coverage more significantly. The source code is available on github [4].

1.3 Thesis Organization

Chapter 2

Background

2.1 Introduction

Fuzzing (short for fuzz testing) is a tool for "finding implementation bugs using malformed/semi-malformed data injection in an automated fashion". Since the late '80s, fuzz testing has proved to be a powerful tool for finding errors in a program. For instance, American Fuzzy Lopper (AFL) has found more than a total of 330 vulnerabilities from 2013 to 2017 in more than 70 different programs [5]. The research on fuzz testing has found its place in software security testing. Liang et al. [1] illustrates the growth of the primary studies from the following publishers: *ACM digital library*, *Elsevier ScienceDirect*, *IEEEXplore digital library*, *Springer online library*, *Wiley InterScience*, *USENIX*, and *Semantic scholar*. The queries for the literature reviews are "fuzz testing", "fuzzing", "fuzzer", "random testing", or "swarm testing" as the keywords of the titles. Figure 2.1 presents the results of the mentioned study.

A *run* is a sequence of instructions that connects the start and termination of a program. A successful run (execution) behaves as the program is intended to

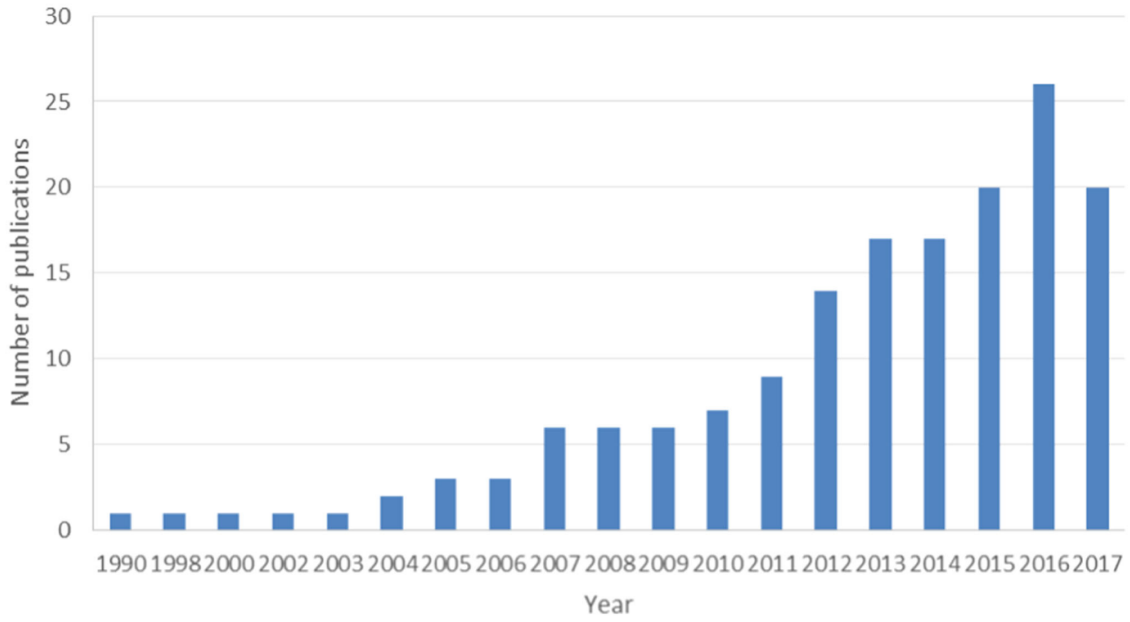


Figure 2.1: Fuzzing papers published between January 1st, 1990 and June 30 2017. [1]

run. An exception is a signal that is thrown, indicating an unexpected behavior. If the exception is not caught before the program's termination, the operating system receives an unfinished task with exception descriptions. From the OS's perspective, the program has crashed and could not finish its execution properly. A software vulnerability is an unexpected state of the program that is failed to be handled. Different states of a program occur by different inputs that a program takes. The inputs such as *environment variables*, *file paths*, or other program's *arguments* are mainly selected to search for the vulnerabilities.

Fuzz testing is the repetitive executions of a target program with different inputs. Fuzz testing takes two main actions in the fuzzing procedure: the fuzzer *generates test cases* for the target program, and each generated (fuzzed) test case is then passed to the program for *execution*. A fuzzer gathers information out of each execution. A *whitebox* fuzzer has access to the source code of the target program. *Analyzing the source code*, *monitoring the execution*, and *validating the returned value of execution*, are of the capabilities of a whitebox fuzzer. Oppositely, a *blackbox* fuzzer does not

have any access to the source code, cannot analyze the execution and does not check the result of the execution. Instead, a blackbox fuzzer focuses on executing more instances of the program blindly. Fuzzers with at least one property from each of the whitebox and blackbox fuzzers are in the category of *greybox* fuzzers.

The common strategies for fuzzing new test cases include *genetic algorithms*, *coverage-based (coverage-guided) strategies*, *performance fuzzing*, *symbolic execution*, *taint-based analysis*, etc. Genetic algorithms (GA) are *evolutionary algorithms* for generating solutions to *search* and *optimization problems*. GA has a population of solutions that their evaluations affect their survivability for the next generation. Inspired by the biological operations, GA processes the selected (survived) population and applies *mutations* and other modifications on them, resulting in a new generation of the population [6, 7]. Coverage-guided strategy is a genetic algorithm that utilizes *concrete analysis* of the *execution-path* of a program. A concrete analysis investigates the runtime information of an executive program, and the graph of the executed instructions (execution-path) can be collected through this analysis. Symbolic executions determine the constraints that change the execution-paths [8]. Performance fuzzing is a coverage-based technique that generates *pathological inputs*. "Pathological inputs are those inputs which exhibit worst-case algorithmic complexity in different components of the program" [9]. A taint-based analysis of a program tracks back the variables that cause a state of the executing program. This approach can detect vulnerabilities with no false positives [10].

American Fuzzy Lopper (AFL) [11] is a coverage-based greybox fuzzer, that is originally considering the number of times each *basic block* of execution is visited. Each basic block is a sequence of instructions with no branches except the entry (jump in) and exit (jump out) of the sequence. AFL is published with two default tools for collecting the runtime information: *LLVM* [12] and *QEMU* [13]. "The

LLVM Project is a collection of modular and reusable compiler and toolchain technologies. Despite its name, LLVM has little to do with traditional virtual machines. The name "LLVM" itself is not an acronym; it is the full name of the project." AFL acts as a **whitebox** fuzzer in *llvm-mode*. In **llvm-mode**, AFL provides the recipe for compiling the target program with coverage information. The resulting compiler adds *static instrumentations* (**SI**) to the program. Instrumentation is the process of injecting logging instructions into the program, and SI refers to the instrumentations applied on a binary before execution. The added instructions store the code coverage and AFL can use them in Fuzzing. QEMU (Quick EMUlator) is an open-source emulator and virtualizer that helps AFL with *dynamic instrumentation* (**DI**). In DI, the instructions are inserted in runtime, and an emulator such as QEMU helps AFL with discovering the code coverage [14]. *DynamoRIO* [15], *Frida* [16], and *PIN* [17] are some other examples of pioneer DI tools.

In this chapter, we begin with reviewing the previous works that lead to this thesis 2.2. Next, we describe the implementation of AFL and its llvm-mode in **??**. We wrap up this chapter with conclusions.

2.2 Literature Review

Fuzzing searches for software vulnerabilities. "Vulnerability" has different definitions under various organizations and researches. For instance, *International Organization for Standardization (ISO)* defines vulnerability as: "A weakness of an asset or group of assets that can be exploited by one or more threats, where an asset is anything that has value to the organization, its business operations and their continuity, including information resources that support the organization's mission." [18] Yet, the definition needs more details for software.

2.2.1 Software vulnerability

According to the *Open Web Application Security Project (OWASP)*: "A vulnerability is a hole or a weakness in the application, which can be a design flaw or an implementation bug, that allows attackers cause harm to the stakeholders of an application. Stakeholders include the application owner, application users, and other entities that rely on the application." The existence of software vulnerabilities may be compromised and may become an attack target for hackers; this makes the software unreliable for its users.

To exploit a vulnerability, an attacker calls an execution containing the bug and redirects the program's flow with appropriate inputs. An exploitable vulnerability may escalate privileges, leak information, modify/destroy protected data, stop services, execute malicious code, etc. [19]. An analysis of the program may prevent the exposure of vulnerabilities and stop further harm. Various techniques are used to identify weaknesses and vulnerabilities of software. Techniques such as *static analysis*, fuzzing, taint analysis and symbolic execution, etc. are the most common techniques that can be used cooperatively for error detection [20]. The static analysis evaluates the source code or binary to expose the vulnerabilities without executing the program.

To investigate a program for bugs, a model that helps the research is **Control Flow Graph (CFG)**. CFG is a directed graph whose nodes are the basic blocks of the program, and its edges are the flow path of the execution between two consecutive basic blocks. For instance, the Figure 2.2a illustrates the CFG for *bubblesort* algorithm (Algorithm 1). The branches in CFG split after a *conditional instruction* and a relevant *jump instruction*.

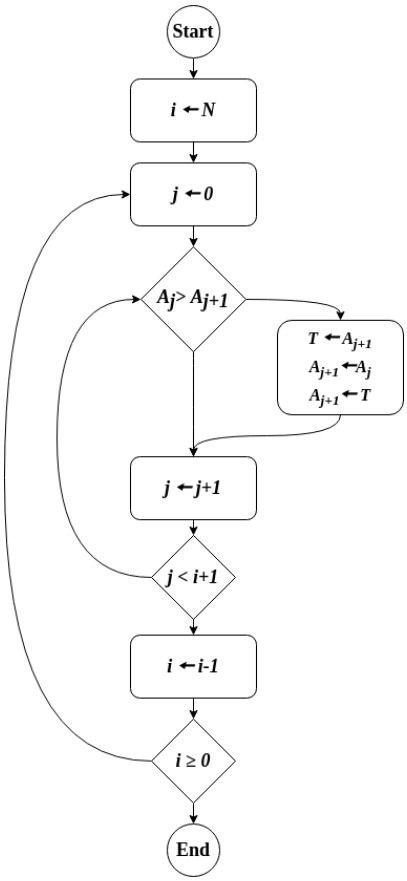
An execution processes a path (sequence) of instructions from an entry to any

Algorithm 1: Pseudocode of bubblesort on array A of size N

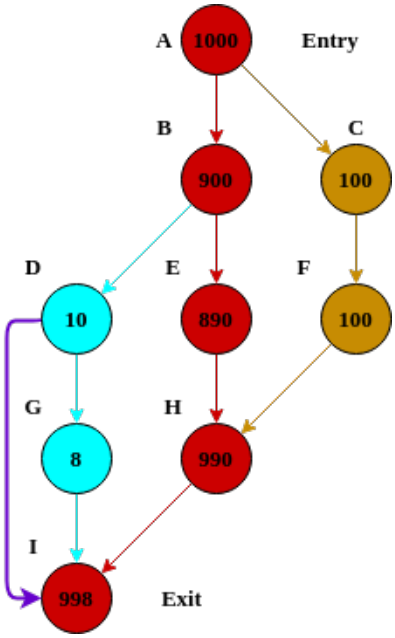
```
   Input: A, N
 1 i ← N;
 2 do
 3 |   j ← 0;
 4 |   do
 5 |   |   if A_j > A_{j+1} then
 6 |   |   |   SWAP(A_j, A_{j+1});
 7 |   |   j ← j + 1;
 8 |   while j < i + 1;
 9 |   i ← i − 1;
10 while i >= 0;
```

exit location of the program. For instance, consider Figure 2.2b as a CFG illustrating the executed paths of 1000 trials of the program's execution. The numbers in the basic blocks indicate the number of times each basic block is visited. A path such as $A \rightarrow B \rightarrow E \rightarrow H \rightarrow I$ has been explored more than other execution paths. Basic block D is visited occasionally and the edge $D \rightarrow I$ directly goes to the Exit, representing bugs in basic block D. These 1000 trials have discovered 9 seperable basic blocks, but it does not imply that there is no other basic blocks or edges revealed after more trials. Code coverage measures number of basic blocks which could be reached in an experiment of trials.

Denial of service (DoS) is a category of vulnerabilities through network that prevents services from correctly responding back to the users. "There are many ways to make a service unavailable for legitimate users by manipulating network packets, programming, logical, or resources handling vulnerabilities, among others. If a service receives a very large number of requests, it may cease to be available to legitimate users. In the same way, a service may stop if a programming vulnerability is exploited, or the way the service handles resources it uses" [21]. In software domain, the vulnerability is either due to an early termination through a crash, or the program terminates with a timeout.



(a) Control Flow Graph of bubble-sort algorithm [Algorithm 1]



(b) CFG Heatmap of Algorithm 1. In 1000 runs, different paths are discovered.

Figure 2.2: Control Flow Graph

The vulnerabilities arise after target program executes with a triggering input. Miller introduced fuzz testing to examine the vulnerabilities of a collection of Unix utilities [22]. The results showed that a random fuzzing on different versions of the utilities could discover bugs in 28% of the targets. The automation in testing programs helps the researchers with validating the reliability of a program. The early fuzzers mimic a procedure of searching for the bugs by starting with *identification* of the target program and its inputs. Next, the fuzzing loop initiates, and the program is run with fuzzed inputs as long as the fuzz testing is not terminated. Figure 2.3 depicts the fuzz testing procedure defined by Sutton et al. [2]. Based on the definitions, a standard fuzzer consists of:

- Target identification
- Inputs identification
- Fuzzed data generation
- Execution of target with fuzzed data
- Exceptions monitoring
- Exploitability determination

Target is a software or a combination of executables and hardware [23]. A targeted software is any program that a machine can execute. Fuzzer needs to know the command for executing the target program and the inputs (arguments) of the program. **Inputs** are a set of environmental variables, file formats, and any other parameters that affect the execution. The initial seeds of the inputs can guide the fuzzer for finding more complex test cases, yet, it is not mandatory to provide seeds, and a fuzzer can generate valid inputs *out of thin air* [24]. After the initial setup, the **fuzzing loop** begins iterating. In each iteration the fuzzer **executes** the target with the **provided test cases**. Fuzzer then proceeds to detect exceptions returned

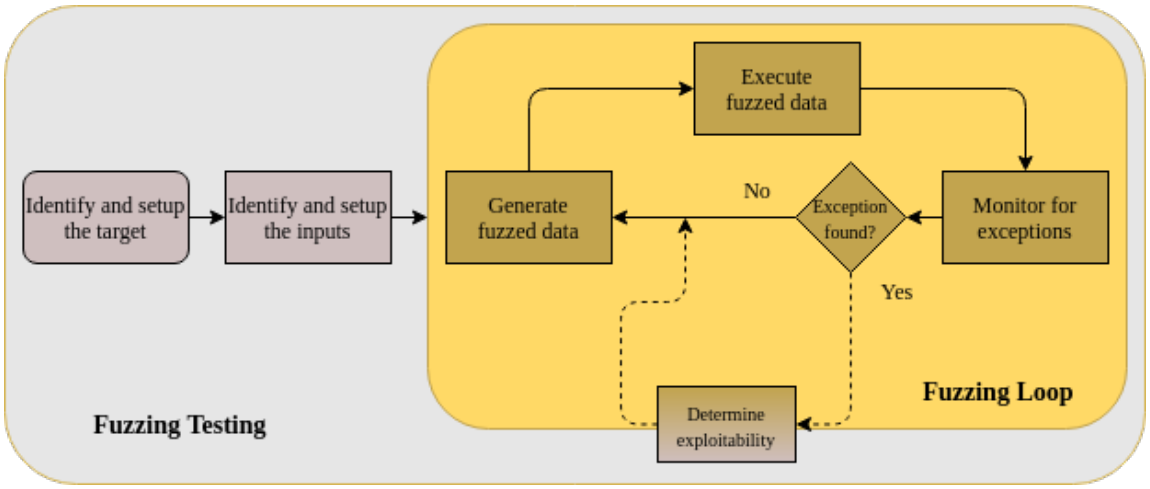


Figure 2.3: Fuzzing phases. Inspired by the definition of Sutton et al. [2]

from the executions, and considers the executed input responsible for causing a **vulnerability**. The vulnerability can then be analyzed for **exploitability** in the last stage. An exploitable vulnerability can compromise the system and initiate an anomaly.

The categories for fuzzers with different **program awareness** and different **techniques for fuzzing** the inputs help the community find different applications of the fuzzers for discovering more vulnerabilities. For instance, a developer uses a whitebox fuzzer to assess the immunity of the program (source-code accessible) against malicious activities. On the other hand, an attacker may use a blackbox fuzzer to attack a remote program blindly. A researcher may use a coverage-based fuzzer to consider the execution paths as a variable to reach more regions of the code and detect more crashes; hence, another researcher may use a performance fuzzer to reveal the test cases causing performance issues.

2.2.2 Program awareness

The *colorful* representation of fuzzers depends on the amount of information collected from a symbolic/concrete execution. A blackbox fuzzer does not gather any information from the execution. In contrast, whitebox fuzzers have all the required access to the program's source code, and greybox fuzzing covers the gray area between the mentioned types.

2.2.2.1 Blackbox fuzzing

Blackbox fuzz testing is a general method of testing an application without struggling with the analysis of the program itself. The target of an analysis executes after calling the proper API's, and the errors are expected to occur in the procedure of trying

various inputs. Blackbox fuzzing is an effective technique though its simplicity [25].

The introduced fuzzer by Miller [22] was of the very first naive blackbox fuzzers. It runs the fuzzing for different lengths of inputs for each target (of the total 88 Unix utilities) and expects a **crash**, **hang**, or a **succeed** after the execution of the program. Each input is then fuzzed with a random mutation to generate new test cases. One of the **downsides** of blackbox fuzzing is that the program may face branches with *magic values*, constraining the variables to a specific set of values; for instance, as shown in Listing 2.1, the chance of satisfying the equation `magic_string=="M4G!C"` and taking the `succeed()` path is almost zero. In [26] and [27] a set of network protocols are fuzzed in a blackbox manner, but as the target is specified, the performance is enhanced drastically. Any application on the web may be considered a blackboxed program as well, so as [28] and [29] have targeted web applications and found ways to attack some the websites, looking for different vulnerabilities, such as XSS.

```
1  string magic_string = random_string();
2  if(magic_string == "M4G!C")
3      return succeed();
4  else
5      return failed();
```

Listing 2.1: Magic Value: `M4G!C` is a magic value

A blackbox fuzzer is unaware of the program's structure and cannot monitor it's execution. The **benefit** of using a blackbox fuzzer is the speed of test case generation; the genuine compiled target program is being tested and the fuzzer does not put an effort on processing the inputs and executions. In addition, a blackbox fuzzer is featured to target external programs by using the standard interfaces of those programs. For instance, IoTFuzzer [30] is an Internet of Things (IOT) blackbox fuzzer, "which aims at finding memory corruption vulnerabilities in IoT devices without access to their firmware images." In a recent research by Mansur et al. [31], they introduce a blackbox fuzzing method for detecting bugs in Satisfiability Modulo

Theories (SMT) problems. As a result, blackbox fuzzing suggests a general solution in diverse domains. On the other hand, one of **drawbacks** of using blackbox fuzzing is that it finds *shallow* bugs. A shallow vulnerability is an error that appears in the early discovered basic blocks in the CFG of the program. The reason behind this disadvantage is that blackbox fuzzing is **blind** in understanding the execution, and cannot analyze the CFG.

2.2.2.2 Whitebox fuzzing

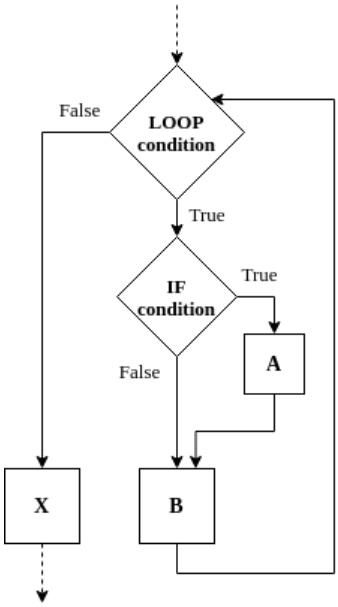
Whitebox fuzzing works with the source code of the target. The source code contains the logic of the program and can anticipate the executions' behavior without executing the program (concretely). Symbolic execution [32] is a reliable whitebox fuzzing strategy that analyzes the source code. This analysis replaces the variables with symbols that consider the constraints for each data. This technique helps its fuzzer discover inputs that increase code coverage by discovering new branches after conditional instructions were satisfied. This method detects *hidden* bugs faster due to the powerful constraint solvers [33]. Although the symbolic execution can solve the conditional branching theoretically, this technique suffers from *path explosion* problem. As an example, in Figure 2.4a a sample section of a program containing a `loop` and an `if` statement within the loop. Figure 2.4b shows the tree of the actions taken until the program reaches the basic block X. Solving the current loop requires an exponentially growing number of paths that the fuzzer needs to visit. Whitebox fuzzing is not very practical in the industry as it is expensive (time-consuming / resource-consuming) and requires the source code, which may not be available for testers.

SAGE [34], a whitebox fuzzer, was developed as an alternative to blackbox fuzzing to cover the lack of blackbox fuzzers [35]. It can also use dynamic and *concolic*

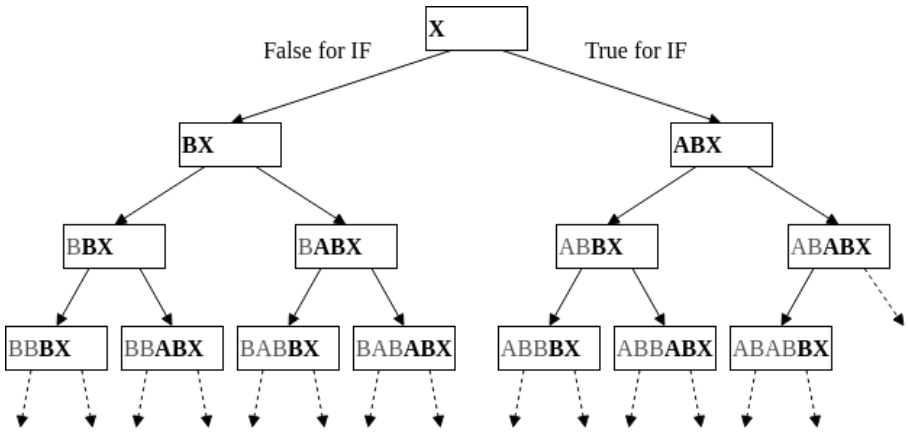
execution [36] and use taint analysis to locate the regions of seed files influencing values used by the program [37]. Concolic execution is an effective combination of symbolic execution and concrete (dynamic) executions; in a dynamic execution the fuzzer executes the program and analyzes the run. Godefroid et al. [38] have also introduced a whitebox fuzzer that investigates the grammar for parsing the input files without any prior knowledge.

2.2.2.3 Greybox fuzzing

Greybox fuzzing resides between whitebox and blackbox fuzzing, as it has partial knowledge (awareness) about the internals of the target application. The source code is not analyzed, but the executions of the binary files are the main data source for discovering the vulnerabilities in action; the actual application's logic is not considered for the analysis, but the instructions illustrate an overview of the compiled



(a) Path explosion



(b) Path explosion tree

Figure 2.4: Path explosion example

program's logic. A concrete execution of a program represents a reproducible procedure that is executed and can be monitored for its behavior detection. Greybox fuzzer obtains the runtime information from the code instrumentation, and by using other techniques such as taint analysis, concolic executions (obtaining the logic from the binary), and methods for acquiring more information after the **partial knowledge** of the program [1, 39].

The code coverage is a viable feature for detecting the new paths that the fuzzer never executed. Registering new paths for testing helps fuzzers in finding different regions of the code for potential vulnerabilities. Later the fuzzer tests the input that caused the new path to check if fuzzing the input can reveal a new vulnerability after constructing tweaked inputs out of the current input. This loop of testing the different inputs continues until specific termination signals show up. AFLGo [40] is a greybox fuzzer that tries digging into the deeper application's basic blocks so that it can reach a specific region. AFLGo focuses on fuzzing more of the inputs that guide the execution as it gets closer to the specified region. This greybox fuzzer shows effective performance in testing a program for detecting errors in new patches of an application and helps with crash reproduction. Another greybox fuzzer, VUzzer [41] enhances the instrumentation to collect control- and data-flow features, which leads to guiding the agnostic fuzzer to find more *intersting* inputs, with less effort (fewer trials of the fuzzed inputs). The core feature in a greybox fuzzer is the *application agnosic* characteristic that targets any executable and observable program in the fuzzer's environment.

2.2.3 Input generation

Greybox fuzz testing requires features to distinguish between various inputs and pick the test cases that help the fuzzer find bugs. Code coverage is a distinguishing feature

for preference over the inputs. As described before 2.2.1, code coverage summarizes the behavior of an execution, and does not analyze the instructions, instead, the graph of the basic blocks (CFG) is analyzed. For **coverage-guided** fuzzing, the corpus of inputs extends as the fuzzer finds new *execution paths*. On the other hand, a **performance-guided** fuzzer seeks *resource-exhaustive procedures*.

2.2.3.1 Coverage-guided fuzzing

Coverage-based fuzzing is a technique for fuzz testing that instruments the target without analyzing the logic of the program. In a greybox and whitebox coverage-based fuzzing, the instrumentation detects the different paths of the executions [1]. The applied instrumentation collects runtime information such as data coverage, statement coverage, block coverage, decision coverage, and path coverage [42]. Bohme et al. [8] introduced a coverage-based greybox fuzzer that benefits from the Markov Chain model. The fuzzer calculates the *energy* of the inputs based on the **potency of a path for discovery of new paths**. Later, the inputs with higher energy add more fuzzed inputs to the queue.

Steelix [43] is a coverage-guided greybox fuzzer. It implements a coverage-based fuzz testing that is boosted with a *program-state based* instrumentation for collecting the *comparison progress* of the program. The comparison progress keeps the information about *interesting comparisons*. The heavy-weight fuzzing process of Steelix contains an initial light-weight static analysis of the binary. The static analysis returns the basic block and comparison information. Later, the concrete execution of the fuzzed test cases determines the state of the program based on the triggered comparison jumps. In addition to the coverage increasing generation of inputs, Steelix knows how to solve the *magic* comparisons, and looks for new states of the program based on the resolved comparisons.

Types	Benefits	Limitations	Example Fuzzers
Whitebox	Deep/Hidden bug finding	- Path Explosion - Accessibility to source code	SAGE BuzzFuzz
Blackbox	- Fast test case generation - General applicability	- Shallow bug finding - Blind	LigRE Storm
Greybox	- Deep bug finding - General applicability	- Access to binary - Requires instrumentation	AFL LibFuzzer

Table 2.1: Program awareness for fuzzing

The code coverage is measured by considering a light-weight instrumentations. This method helps fuzzing to monitor the program without changing the program's resource usage (time, memory, etc.) by a noticeable amount. Hence, due to unaccessibility to the source code, dynamic instrumentation is used as a reliable technique for collecting the runtime information. The trade off for using DI is the increasing performance cost; for instance, QEMU costs 2-5x slower executions [14].

2.2.3.2 Performance-guided fuzzing

To enhance the capability of a coverage-based fuzzer, a performance-guided fuzzing technique collects resource-usage information, and leverages code coverage techniques for exploring the CFG. SlowFuzz [44] is a performance-guided coverage-based greybox fuzzer, which measures the length of the executed instructions in a total (complete) execution. SlowFuzz has an interest in evolving the corpus of test cases to discover new paths or generate more resource exhaustive executions. Another

Types	Features	Drawbacks	Examples
Coverage-guided	Light-weight instrumentation	Low guidance measurements	AFL LibFuzzer Honggfuzz
Performance-guided	- More features for guidance - Find resource-exhaustion	Heavy weight instrumentation	SlowFuzz PerfFuzz MemLock

Table 2.2: Input generation techniques for fuzzing

performance-guided fuzzer, PerfFuzz [9] aims to generate inputs for executions with higher **execution time** by counting the number of times each edge (jump out of basic block) of the CFG is visited. Next, inputs with higher edge counts take more effect on the corpora's evolution. These two performance fuzzers can detect pathological inputs related to CPU usage. Memlock [45] guides the performance of the fuzzing to produce memory-exhaustive inputs. It investigates memory usage by calculating the maximum runtime memory required during executions. MemLock uses static performance instrumentations for profiling memory usage.

2.3 American Fuzzy Lopper (AFL)

Michal Zalewski developed American Fuzzy Lopper as a coverage-guided greybox fuzzer. He introduces this open-source project as "a security-oriented fuzzer that employs a novel type of compile-time instrumentation and genetic algorithms to automatically discover clean, interesting test inputs that trigger new internal states of the targeted binary. This substantially improves the functional coverage for the fuzzed code. The compact synthesized corpus produced by the tool help seed other, more labor- or resource-intensive testing regimes down the road." [46] AFL is designed to perform **fast** and **reliable**, and at the same time, benefits from the **simplicity** and **chainability** features [47]:

- **Speed:** Avoiding the time-consuming operations and increasing the number of executions over time.
- **Reliability:** AFL takes strategies that are program-agnostic, leveraging only the coverage metrics for more discoveries. This feature helps the fuzzer to perform consistently in finding the vulnerabilities in different programs.

- **Simplicity:** AFL provides different options, helping the users enhance the fuzz testing in a straightforward and meaningful way.

- **Chainability:** AFL can test any binary which is executable and is not constrained by the target software. A driver for the target program can connect the binary to the fuzzer.

AFL uses both dynamic and static instrumentation to profile executions; the first one requires binary files, and the SI steps in at compile-time (requiring source code). AFL uses QEMU (Quick EMUlator) to perform the DI. DI allows instrumentating closed-source binaries [14]. The emulator wraps the genuine instructions into analyzable modules, which helps with the construction of the CFG. SI is a faster method for fuzzing with AFL, which causes an average slow down of 10-100% for each execution. AFL currently uses **LLVM** (Low-Level Virtual Machine) for injecting code coverage instructions into the program [48]. Unlike DI, `llvm-mode` configures the source code such that the CPU can execute the instructions directly, and there is no need for any extra environment to profile executions. In this article, the LLVM mode is described in more detail.

2.3.1 LLVM

"The LLVM Project is a collection of modular and reusable compiler and toolchain technologies. Despite its name, LLVM has little to do with traditional virtual machines. The name **LLVM** itself is not an acronym; it is the full name of the project." [12] Two of the relevant projects used by AFL are as follow:

- The **LLVM Core** libraries contain source/target-independent optimizers as well as code generators for popular CPUs. These well-documented modules

assist development of a custom compiler in every step (*pass*) through the conversion of source code to executable binary file.

- **Clang** [49] provides a front-end for compiling C language family (C, C++, Objective C/C++, OpenCL, CUDA, and RenderScript) for the LLVM Project. Clang uses the LLVM Core libraries to generate an *Intermediate Representation* (**IR**) of the source code [50]. The IR is then translated into an executable binary for the machine's CPU (Figure 2.5).

AFL utilizes the compilation *passes* of Clang with a custom *module pass*. Passes are the modules performing the transformations and optimizations of a compilation. A pass builds the analysis results that are used by these transformations, and a sequence of passes construct the compiler. AFL's instrumentation takes the whole program as one module and analyses it to detect the basic blocks.

2.3.1.1 Static Instrumentation and Code Coverage

AFL's static instrumentation starts with the allocation of a shared memory. This shared memory stands between AFL's fuzzer and each program's execution. Everytime the instrumentated program is run, the injected instructions fill the shared memory with the coverage status of the execution. After the termination of the

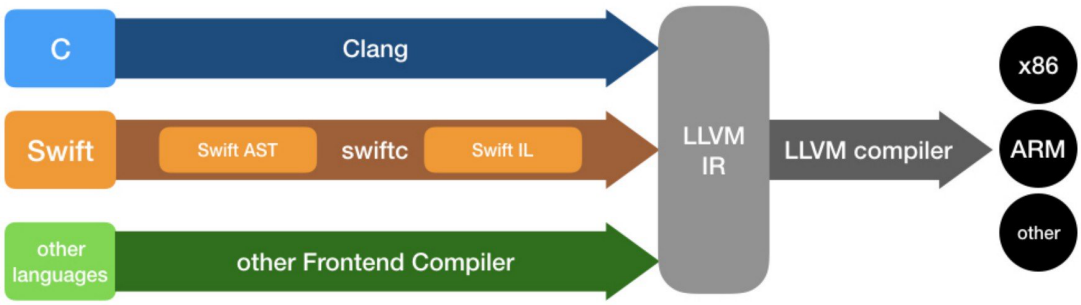


Figure 2.5: LLVM architecture: A front-end compiler generates the LLVM IR, and then it is converted into machine code [3]

process, AFL continues its fuzzing procedure. Shared memory is updated with new execution's data, and AFL can use it to evaluate the performance of the recent execution. The runtime initialization recipe is saved in `llvm-mode/waffle-llvm-rt.o.c` of the project.

```
1    cur_location = <COMPILE_TIME_RANDOM>;
2    shared_mem[cur_location ^ prev_location]++;
3    prev_location = cur_location >> 1;
```

Listing 2.2: Select element and update in shared_mem

Next, the AFL's module pass is called. In this pass, AFL iterates over the all functions of the module, and digs into the basic blocks of the functions. Clang statically generates the CFG of the program, and AFL uses this graph to find the entry of each basic block. To store the execution path, AFL marks each basic block with a random integer. The execution path is hashed with these values as the program steps into basic blocks. This hashed number specifies an index on the shared memory. These static calculations end with an increment on the content of the hashed location. [Listing 2.2] An snippet of the AFL's instrumentation pass is shown in Listing 2.3.

```
1  // LLVM-mode instrumentation pass
2  bool AFLCoverage::runOnModule(Module &M) {
3
4    /* Instrument all the things! */
5    for (auto &F : M)
6      for (auto &BB : F) {
7        basic_block::iterator IP = BB.getFirstInsertionPt();
8        IRBuilder<> IRB(&(*IP));
9
10       if (AFL_R(100) >= inst_ratio) continue;
11
12       /* Make up cur_loc */
13       unsigned int cur_loc = AFL_R(MAP_SIZE);
14       ConstantInt *CurLoc = ConstantInt::get(Int32Ty, cur_loc);
15
16       /* Load prev_loc */
17       LoadInst *PrevLoc = IRB.CreateLoad(AFLPrevLoc);
18       PrevLoc->setMetadata(M.getMDKindID("nosanitize"), MDNode::get(
     C, None));
19       Value *PrevLocCasted = IRB.CreateZExt(PrevLoc, IRB.getInt32Ty
     ());
20
```

```
21        /* Load SHM pointer */
22        LoadInst *MapPtr = IRB.CreateLoad(AFLMapPtr);
23        MapPtr->setMetadata(M.getMDKindID("nosanitize"), MDNode::get(C
    , None));
24        Value *MapPtrIdx =
25            IRB.CreateGEP(MapPtr, IRB.CreateXor(PrevLocCasted, CurLoc)
    );
26
27        /* Update bitmap */
28        LoadInst *Counter = IRB.CreateLoad(MapPtrIdx);
29        Counter->setMetadata(M.getMDKindID("nosanitize"), MDNode::get(
    C, None));
30        Value *Incr = IRB.CreateAdd(Counter, ConstantInt::get(Int8Ty,
    1));
31        IRB.CreateStore(Incr, MapPtrIdx)
32            ->setMetadata(M.getMDKindID("nosanitize"), MDNode::get(C,
    None));
33
34        /* Set prev_loc to cur_loc >> 1 */
35        StoreInst *Store =
36            IRB.CreateStore(ConstantInt::get(Int32Ty, cur_loc >> 1),
    AFLPrevLoc);
37        Store->setMetadata(M.getMDKindID("nosanitize"), MDNode::get(C,
     None));
38
39        inst_blocks++;
40      }
41
42    return true;
43  }
```

Listing 2.3: AFLCoverage module

Figure 2.6 shows an example of how the instrumentation configures the paths. Suppose that we have an instrumented program with the random values which are set in compile time. (for simplicity, suppose that initially random value $cur\_location = 1010$) Running the first basic block assigns CUR_HASH to $73 \oplus 1010 = 955$; the content of index 955 of shared memory is then increased by one, and the execution continues to the next basic block. Supposing basic block 2 is the next block, the content of $shared\_mem[310 \oplus (73 >> 1) = 274]$ is incremented by one, and so on. After the termination of this run, the content of the shared memory contains a hashing of the path. For instance, taking the path $1 \rightarrow 2 \rightarrow 5$ results in an array of zeros except for $\{51 : 1, 274 : 1, 955 : 1\}$ as the hashing of the path ($\{index:\ value\}$).

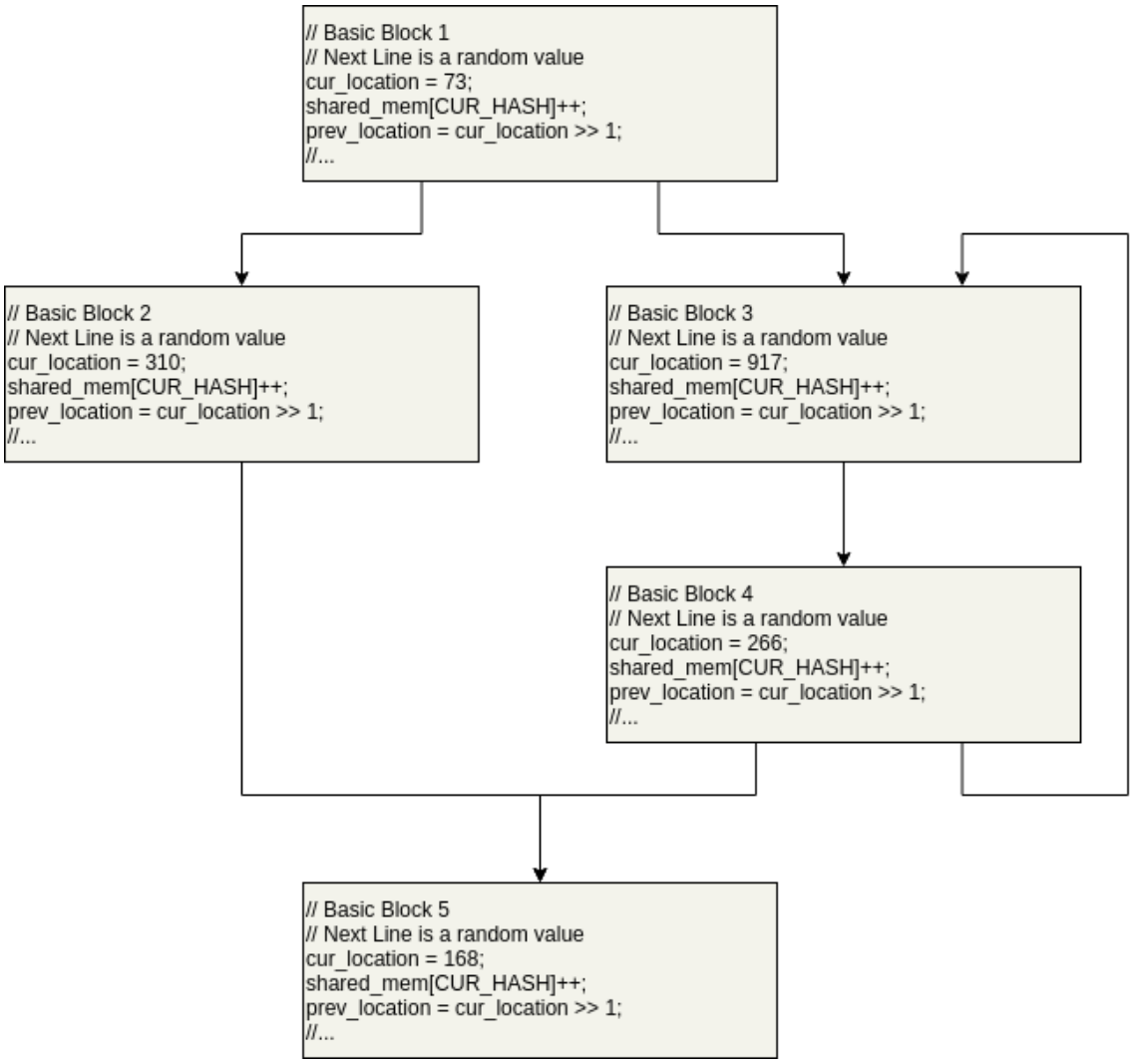


Figure 2.6: Example for instrumented basic blocks

2.3.2 AFL Fuzz

Fuzzing can be started after the binary with code coverage instrumentations are applied. First, AFL instantiates the environment variables. A queue of test case entries is created, which stores information about the program's executions over the inputs. The fuzzing loop begins after the environmental set up. In each iteration, AFL selects the first entry of the queue as the current entry for fuzzing. This entry is then analyzed and the input is passed to the program for testing. The function `fuzz_one()` is responsible for generating and testing new inputs from the current entry. The fuzzing loop ends with *updating the bitmaps scores*, which analyzes the performance of the current fuzz (Algorithm 2).

Algorithm 2: afl-fuzz

Input: in_dir, out_dir, $instrumented\ Target$

```
1 initialize fuzzer;
2 while fuzzing is not terminated do
3 |   cull_queue();
4 |   Entry ← q.first_entry();
5 |   fuzz_one(Entry);
```

At the beginning of the loop, AFL processes the queue to learn about the higher priorities for inputs. This procedure involves scanning the path that was taken in the recent execution and determines if it is a favorable input for fuzzing in the future. This analysis maintains inputs with the highest effectiveness on each path, and if a path with new behavior is seen, it is marked as an *favorable input*. Next, AFL selects the next input in the queue of fuzzing.

2.3.2.1 fuzz_one()

The selected queue entry must be caliberated (if not before) to retreive the performance of the execution and decide on how favorable the input is for fuzzing.

Algorithm 3: $fuzz\_one$: Fuzz one Entry

Input: $queueEntry$

```
T ← Entry.test_case;
calibrate(T);
trim(T);
perf_score ← calculate_score(T);
if deterministic_mode then
    deterministic_stages(T);
MX ← calc_stages(perf_score, C);
foreach element in (0, MX) do
    random_havoc(T);
```

AFL checks the favor of an input by calling `update_bitmap_score()` function. This method assigns a **favor-factor** (Eq 2.1) to each queue_entry and marks the **favorite entries**, as they execute faster and the size of the files are smaller than the rest of the corpus. AFL finds a favorable path for "having a minimal set of paths that trigger all the bits seen in the bitmap so far, and focus on fuzzing them at the expense of the rest." [11]

$$fav\_factor = e.exec\_time \times e.length \tag{2.1}$$

The evolutionary algorithms for generating new entries are applied in two stages: **deterministic** and **random_havoc** stages. As shown in Algorithm 3, AFL initially tries the basic, deterministic algorithms. These algorithms are executed for a specific number of times, in the same order, and once for each fuzzing trial. Bit-flipping, byte-flipping, simple arithmetic operations, using known integers and values from dictionaries, are a sequence of mutations that AFL applies on an entry in **deterministic** stage. Each one of the above operations tweaks a small portion of the fuzzed input and does not modify the file in large portions - up to 32 bits changes in each tweak.

The **havoc** stage is a cycle of stacked random tweaks. AFL assesses the current entry to insert into the queue. Each mutation is selected randomly, and with a higher `perf_score`, this stage continues more fuzzing over the current entry. The `random_havoc` stage consists of techniques such as bit flips, overwriting with random and interesting integers, block deletion, block duplication, and (if supplied) assorted dictionary-related operations [51]. An abstract implementation of the `havoc_stage` can be found in Appendix 6.A.1.

2.3.2.2 calculate_score()

This function calculates how much AFL desires to iterate in havoc stage, for the current entry. By default, AFL is interested in fuzzing an input with less execution-time, and simultaneously, showing more coverage, and it's generation depth is higher. The depth of a child entry is one more than the depth of it's parent [Snippet of code 2.4]:

```
/* Calculate case desirability score to adjust the length of havoc
   fuzzing. A helper function for fuzz_one(). Maybe some of these
   constants should go into config.h. */

static u32 calculate_score(struct queue_entry* q) {
  u32 perf_score = 100;

  /* Adjust score based on execution speed of this path, compared to
     the global average. Multiplier ranges from 0.1x to 3x. Fast
     inputs are less expensive to fuzz, so we're giving them more air
     time. */

  if (q->exec_us * 0.1 > avg_exec_us) perf_score = 10;
  else if (q->exec_us * 4 < avg_exec_us) perf_score = 300;
  // Check other conditions in between

  /* Adjust score based on bitmap size. The working theory is that
     better coverage translates to better targets. Multiplier from
     0.25x to 3x. */
  if (q->bitmap_size * 0.3 > avg_bitmap_size) perf_score *= 3;
  else if (q->bitmap_size * 3 < avg_bitmap_size) perf_score *= 0.25;
  // Check other bitmap_sizes in between

  /* Adjust score based on handicap. Handicap is proportional to how
     late in the game we learned about this path. Latecomers are
```

```
    allowed to run for a bit longer until they catch up with the
    rest. */
18
19  /* Final adjustment based on input depth, under the assumption
    that fuzzing deeper test cases is more likely to reveal stuff
    that can't be discovered with traditional fuzzers. */
20
21  switch (q->depth) {
22    case 0 ... 3:   break;
23    case 14 ... 25: perf_score *= 4; break;
24    // Check other cases in between
25    default:        perf_score *= 5;
26  }
27
28  /* Make sure that we don't go over limit. */
29  if (perf_score > HAVOC_MAX_MULT * 100) perf_score = HAVOC_MAX_MULT
      * 100;
30
31  return perf_score;
32 }
```

Listing 2.4: An abstract implementation of calculate_score()

2.3.2.3 common_fuzz_stuff()

The newly fuzzed (generated) inputs must pass `common_fuzz_stuff()` for validating and instantiating a `queue_entry`. The validation checks the length of the fuzzed file, executes the program and keeps the exit-value of the execution. In the end, AFL calls `save_if_interesting()` to insert the entry into the queue, if it is interesting. The function `has_new_bits()` considers how interesting an entry is.

```
1  /* Write a modified test case, run program, process results. Handle
      error conditions, returning 1 if it's time to bail out. This is
      a helper function for fuzz_one(). */
2
3  EXP_ST u8 common_fuzz_stuff(char** argv, u8* out_buf, u32 len) {
4    // Validate the file
5    // ...
6    // Validate the execution
7    fault = run_target(argv, exec_tmout);
8    // If the file is "interesting", add it into queue
9    queued_discovered += save_if_interesting(argv, out_buf, len, fault
       );
10   // ...
11   return 0;
12 }
13
```

```
/* Check if the result of an execve() during routine fuzzing is
   interesting, save or queue the input test case for further
   analysis if so. Returns 1 if entry is saved, 0 otherwise. */

static u8 save_if_interesting(char** argv, void* mem, u32 len, u8
   fault) {
  if (fault == crash_mode) {
      hnb = has_new_bits(virgin_bits);
  }
  if(!hnb) return 0;

  queue_top->exec_cksum = hash32(trace_bits, MAP_SIZE, HASH_CONST);

  /* Try to calibrate inline; this also calls update_bitmap_score()
   when successful. */
  res = calibrate_case(argv, queue_top, mem, queue_cycle - 1, 0);

  // Save the file and return
}
```

Listing 2.5: An abstract implementation of common_fuzz_stuff()

2.3.2.4 has_new_bits()

AFL checks the last execution and if there are newly visited edges, the input gets higher priority in the queue. This function is called after each execution, and to evade from a bottleneck, AFL implements the function to be executed as fast as possible [Listing 2.6].

```
/* Check if the current execution path brings anything new to the
   table. Update virgin bits to reflect the finds. Returns 1 if the
    only change is the hit-count for a particular tuple; 2 if there
    are new tuples seen. Updates the map, so subsequent calls will
   always return 0.

   This function is called after every exec() on a fairly large
   buffer, so it needs to be fast. We do this in 32-bit and 64-bit
   flavors. */

static inline u8 has_new_bits(u8* virgin_map) {
  u64* current = (u64*)trace_bits;
  u64* virgin  = (u64*)virgin_map;
  u32  i = (MAP_SIZE >> 3);
  while (i--) {

  /* Optimize for (*current & *virgin) == 0 - i.e., no bits in
   current bitmap that have not been already cleared from the
   virgin map - since this will almost always be the case. */
```

```
12
13      if (unlikely(*current) && unlikely(*current & *virgin)) {
14        if (likely(ret < 2)) {
15          u8* cur = (u8*)current;
16          u8* vir = (u8*)virgin;
17
18          /* Looks like we have not found any new bytes yet; see if
      any non-zero bytes in current[] are pristine in virgin[]. */
19          if ((cur[0] && vir[0] == 0xff) || (cur[1] && vir[1] == 0xff)
       ||
20              (cur[2] && vir[2] == 0xff) || (cur[3] && vir[3] == 0xff)
       ||
21              (cur[4] && vir[4] == 0xff) || (cur[5] && vir[5] == 0xff)
       ||
22              (cur[6] && vir[6] == 0xff) || (cur[7] && vir[7] == 0xff)
      ) ret = 2;
23          else ret = 1;
24        }
25        *virgin &= ~*current;
26      }
27      current++; virgin++;
28    }
29
30    if (ret && virgin_map == virgin_bits) bitmap_changed = 1;
31    return ret;
32  }
```

Listing 2.6: The implementation of has_new_bits()

2.3.3 Status screen

The **status screen** is a UI for the status of the fuzzing procedure. As it is shown in Figure 2.7, there are various stats provided in real-time updates:

1. **Process timing**: This section tells about how long the fuzzing process is running.

2. **Overall results**: A simplified information about the progress of AFL in finding paths, hangs, and crashes.

3. **Cycle progress**: As mentioned before, AFL takes one input and repeats mutating it for a while. This section shows the information about the current

cycle that the fuzzer is working with.

4. **Map coverage**: The AFL's documentation explains the information in this section as: "The section provides some trivia about the coverage observed by the instrumentation embedded in the target binary. The first line in the box tells you how many branches we have already hit, in proportion to how much the bitmap can hold. The number on the left describes the current input; the one on the right is the entire input corpus's value. The other line deals with the variability in tuple hit counts seen in the binary. In essence, if every taken branch is always taken a fixed number of times for all the inputs we have tried, this will read "1.00". As we manage to trigger other hit counts for every branch, the needle will start to move toward "8.00" (every bit in the 8-bit map hit) but will probably never reach that extreme.

   Together, the values can help compare the coverage of several different fuzzing jobs that rely on the same instrumented binary."

5. **Stage progress**: The information about the current mutation stage is briefly provided here. This regards to `fuzz_one()` function in which the new fuzzed

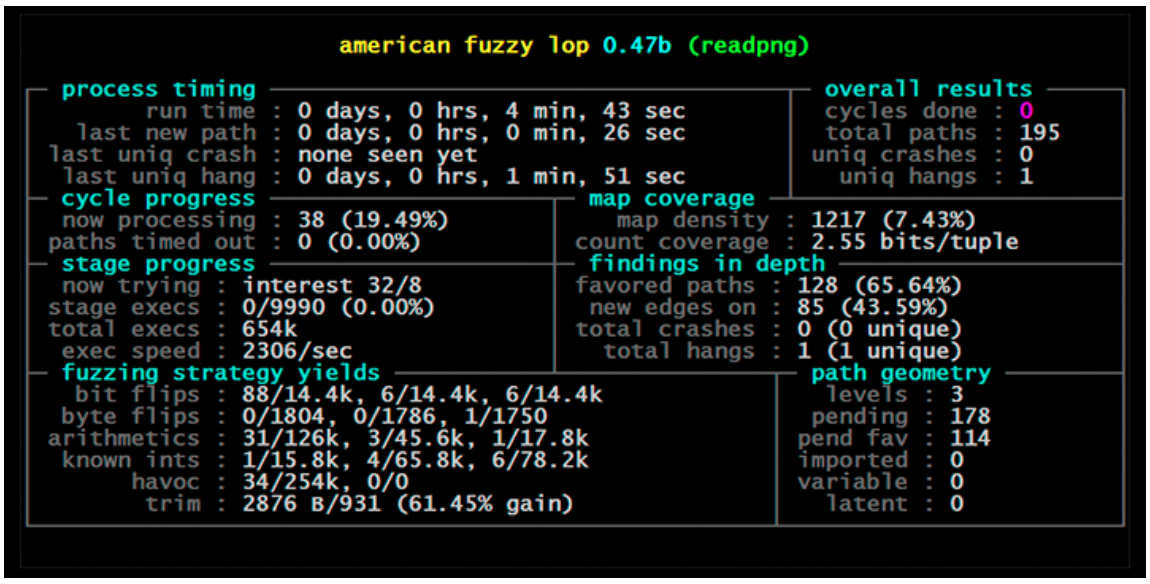


Figure 2.7: AFL status screen

inputs are being generated through mutation stages.

6. **Findings in depth**: The number of crashes and hangs and any other findings are presented in this section.

7. **Fuzzing strategy yields**: To illustrate more stats about the strategies used since the beginning of fuzzing. For the comparison of those strategies, AFL keeps track of how many paths it has explored, in proportion to the number of executions attempted.

8. **Path geometry**: The information about the inputs and their depths, which says how many generations of different paths were produced in the process. The depth of an input referes to which generation the input belongs to. Considering the first input seeds as depth 0, the generated population from these inputs increase the depth by one. This shows how far the fuzzing has progressed.

2.3.4 AFL fuzzing chain

Figure 2.8 illustrates the procedure of fuzzing, from static intrumentation to fuzz testing the target and outputing results. To start the procedure, AFL instrumentates the program and configures the target binary for fuzz testing stage. To perform the instrumentation, AFL calls its own compiler, which applies the instrumentation when it's process is finished [Listing 2.7]:

```
afl-clang sample.c -o sample_inst
```

Listing 2.7: Instrument *sample_vul*.c

The result file, `sample_inst`, is an executable which contains shared memory for later analysis in fuzzing. Now AFL can start testing the program for probable vulnerabilities. The test requires the input and output directories, as well as

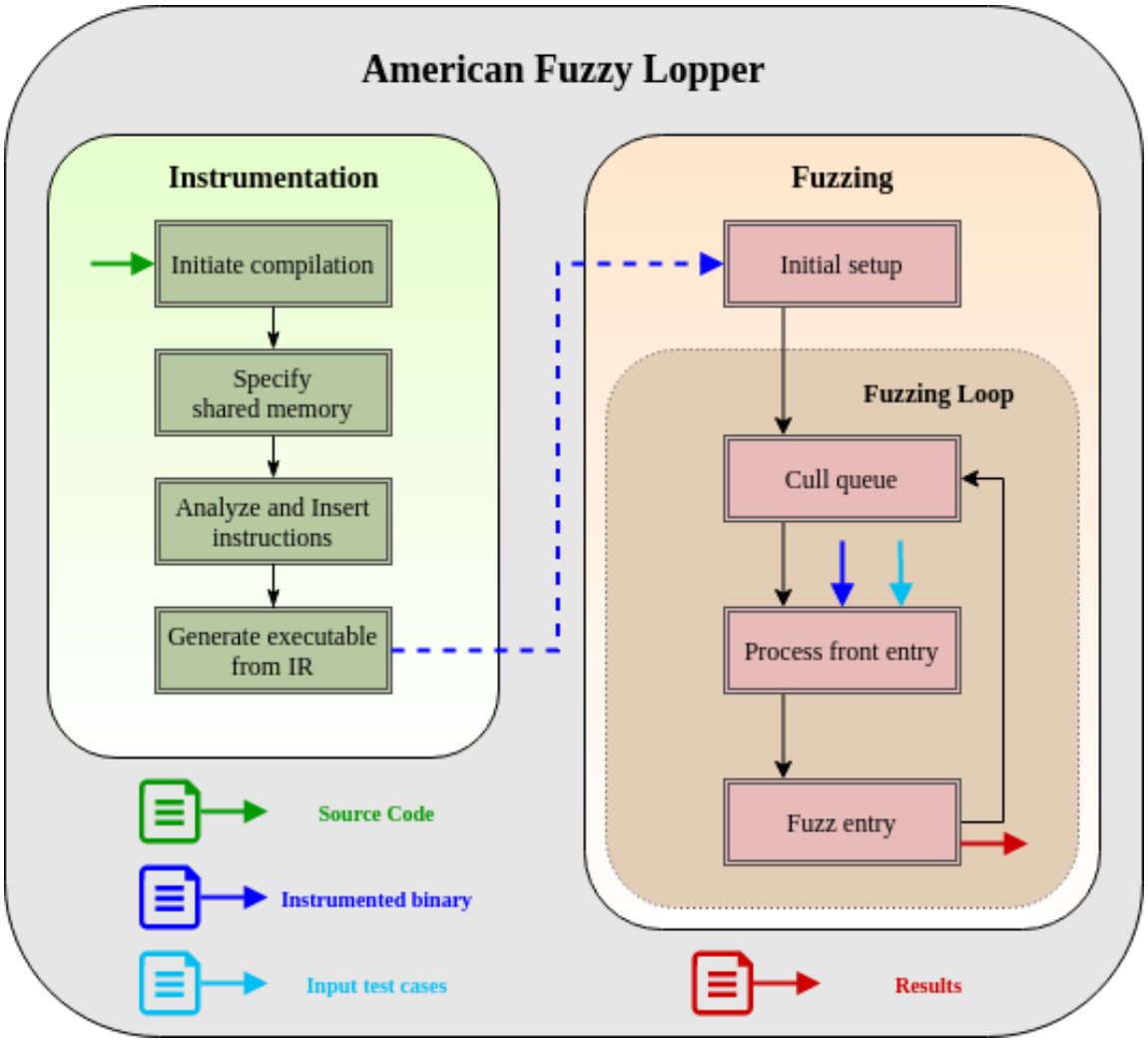


Figure 2.8: An overview of the whole fuzzing procedure of AFL

the command for executing the program [Listing 2.8]. The fuzzing continues until recieving a halt signal (For instance, by pressing *Ctrl+C*).

```
# afl-fuzz -i <in_dir> -o <out_dir> [options] -- /path/to/fuzzed/app [params]
afl-fuzz -i in_dir -o out_dir -- ./sample_inst
```

Listing 2.8: Execute AFL

2.4 Concluding remarks

In this chapter, we reviewed the previous works that inspired us for the development of Waffle. We covered these topics:

- A brief description of the previous fuzzers.
- The recognition of whitebox, blackbox and greybox fuzzers.
- Code coverage technique and its applications in fuzz testing were explained.
- We briefly explained the instrumentation with LLVM and visitor functions.
- We dug into the state-of-the-art fuzzer, AFL, and researched its fuzzing procedure.

In the next chapter we will explore more into the modifications we applied on AFL to achieve Waffle.

Chapter 3

Proposed Fuzzer

3.1 Introduction

The benefit of using a performance-guided fuzzing technique elevates the fuzzer to discover the worst-case scenario of a program. The memory-guided fuzzing can target data structures and memory usage, revealing vulnerable memory allocations. Fuzzers such as SlowFuzz and PerfFuzz monitor the performance related instructions (such as jumps - resembling basic blocks) to evaluate the CPU-usage of an execution. One of the limitations of the previous performance-guided fuzzers is that they do not consider both of the mentioned features (memory/CPU-usage) together. As a result, to analyze a program for its memory and CPU exhaustion, the corpus of both memory-guided and CPU-guided fuzzers should be merged. We suggest two solutions for the privious problem:

1. Parallel fuzzing: The corpus of the generated inputs (fuzzed inputs) contains the latest findings of a fuzzer. A coverage-based fuzzer seeks for new code coverages, and eventually, the corpus evolves with coverage-guided inputs. In

a performance-guided fuzzing, the inputs gradually produce fuzzed data which uses more resources. Concurrent fuzzing suggests that if the corpus (queue of inputs) of different fuzzers is shared with other fuzzers, the outcome follows each feature that the fuzzers were pursuing. The synchronization of the fuzzers is simplified in various state-of-the-art fuzzers. Either of AFL-based or LibFuzzer-based fuzzer (or any other types) can communicate with each other with the provided APIs [52].

2. Waffle: Waffle is a performance-guided AFL-based fuzzer that mitigates the problem of different resource exhaustion. Waffle stands for What An Amazing AFL (WAAAFL). The introduced fuzzer is designed to collect the usages of any type of instruction in a run. Waffle can focus on a set of one or more instructions and searches for the inputs that maximize the occurrences of the targeted instructions. As a result, the genetic algorithm used in the fuzzing stage considers the executions with more instructions as the better genes to be passed to the next generations.

For the rest of this chapter, we describe the design, implementation, and applications of Waffle.

3.2 Waffle

The key observation for the methodology used in Waffle is that the static analysis and instrumentations collect the required features for the evolutionary search techniques for finding inputs that demonstrate worst-case complexity of a test application in a domain-independent way. However, to enable Waffle to efficiently find such inputs, we need to carefully design effective guidance mechanisms and mutation schemes

to drive Waffle's input generation process. We redesign the evolutionary algorithm of AFL with customized guidance mechanisms that are tailored for finding inputs causing worst-case behavior.

Figure 3.1 specifies the modified modules of AFL that introduce Waffle. The shared memory is designed to be capable of storing the *resource complexity* of execution. After the memory instantiation, Waffle investigates the source code (of instructions) and inserts instructions for saving the performance of the run. In the fuzzing phase, Waffle considers the executed instructions of a run and changes the input generation based on the performance of the program.

Next, we will discuss the instrumentation and fuzzing phases of Waffle. To understand the effectiveness of our approach, we first introduce the resource complexity of a program and explain how Waffle pivots on this feature for guiding the

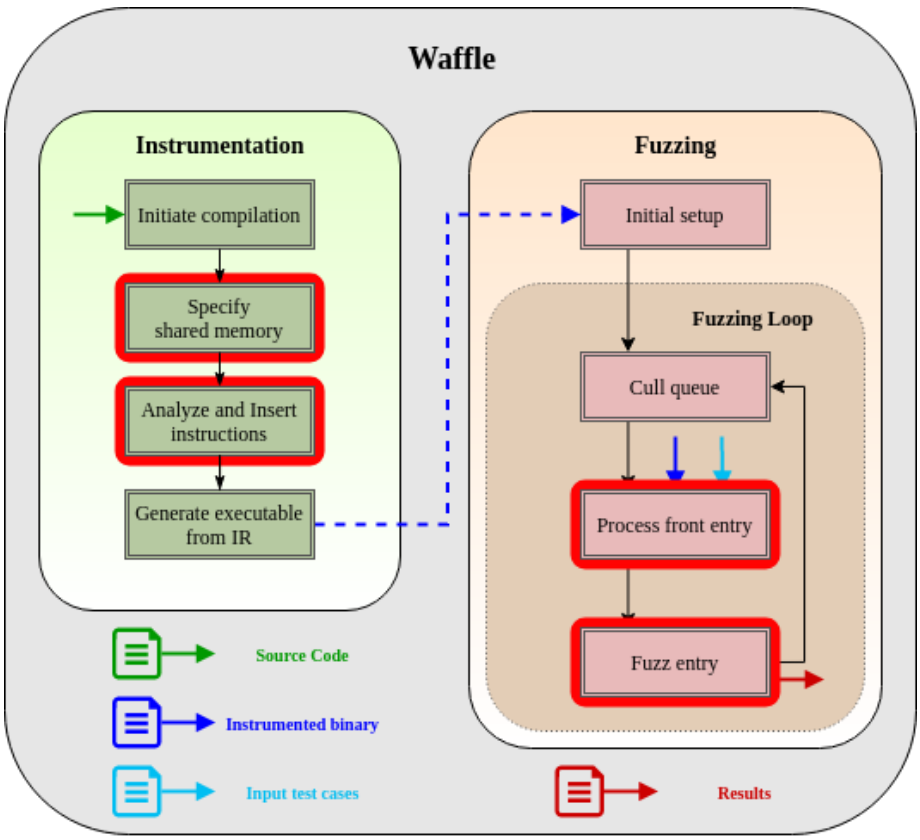


Figure 3.1: Fuzzing phases of Waffle. The red rectangles specify the changed components.

input generation. After that, the instrumentation phase is expanded for discussion, which results in generating an instrumentated binary. The binary file is then passed to the fuzzer, and the evaluation of the inputs takes effect during the fuzzing process.

3.2.1 Resource complexity of execution

We define the **overall resource complexity** (shortened to ORC) of an application as *the amount of resources required to execute a program.* To evaluate the ORC of a program in a concrete execution, each instruction with the involving resources should be monitored. For instance, an instruction such as `memcpy` takes CPU usage for its execution, and may access the program's available memory; a user may consider both the CPU and memory usages and aggregates of the resource complexities of the executed instructions to conclude the ORC.

Waffle *estimates* the ORC of each run to guide the input generation process. This estimation is based on a custom set of **Engaging Instruction**s (EI) which specifies the machine instructions that are being involved in ORC calculation. For example, suppose that `memcpy` is the only selected EI; the resources used by only this instruction are then monitored and the ORC changes for each operation of the instruction. As mentioned in Chapter 2, `perf_score` specifies the number of iterations that an input generates fuzzed inputs in havoc mode. Waffle calculates the AFL's `perf_score` of a run, and brings in the Engaging Instructions' ORC (EI-ORC) of the execution. The snippet of code 3.1 shows the commands that Waffle is using for updating `perf_score`, derived from Listing 2.4. The value of EI-ORC is computed during the execution with the inserted instructions for incrementing the corresponding indices of the shared array. If the input under fuzzing shows an EI-ORC more than the average EI-ORC of the tests, Waffle increases the iterations for fuzzing the input. The multipliers are set theoretically and they require to be

```
static u32 calculate_score(struct queue_entry* q) {
  u32 perf_score = 100;
  u64 avg_ORC = ORC / total_bitmap_entries;
  // ...
  if (q->ORC > avg_ORC * 3) perf_score *= 1.4;
  else if(q->ORC > avg_ORC * 2) perf_score *= 1.2;
  else if(q->ORC > avg_ORC) perf_score *= 1.05;
  else if(q->ORC > avg_ORC * 0.75) perf_score *= 0.7;
  else perf_score *= 0.5;
  // ...
}
```

Listing 3.1: The added commands for entailing the ORC in `perf_score`

tuned for better results.

3.2.2 Instrumentation

Waffle starts its instrumentation by specifying the shared memory region. Waffle uses two memory regions for this purpose:

- An array of 4 bytes cells for tracking the code coverage and the ORC of each basic block. The code coverage works the same as AFL does and the increaments in cells is an attribute for detecting a new path/behavior. The array's length is the same as the AFL's shared array, and as a result, the Waffle's array requires 4x space (Listing 3.2). Waffle keeps the basic block's ORCs to discover the basic blocks that can contribute more increments in the `total_ORC`.

- To decrease the computational overhead in the fuzzing stage, Waffle stores the summation of all ORCs in an 8 byte integer. As shown in the following code 3.3, function `addORC` is responsible for adding the value of an ORC to the `total_ORC`. The functions `traceBegin` and `traceEnd` are assigned with the attributes of constructors and destructors. The constructor is called as this shared library is loaded, and the destructor is called before the file is unloaded.

```
// snippet of wafl-llvm-rt.o.c

#define ORC_SIZE (1 << 16)

u32  __wafl_ORC_initial[ORC_SIZE];
u32* __wafl_area_ptr = __wafl_ORC_initial;

static void __afl_map_shm(void) {
  u8 *id_str = getenv(SHM_ENV_VAR);

  if (id_str) {
    u32 shm_id = atoi(id_str);
    __wafl_area_ptr = shmat(shm_id, NULL, 0);

    if (__wafl_area_ptr == (void *)-1) _exit(1);

    memset(__wafl_area_ptr, 0, sizeof __wafl_ORC_ptr);
  }
}
```

Listing 3.2: LLVM instrumentation initialization - `__wafl_area_ptr` is the region that is allocated for instruction counters

To finilize the storage of `total_ORC`, the value is stored in the shared memory when the destructor is being called.

```
static int total_ORC = 0;

void __attribute__((constructor)) traceBegin(void) {}

void __attribute__((destructor)) traceEnd(void) {
  unsigned char *orc_str = getenv(ORC_ENV_VAR);

  if (mem_str) {
    unsigned int shm_mem_id = atoi(mem_str);
    u64 *TORC;

    TORC = shmat(shm_mem_id, NULL, 0);
    if (TORC == (void *)-1) _exit(1);

    *TORC = total_ORC;
  }
}

void addORC(int cnt) {
  total_ORC += cnt;
}
```

Listing 3.3: sys_data in instrumentation

Waffle uses *LLVM's instruction visitor functions* [53] to investigate and count

engaging features in the machine code. LLVM provides functions for `getting` and `setting` the instructions in a range of address in the code section of the program. This API is applied on the IR of the program and Waffle uses it in the Module Pass of the compilation. Listing 3.4 shows an example of how Waffle implements the counters for instructions; the member function `visitInstruction(Instruction &I)` checks if the instruction is of **any** type, and as a result, an instance of the class `CountAllVisitor` can contain the occcurences of (any) instructions in a range of instruction pointers.

```
1  #include "llvm/IR/InstVisitor.h"
2
3  struct CountAllVisitor : public InstVisitor<CountAllVisitor> {
4    unsigned Count;
5    CountAllVisitor() : Count(0) {}
6
7    // Any visited instruction is counted in a specified range
8    void visitInstruction(Instruction &I) {
9      ++Count;
10   }
11 };
```

Listing 3.4: Visitors example

A snippet of the Module Pass is shown in Listing 3.5. In line 6 the pointer to the shared array is introduced; Lines 10 to 14 includes the previously defined function for sum of ORCs, `addORC()`. After the initial set up, Waffle digs into the basic blocks and create and instance of the `CountAllVisitor` struct. By passing the current basic block to the visitor, the visitation of EI is stored in `CAV`. The linear increment in `CAV` has a relatively large variance in effectiveness of each basic block in changing the total ORC. For instance, if Waffle chooses to count all instructions in the execution, the basic blocks contributed an average of 18 instructions for the ORC [1]. To reduce the impact of large numbers in ORC, Waffle calculates the logarithm of the each counter:

[1] Tested C++ implementations of QuickSort, MergeSort, and DFS

$$CNT = \log_2^{CAV+1} \tag{3.1}$$

The EI-ORC of a basic block is then prepared for storage in both of the storages. Waffle inserts instructions for loading the according index in the shared memory, adds the reduced estimation of EI-ORC to the loaded value, and stores the result back in the same index. Finally, Waffle adds `CNT` to the `total_ORC` by calling the function `addORC` (Line 42).

```
1  // snippet of wafl-llvm-pass.so.cc
2  #include <math.h>
3  // ...
4  bool WAFLCoverage::runOnModule(Module &M) {
5    // ...
6    GlobalVariable *WAFLMapPtr =
7      new GlobalVariable(M, PointerType::get(Int32Ty, 0), false,
8      GlobalValue::ExternalLinkage, 0, "__wafl_area_ptr");
9
10   llvm::FunctionType *ORCIncrement =
11     llvm::FunctionType::get(builder.getVoidTy(), ORC_args, false);
12   llvm::Function *ORC_Increment =
13     llvm::Function::Create(ORCIncrement,
14       llvm::Function::ExternalLinkage, "addORC", &M);
15   // ...
16   for (auto &F : M) {
17     for (auto &BB : F) {
18       /* Count the instructions */
19       CountAllVisitor CAV;
20       CAV.visit(BB);
21
22       // ...
23       LoadInst *ORCPtr = IRB.CreateLoad(WAFLMapPtr);
24       MapPtr->setMetadata(M.getMDKindID("nosanitize"),
25         MDNode::get(C, None));
26
27       Value* EdgeId = IRB.CreateXor(PrevLocCasted, CurLoc);
28       Value *ORCPtrIdx =
29           IRB.CreateGEP(ORCPtr, EdgeId);
30
31       /* Setup the counter for storage */
32       u32 log_count = (u32) log2(CAV.Count+1);
33       Value *CNT = IRB.getInt32(log_count);
34
35       LoadInst *ORCLoad = IRB.CreateLoad(ORCPtrIdx);
36       Value *ORCIncr = IRB.CreateAdd(ORCLoad, CNT);
37
38       IRB.CreateStore(ORCIncr, ORCPtrIdx)
39         ->setMetadata(M.getMDKindID("nosanitize"),
```

```
40          MDNode::get(C, None));
41
42        IRB.CreateCall(ORC_Increment, ArrayRef<Value*>({ CNT }));
43
44        inst_blocks++;
45      }
46    }
47  }
```

Listing 3.5: LLVM-mode instrumentation pass

Waffle builds its own compiler using the above definitions in instrumentation stage. By making (compiling) the files in `llvm-mode` directory, an executable compiler, `waffle-clang` is generated. This compiler scans the source code of the program, and creates a binary file with the logic of the program, and the intended instrumentation:

```
./waffle-clang target.c -o instr_target.bin
```

3.2.3 Fuzzing

Algorithm 4: $waffle - fuzz$

Input: *queueEntry*

initialize fuzzer;
while *fuzzing is not terminated* **do**
    cull_queue();
    $T \leftarrow q.first\_entry()$;
    $calibrate(T)$;
    $trim(T)$;
    $perf\_score \leftarrow calculate\_score(T)$;
    if *deterministic_mode* **then**
        $deterministic\_stages(T)$;
    $MX \leftarrow calc\_stages(perf\_score, \mathcal{C})$;
    foreach *element in* $(0, MX)$ **do**
        $random\_havoc(T)$;

Algorithm 5 illustrates the fuzzing procedure in more details. Waffle processes the front queue's entry to check if the current input is bringing something new to

the corpus. The front test case T is first *calibrated* to ensure that the input has been processed correctly. In the caliberation phase, the program is executed with T as input, and the information such as execution time, length of the input file, and the EI-ORC of execution are collected. These values are then passed to the function `update_bitmap_score()` to evaluate if the test case is a favorable one. A favroable test case is a

Waffle extends the instrumentation and the fuzzing procedure of AFL. The instrumented binary from the previous stage is given to the *waffle-fuzz*, and Waffle develops the new features in *waffle-fuzz.c*.

To analyze the implementation of Waffle, we merge the algorithm 2 and algorithm 3:

Algorithm 5: $waffle - fuzz$

```
   Input: queueEntry
 1 initialize fuzzer;
 2 while fuzzing is not terminated do
 3     cull_queue();
 4     T ← q.first_entry();
 5     calibrate(T);
 6     trim(T);
 7     perf_score ← calculate_score(T);
 8     if deterministic_mode then
 9         deterministic_stages(T);
10     MX ← calc_stages(perf_score, C);
11     foreach element in (0, MX) do
12         random_havoc(T);
```

The lines in red are the instructions that were modified in Waffle.

Calibration

Each entry of the queue is calibrated in order to collect the execution stats. Besides the execution-time and the bitmap-coverage information, Waffle runs the target program and collects the added **instruction counters**. Each instruction counter is monitored in the shared_memory, `icnt_bits[]`, and `top_rated_icnt[]` tracks the changes on `icnt_bits[]` in an `struct` of type `queue_entries`, .

Waffle collects the instrumentation's data after running the binary. The values of `icnt_bits` and `trace_bits` track the performance and the coverage-instrumentation. As described in Section Waffle, `sys_data` stores the sum of the instruction counters.

AFL checks the uniqueness of an execution by keeping a hashed value of `trace_bits[]`, representing a unique ID for a path-coverage. Within the discovery of a new coverage, Waffle analyzes both the *coverage* array and *instruction counters* to process the new hit-counts:

- `has_new_bits()`: AFL keeps the hit-counts of `trace_bits[]`, for identifying the new edges appeared in the execution of the current test-case. `trace_bits[]` is a sparse array, and AFL tracks the modified indices for better performance.
- `has_new_icnt()`: In addition to the previous method, Waffle searches for the highest values in `icnt_bits[]`. Each cell in `icnt_bits` contains 4 bytes of information. We saw in Listing 3.5 that in an index, such as `i`, `icnt_bits[i]` is added with `CNT`, while the increments in `trace_bits[]` are always by one. An analysis on `./sample_vul_instr` showed that the average value for `CNT`s is more than 3. As a result, the variance for the values in `icnt_bits[]` is higher than `trace_bits[]`'s. To decrease this variance and enhance the performance of Waffle, it leverages a constant float number, `MAX_CNT_MULT`:

```
static inline u8 has_new_icnt() {
  // #define MAX_CNT_MULT 1.05
  int ret = 0;
  for (int i = 0; i < ICNT_SIZE; i++) {
    if (unlikely(icnt_bits[i]) && unlikely(icnt_bits[i] >
     MAX_CNT_MULT*max_icnts[i])) {
       if(likely(ret<2)) {
         ret = 2;
         max_icnts[i] = icnt_bits[i];
       }
       else ret = 1;
    }
  }
  return ret;
}
```

Listing 3.6: has_new_icnt()

By default, Waffle sets $MAX\_CNT\_MULT = 1.05$, which means it expects at least 5% increase for `icnt_bits[i]` before updating the content of index i.

The length of both `icnt_bits[]` and `trace_bits[]` is the same, but `icnt_bits` consumes 4x more of the memory:

```
#define MAP_SIZE_POW2    16
#define MAP_SIZE         (1 << MAP_SIZE_POW2)
#define ICNT_SIZE        MAP_SIZE

EXP_ST u8* trace_bits;   /* SHM with coverage bitmap    */
EXP_ST u32* icnt_bits;   /* SHM with performance bitmap */
```

Listing 3.7: Configurations of the bitmaps

After analyzing the execution information, the calibration stage updates the undefined or old values of the current `queue_entry`.

Calculate performance score

The most favorable entries for Waffle, are the inputs with the highest `total_icnt`. In addition to the calculations of AFL, Waffle also compares the `q->total_icnt` with the average `total_icnt` of all previous entries, `avg_total_icnt`.

```
static u32 calculate_score(struct queue_entry* q) {
  u32 perf_score = 100;
```

```
  u64 avg_ORC = ORC / total_bitmap_entries;
  // ...
  if (q->ORC > avg_ORC * 3) perf_score *= 1.4;
  else if(q->ORC > avg_ORC * 2) perf_score *= 1.2;
  else if(q->ORC > avg_ORC) perf_score *= 1.05;
  else if(q->ORC > avg_ORC * 0.75) perf_score *= 0.7;
  else perf_score *= 0.5;
  // ...
}
```

Listing 3.8: The modifications of Waffle in `calc_score()`

With all these modifications, Waffle can start it's fuzzing. The only difference between the execution of Waffle and AFL, is the name of the fuzzer.

```
# waffle-fuzz -i <in_dir> -o <out_dir> [options] -- /path/to/fuzzed/app [params]
waffle-fuzz -i in_dir -o out_dir -- ./sample_vul_waffle
```

Listing 3.9: Execute AFL

3.3 Concluding remarks

This chapter introduced the development of Waffle. Waffle extends AFL in two parts:

1. **Instrumentation**: **llvm_mode** directory is responsible for the instrumentation in Waffle. As we explained in this chapter, `llvm_mode/waffle-llvm-rt.o.c` contains the recipe for instrumenting the program in the compilation.

   AFL only keeps a coverage-bitmap, but in addition to the coverage-finding methodology, Waffle leverages the **visitor functions** in LLVM for assessing the more resource-exhaustive executions. Visitor functions count the targeted instructions, and Waffle saves the result in an extra *shared_memory*.

   Waffle counts the instructions in each basic block, and reduces the counted values for saving into the memory. The size of the *shared_memory* has increased 4x in Waffle.

2. **Fuzzing**: Waffle uses the coverage bitmap and the instruction-counter bitmap for emphasizing the more beneficial fuzzing entries. The main changes are in the procedures of the functions `calibrate_case` and `calc_score()`. Generally speaking, an interesting test-case runs faster, has more code coverage, and executes more instructions from a specified set of instructions.

We also reviewed some of the modifications in the source code to Waffle's project. The project is located on github, in a public repository [4].

Chapter 4

Simulation

4.1 Introduction

We developed Waffle to analyze the executables, with experimental instrumentation, to enhance the performance of AFL in finding test-cases exposing vulnerabilities due to resource-exhaustion. In this chapter, we compare the performance of Waffle with state-of-the-art coverage-based fuzzers, **AFL** [11], and **libfuzzer** [54]. To evaluate the performance of Waffle, we use **fuzzbench** [55] comparing the fuzzers on different programs.

In the next section, we briefly describe the **fuzzbench** project, and explain how we utilize this service in this thesis. Next, we evaluate our work, and we continue with a discussion on the performance of Waffle.

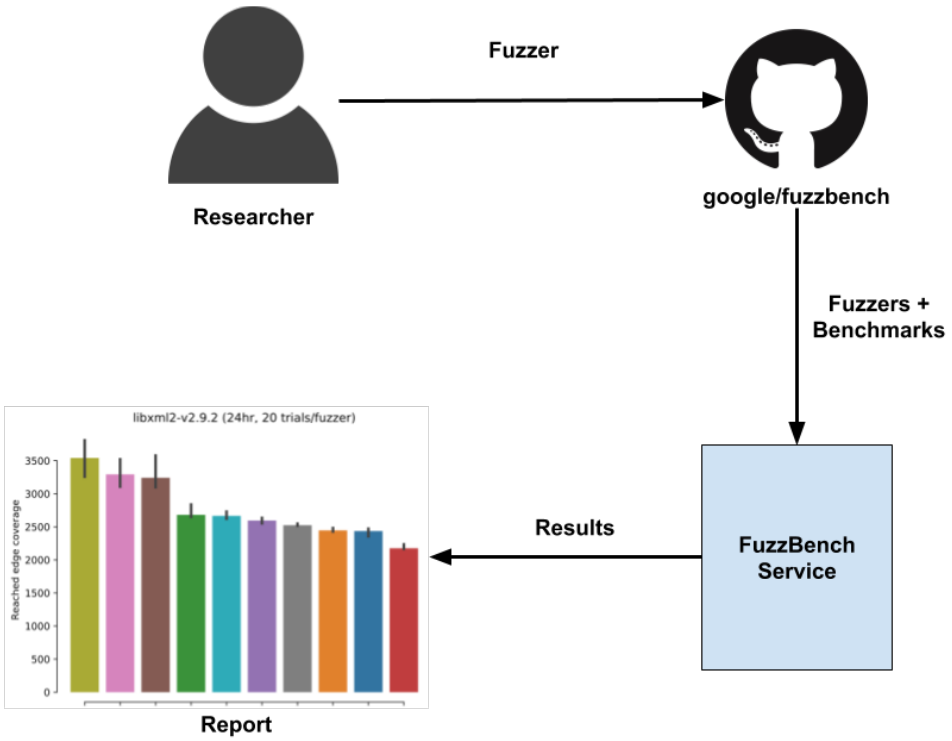


Figure 4.1: Fuzzbench overview

4.2 FuzzBench

Fuzzer Benchmarking As a Service

"FuzzBench is a free service that evaluates fuzzers on a wide variety of real-world benchmarks, at Google scale. The goal of FuzzBench is to make it painless to rigorously evaluate fuzzing research and make fuzzing research easier for the community to adopt." [55]

Of the main features of Fuzzbench, we use the following features to test Waffle:

- **Fuzzer API:** An API for integrating fuzzers.
- **Custom/Standard benchmarks:** FuzzBench provides a set of real-world

benchmarks. In addition, we can add our custom benchmarks or use any **OSS-Fuzz** project as a benchmark.

- **Reporting:** A reporting library is provided for generating graphs and statistical tests. These reports illustrate the performance of each fuzzer on different aspects. The evaluations are based on the stats such as the performance of fuzzers in finding unique vulnerabilities, or the growth and statistics of the code coverage during the experiments.

Add Waffle to FuzzBench

The current version of FuzzBench contains more than 30 different fuzzers available for testing. To evaluate Waffle, we need to first add Waffle to the list of known fuzzers that FuzzBench could communicate with. FuzzBench requires three files to provide the instructions for introducing a fuzzer:

- `builder.Dockerfile`: This file builds the fuzzer in a docker container. The recipe can be found in Appendix 6.B.1.
- `runner.Dockerfile`: This file defines the image that will be used to run benchmarks with Waffle.

```
1 FROM gcr.io/fuzzbench/base-image
```

- `fuzzer.py`: This file explains how to build and fuzz benchmarks using Waffle [Appendix 6.B.2].

According to the steps suggested for running an experiment, we add Waffle to FuzzBench, and we can assess if the fuzzer is working properly in the FuzzBench's environment.

```
export FUZZER_NAME=waffle
export BENCHMARK_NAME=libpng-1.2.56

# Building the fuzzer and benchmark in the fuzzer's environment
make build-$FUZZER_NAME-$BENCHMARK_NAME

# Required for evaluating the experiment
make format
make presubmit
```

Listing 4.1: Final steps for adding Waffle to FuzzBench

We faced some problems while adding Waffle, as the FuzzBench project **must** be built before the fuzzer is inserted into the `fuzzers` directory [56]. Otherwise, **local experiments** would fail due to existing bugs.

Start an experiment

There are three methods for initiating an experiment in FuzzBench:

- **Request in FuzzBench** "The FuzzBench service automatically runs experiments that are requested by users twice a day at 6:00 AM PT (13:00 UTC) and 6:00 PM PT (01:00 UTC). [57]"
- **Setting up a Google Cloud Project:** We can run our experiment on **GCP** [58].
- **Run a local experiment:** We can start the experiment on a non-cloud platform as well. Running a experiment on a local computer may lack enough resources for running different tests in parrallel.

We use a **local experiment** for evaluations. The local computer runs on Ubuntu 18.04 64bits, with Intel® Core™ i7-3770 CPU @ 3.40GHz × 8, and 16

GBs of RAM. The measurements for the performance of HDD, show 30MB/s for reading from the disk, and can write for 25MB/s.

4.3 FuzzBench Reports

FuzzBench starts reporting after building the project in a local experiment. Building AFL and Waffle on a benchmark such as *libpng-1.2.56* took 30 minutes on the local computer, and FuzzBench doesn't generate any reports before that.

We tested Waffle in 6-hours experiments. The test computer could not run an experiment with more than **two fuzzers** and **one benchmark**, and the higher setups fail to finish. Each experiment contains **3** trials for each pair of $< FuzzerX, Benchmark >$, where FuzzerX is either Waffle, AFL, or LibFuzzer(LF).

None of the trials could find any crashes/hangs during 6-hours trials.

Our experiments are:

1. Waffle vs AFL on libpng-1.2.56
2. Waffle vs LibFuzzer on libpng-1.2.56
3. Waffle vs AFL on openthread-2019-12-23
4. Waffle vs LibFuzzer on openthread-2019-12-23
5. Waffle vs AFL on php_php-fuzz-execute
6. Waffle vs LibFuzzer on php_php-fuzz-execute
7. Waffle vs AFL on curl_curl_fuzzer_http
8. Waffle vs AFL on sqlite3_ossfuzz

We evaluate the results according to the generated reports. The graphs [Figures 4.2, **??**, and **??**] illustrate the covered regions of the code in each experiment, the pairwise unique coverage, and the growth of the code coverage over time. Green color represents Waffle in all figures.

For the benchmarks *libpng-1.2.56*, *php_php-fuzz-execute*, and *openthread*, we analyzed the performance of Waffle with each on of the other fuzzers. In our setups, we continued testing *sqlite3_ossfuzz* and *curl_curl_fuzzer_http* with Waffle and AFL for further investigations.

Performance measurements

FuzzBench compares the performance of the fuzzers based on the discovered code coverage of each experiment. Meaning that, for example, FuzzBench does not check how many executions a fuzzer performs; instead, it considers the variety of the generated inputs, according to their execution paths.

Table 4.1 shows the summary of our results. The table shows the coverage stats for the participating fuzzers; the columns are $mean coverage$, $standard deviation$, and the number of $unique findings$ of each fuzzer in each experiment.

Figure 4.2 shows the growth of the code coverage that each fuzzer had explored. In testing *libpng* [4.2a], *openthread* [4.2c], and *curl* [4.2g], we can see that both Waffle and AFL eventually converge, and it suggests that, here, Waffle performs indifferently in the discovery of new regions of code (higher code coverage). Waffle also shows latency in generating the first generations of the inputs and continues a close competition with AFL.

For *php_php-fuzz-execute*, AFL shows 15% better performance; however, for the

Benchmark	Fuzzer	Waffle Mean Coverage	Fuzzer Mean Coverage	Waffle STD	Fuzzer STD	Unique (Waffle/Fuzzer)
libpng-1.2.56	AFL	1509	1510	0.57	0.57	0/1
libpng-1.2.56	LibFuzzer	1509	1951	0.57	6.65	0/425
php_php-fuzz-execute	AFL	147945	169447	5451.77	2069.34	1270/18902
php_php-fuzz-execute	LibFuzzer	145816	138666	2580.20	234.08	10179/335
openthread-2019-12-23	AFL	5226	5216	12.58	24.13	0/2
openthread-2019-12-23	LibFuzzer	5242	5852	3.21	24.24	6/384
sqlite3_ossfuzz	AFL	33510	32245	2631.01	872.98	1435/1088
curl_curl_fuzzer_http	AFL	17142	17290	215.89	192.12	55/154

Table 4.1: Statistics of the experiments.

other benchmark, *sqlite3_ossfuzz*, Waffle has enhanced the performance of AFL by 4%.

LibFuzzer is showing better performance than Waffle as in Figures 4.2b and 4.2d. LibFuzzer found 30% and 12% more code coverage for fuzzing *libpng* and *openthread*, respectively. On the other hand, fuzzing *php* has 5% more code coverage under Waffle.

Comparing the graphs on the left column (AFL) and the right column (LF) for the benchmarks, *libpng*, *openthread*, and *php*, shows the following rankings:

1. **libpng:** 1: LibFuzzer. 2: Waffle/AFL.
2. **openthread:** 1: LibFuzzer. 2: Waffle/AFL.
3. **php:** 1: AFL. 2: Waffle. 3: LibFuzzer.

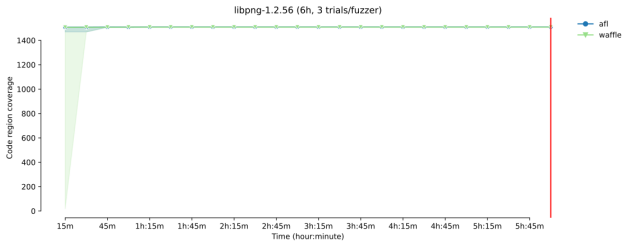
In the third scenario, we see that in the *6-hours* trials, Waffle succeeds LibFuzzer for fuzzing *php*.

In Figure **??**, we can analyze the distribution of the code-coverages of each trial pair. The code coverage of AFL shows lower deviations compared to Waffle.

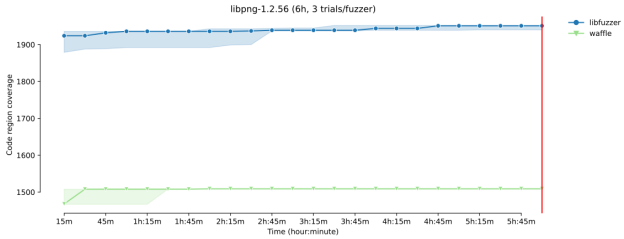
In the end, the number of unique findings of each fuzzer is shown in the last column. Overally speaking, Waffle outperforms AFL in fuzzing *sqlite3*

4.4 Performance Bottlenecks of Waffle

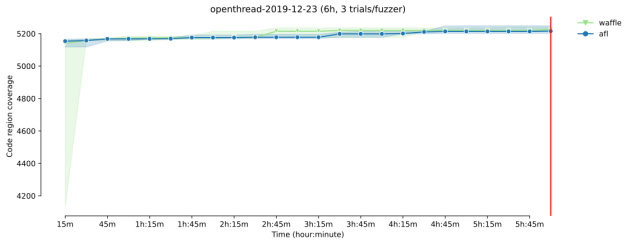
As we explained in Chapter 3, after each execution of the target program, Waffle runs the function `has_new_icnt()` after `has_new_bits()`, for detecting the changes



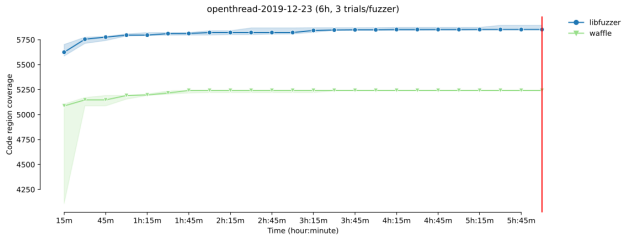
(a) Waffle-AFL libpng-1.2.56



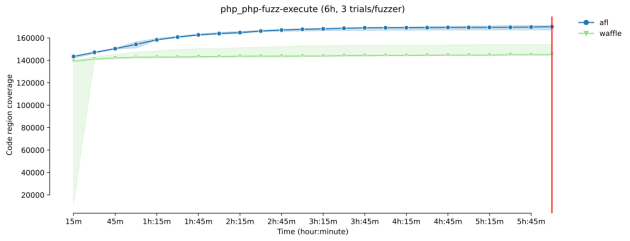
(b) Waffle-LF libpng-1.2.56



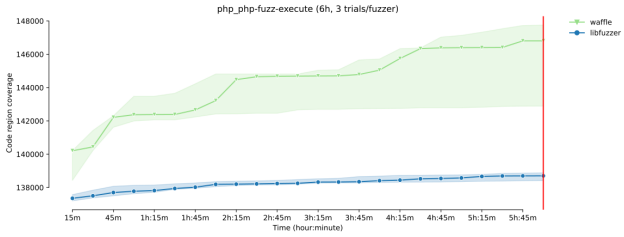
(c) Waffle-AFL openthread-2019-12-23



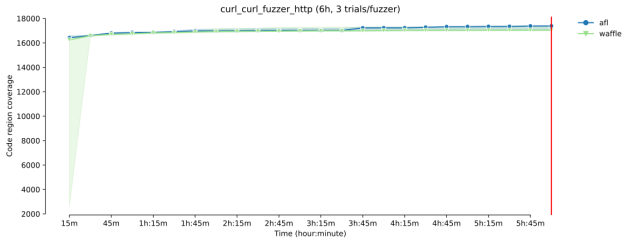
(d) Waffle-LF openthread-2019-12-23



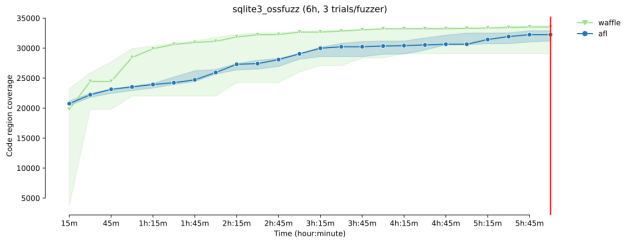
(e) Waffle-AFL php_php-fuzz-execute



(f) Waffle-LF php_php-fuzz-execute



(g) Waffle-AFL curl_curl_fuzzer_http

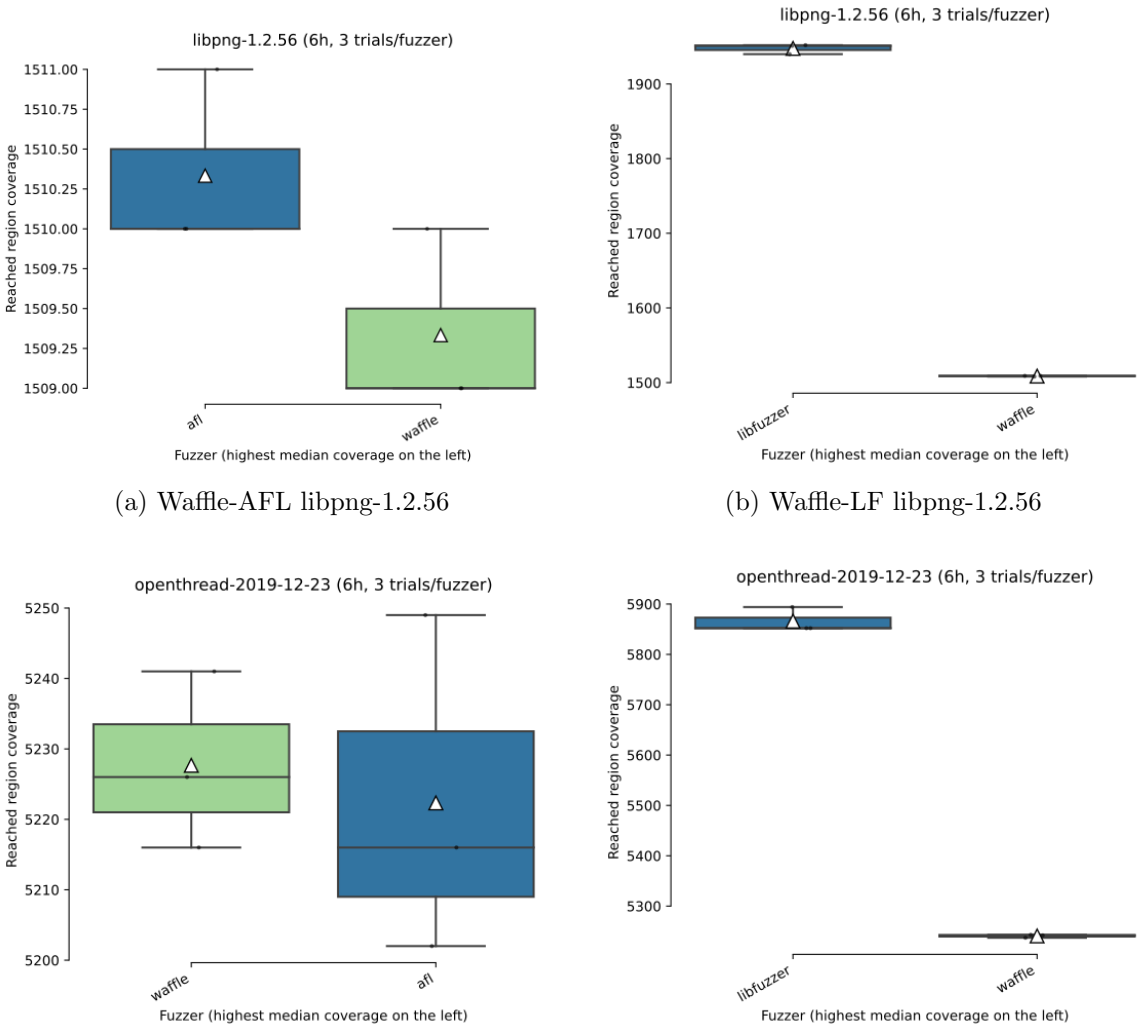


(h) Waffle-AFL sqlite3_ossfuzz

Figure 4.2: Mean code coverage growth over time

of the instruction counters on each edge. `has_new_icnt()` helps Waffle prioritize the edges that their instruction counters increase faster.

To investigate the performance changes for the insertion of `has_new_icnt()`, we ran this function on a sparse array of 32bit integers. On the other hand, we ran the



(a) Waffle-AFL libpng-1.2.56

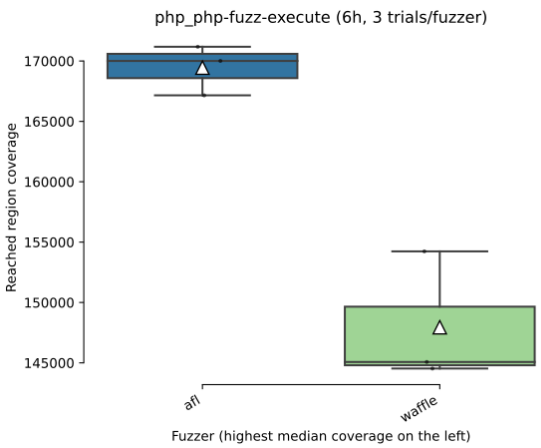
(b) Waffle-LF libpng-1.2.56

(c) Waffle-AFL openthread-2019-12-23

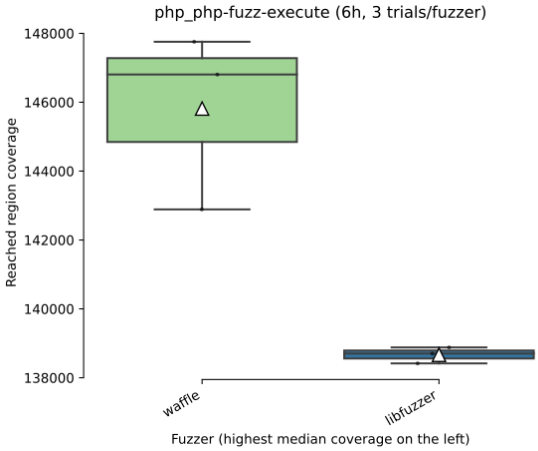
(d) Waffle-LF openthread-2019-12-23

Figure 4.3: Reached code coverage distribution

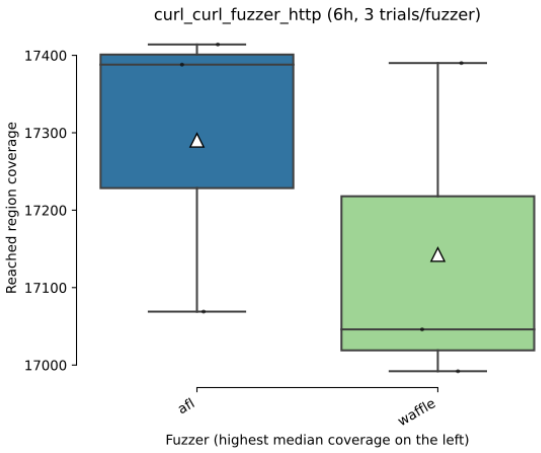
function `has_new_bits()` on a sparse array of 8bit integers, for the same number of iterations. The results showed that the trial of `has_new_icnt()` takes 15000 milliseconds, while the mentioned execution of `has_new_bits()` takes 1500 milliseconds, on the local computer. As a result, the execution of both of the functions consecutively, takes **11x** longer.



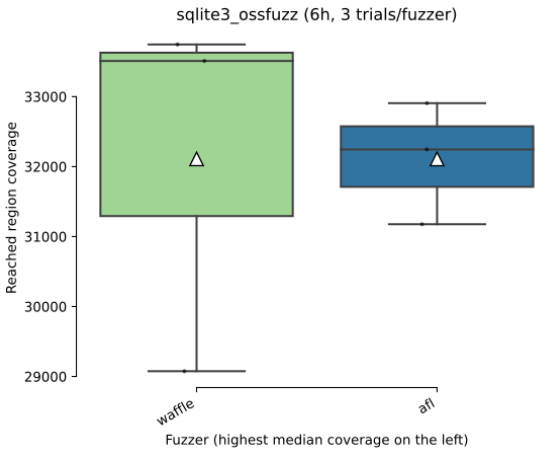
(e) Waffle-AFL php_php-fuzz-execute



(f) Waffle-LF php_php-fuzz-execute



(g) Waffle-AFL curl_curl_fuzzer_http



(h) Waffle-AFL sqlite3_ossfuzz

Figure 4.3: Reached code coverage distribution (cont.)

Chapter 5

Future Works and Conclusions

Bibliography

[1] Hongliang Liang, Xiaoxiao Pei, Xiaodong Jia, Wuwei Shen, and Jian Zhang. Fuzzing: State of the art. *IEEE Transactions on Reliability*, 67(3):1199–1218, 2018.

[2] Michael Sutton, Adam Greene, and Pedram Amini. *Fuzzing: brute force vulnerability discovery*. Pearson Education, 2007.

[3] OmniSci. What is llvm. `https://www.omnisci.com/technical-glossary/llvm`, 2020. [Online]; accessed in 2020.

[4] Waffle project. `https://github.com/behnamarbab/memlock-waffle/tree/waffle`, 2021.

[5] Afl-cve. `https://github.com/mrash/afl-cve`, 2019.

[6] Wolfgang Banzhaf, Peter Nordin, Robert E Keller, and Frank D Francone. *Genetic programming: an introduction*, volume 1. Morgan Kaufmann Publishers San Francisco, 1998.

[7] Darrell Whitley. A genetic algorithm tutorial. *Statistics and computing*, 4(2):65–85, 1994.

[8] Marcel Böhme, Van-Thuan Pham, and Abhik Roychoudhury. Coverage-based greybox fuzzing as markov chain. *IEEE Transactions on Software Engineering*, 2017.

[9] Caroline Lemieux, Rohan Padhye, Koushik Sen, and Dawn Song. Perffuzz: Automatically generating pathological inputs. In *Proceedings of the 27th ACM SIGSOFT International Symposium on Software Testing and Analysis*, pages 254–265. ACM, 2018.

[10] James Newsome and Dawn Xiaodong Song. Dynamic taint analysis for automatic detection, analysis, and signaturegeneration of exploits on commodity software. In *NDSS*, volume 5, pages 3–4. Citeseer, 2005.

[11] american fuzzy lop - a security-oriented fuzzer. `https://github.com/google/AFL`, 2021.

[12] LLVM. Llvm project. `http://llvm.org/`, 2020. [Online]; accessed in 2020.

[13] Fabrice Bellard. Qemu, a fast and portable dynamic translator. In *USENIX annual technical conference, FREENIX Track*, volume 41, page 46. Califor-nia, USA, 2005.

[14] High-performance binary-only instrumentation for afl-fuzz. `https://github.com/mirrorer/afl/blob/master/qemu_mode/README.qemu`, 2020.

[15] Dynamorio. `https://dynamorio.org/`, 2021.

[16] Dynamic instrumentation toolkit for developers, reverse-engineers, and security researchers. `https://frida.re/`, 2021.

[17] Pin - a dynamic binary instrumentation tool. `https://software.intel.com/content/www/us/en/develop/articles/pin-a-dynamic-binary-instrumentation-tool.html`, 2021.

[18] Iso 27005, information technology — security techniques — information security risk management (third edition). https://www.iso27001security.com/html/27005.html, 2018.

[19] Yung-Yu Chang, Pavol Zavarsky, Ron Ruhl, and Dale Lindskog. Trend analysis of the cve for software vulnerability management. In *2011 IEEE Third International Conference on Privacy, Security, Risk and Trust and 2011 IEEE Third International Conference on Social Computing*, pages 1290–1293. IEEE, 2011.

[20] Yunfei Su, Mengjun Li, Chaojing Tang, and Rongjun Shen. An overview of software vulnerability detection. *International Journal of Computer Science And Technology*, 7(3):72–76, 2016.

[21] Denial of service software attack - owasp foundation. https://owasp.org/www-community/attacks/Denial_of_Service, 2021.

[22] Barton P Miller, Louis Fredriksen, and Bryan So. An empirical study of the reliability of unix utilities. *Communications of the ACM*, 33(12):32–44, 1990.

[23] Dokyung Song, Felicitas Hetzelt, Dipanjan Das, Chad Spensky, Yeoul Na, Stijn Volckaert, Giovanni Vigna, Christopher Kruegel, Jean-Pierre Seifert, and Michael Franz. Periscope: An effective probing and fuzzing framework for the hardware-os boundary. In *NDSS*, 2019.

[24] Michal Zalewski. Pulling jpegs out of thin air. https://lcamtuf.blogspot.com/2014/11/pulling-jpegs-out-of-thin-air.html, 2014.

[25] Maverick Woo, Sang Kil Cha, Samantha Gottlieb, and David Brumley. Scheduling black-box mutational fuzzing. In *Proceedings of the 2013 ACM SIGSAC conference on Computer & communications security*, pages 511–522, 2013.

[26] Greg Banks, Marco Cova, Viktoria Felmetsger, Kevin Almeroth, Richard Kemmerer, and Giovanni Vigna. Snooze: toward a stateful network protocol fuzzer.

In *International Conference on Information Security*, pages 343–358. Springer, 2006.

[27] Hugo Gascon, Christian Wressnegger, Fabian Yamaguchi, Daniel Arp, and Konrad Rieck. Pulsar: Stateful black-box fuzzing of proprietary network protocols. In *International Conference on Security and Privacy in Communication Systems*, pages 330–347. Springer, 2015.

[28] Adam Doupé, Ludovico Cavedon, Christopher Kruegel, and Giovanni Vigna. Enemy of the state: A state-aware black-box web vulnerability scanner. In *Presented as part of the 21st {USENIX} Security Symposium ({USENIX} Security 12)*, pages 523–538, 2012.

[29] Fabien Duchene, Roland Groz, Sanjay Rawat, and Jean-Luc Richier. Xss vulnerability detection using model inference assisted evolutionary fuzzing. In *2012 IEEE Fifth International Conference on Software Testing, Verification and Validation*, pages 815–817. IEEE, 2012.

[30] Jiongyi Chen, Wenrui Diao, Qingchuan Zhao, Chaoshun Zuo, Zhiqiang Lin, XiaoFeng Wang, Wing Cheong Lau, Menghan Sun, Ronghai Yang, and Kehuan Zhang. Iotfuzzer: Discovering memory corruptions in iot through app-based fuzzing. In *NDSS*, 2018.

[31] Muhammad Numair Mansur, Maria Christakis, Valentin Wüstholz, and Fuyuan Zhang. Detecting critical bugs in smt solvers using blackbox mutational fuzzing. In *Proceedings of the 28th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*, pages 701–712, 2020.

[32] James C King. Symbolic execution and program testing. *Communications of the ACM*, 19(7):385–394, 1976.

[33] Patrice Godefroid, Michael Y Levin, David A Molnar, et al. Automated whitebox fuzz testing. In *NDSS*, volume 8, pages 151–166, 2008.

[34] Patrice Godefroid, Michael Y Levin, and David Molnar. Sage: whitebox fuzzing for security testing. *Communications of the ACM*, 55(3):40–44, 2012.

[35] Cristian Cadar, Patrice Godefroid, Sarfraz Khurshid, Corina S Pasareanu, Koushik Sen, Nikolai Tillmann, and Willem Visser. Symbolic execution for software testing in practice: preliminary assessment. In *2011 33rd International Conference on Software Engineering (ICSE)*, pages 1066–1071. IEEE, 2011.

[36] Nick Stephens, John Grosen, Christopher Salls, Andrew Dutcher, Ruoyu Wang, Jacopo Corbetta, Yan Shoshitaishvili, Christopher Kruegel, and Giovanni Vigna. Driller: Augmenting fuzzing through selective symbolic execution. In *NDSS*, volume 16, pages 1–16, 2016.

[37] Vijay Ganesh, Tim Leek, and Martin Rinard. Taint-based directed whitebox fuzzing. In *Proceedings of the 31st International Conference on Software Engineering*, pages 474–484. IEEE Computer Society, 2009.

[38] Patrice Godefroid, Adam Kiezun, and Michael Y Levin. Grammar-based whitebox fuzzing. In *ACM Sigplan Notices*, volume 43, pages 206–215. ACM, 2008.

[39] Young-Hyun Choi, Min-Woo Park, Jung-Ho Eom, and Tai-Myoung Chung. Dynamic binary analyzer for scanning vulnerabilities with taint analysis. *Multimedia Tools and Applications*, 74(7):2301–2320, 2015.

[40] Marcel Böhme, Van-Thuan Pham, Manh-Dung Nguyen, and Abhik Roychoudhury. Directed greybox fuzzing. In *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, pages 2329–2344. ACM, 2017.

[41] Sanjay Rawat, Vivek Jain, Ashish Kumar, Lucian Cojocar, Cristiano Giuffrida, and Herbert Bos. Vuzzer: Application-aware evolutionary fuzzing. In *NDSS*, volume 17, pages 1–14, 2017.

[42] Qian Yang, J Jenny Li, and David M Weiss. A survey of coverage-based testing tools. *The Computer Journal*, 52(5):589–597, 2009.

[43] Yuekang Li, Bihuan Chen, Mahinthan Chandramohan, Shang-Wei Lin, Yang Liu, and Alwen Tiu. Steelix: program-state based binary fuzzing. In *Proceedings of the 2017 11th Joint Meeting on Foundations of Software Engineering*, pages 627–637, 2017.

[44] Theofilos Petsios, Jason Zhao, Angelos D Keromytis, and Suman Jana. Slowfuzz: Automated domain-independent detection of algorithmic complexity vulnerabilities. In *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, pages 2155–2168. ACM, 2017.

[45] Cheng Wen, Haijun Wang, Yuekang Li, Shengchao Qin, Yang Liu, Zhiwu Xu, Hongxu Chen, Xiaofei Xie, Geguang Pu, and Ting Liu. Memlock: Memory usage guided fuzzing. In *Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering*, pages 765–777, 2020.

[46] Michal Zalewski. American fuzzy lop.(2014). `http://lcamtuf.coredump.cx/afl`, 2019.

[47] More about afl. `https://afl-1.readthedocs.io/en/latest/about_afl.html`, 2019.

[48] Fast llvm-based instrumentation for afl-fuzz. `https://github.com/google/AFL/blob/master/llvm_mode/README.llvm`, 2019.

[49] Clang: a c language family frontend for llvm. `https://clang.llvm.org/`, 2020. [Online]; accessed in 2021.

[50] Chris Lattner and Vikram Adve. Llvm: A compilation framework for lifelong program analysis & transformation. In *International Symposium on Code Generation and Optimization, 2004. CGO 2004.*, pages 75–86. IEEE, 2004.

[51] Afl user guide. `https://afl-1.readthedocs.io/en/latest/user_guide.html`, 2019.

[52] Tips for parallel fuzzing. `https://github.com/mirrorer/afl/blob/master/docs/parallel_fuzzing.txt`, 2016.

[53] Base class for instruction visitors. `https://llvm.org/doxygen/InstVisitor_8h_source.html`, 2021.

[54] K Serebryany. libfuzzer a library for coverage-guided fuzz testing. *LLVM project*, 2015.

[55] László Szekeres Jonathan Metzman, Abhishek Arya, and L Szekeres. Fuzzbench: Fuzzer benchmarking as a service. *Google Security Blog*, 2020.

[56] Local experiment issue - erro[0612]. `https://github.com/google/fuzzbench/issues/946`, 2021.

[57] Requesting an experiment. `https://google.github.io/fuzzbench/getting-started/adding-a-new-fuzzer/#requesting-an-experiment`, 2021.

[58] Setting up gcp. `https://google.github.io/fuzzbench/running-a-cloud-experiment/setting-up-a-google-cloud-project`, 2021.

Chapter 6

Appendix

6.A Waffle

6.A.1 random_havoc

An abstract implementation of the `havoc_stage` used in AFL and Waffle. Most of the commands are removed, and the remaining comments describe the operations of this stage.

```
1  havoc_stage:
2    /* The havoc stage mutation code is also invoked when splicing
       files; if the splice_cycle variable is set, generate different
       descriptions and such. */
3
4    if (!splice_cycle) {
5      stage_max   = (doing_det ? HAVOC_CYCLES_INIT : HAVOC_CYCLES) *
6                    perf_score / havoc_div / 100;
7    }
8    else {
9      stage_max   = SPLICE_HAVOC * perf_score / havoc_div / 100;
10   }
11
12   /* We essentially just do several thousand runs (depending on
       perf_score) where we take the input file and make random stacked
       tweaks. */
13   for (stage_cur = 0; stage_cur < stage_max; stage_cur++) {
```

```
14      u32 use_stacking = 1 << (1 + UR(HAVOC_STACK_POW2));
15      for (i = 0; i < use_stacking; i++) {
16        switch (UR(15 + ((extras_cnt + a_extras_cnt) ? 2 : 0))) {
17          case 0:
18            /* Flip a single bit somewhere. Spooky! */
19          case 1:
20            /* Set byte to interesting value. */
21          case 2:
22            /* Set word to interesting value, randomly choosing endian
    . */
23          case 3:
24            /* Set dword to interesting value, randomly choosing
    endian. */
25          case 4:
26            /* Randomly subtract from byte. */
27          case 5:
28            /* Randomly add to byte. */
29          case 6:
30            /* Randomly subtract from word, random endian. */
31          case 7:
32            /* Randomly add to word, random endian. */
33          case 8:
34            /* Randomly subtract from dword, random endian. */
35          case 9:
36            /* Randomly add to dword, random endian. */
37          case 10:
38            /* Just set a random byte to a random value. Because, why
    not. We use XOR with 1-255 to eliminate the possibility of a no-
    op. */
39          case 11 ... 12:
40            /* Delete bytes. We're making this a bit more likely than
    insertion (the next option) in hopes of keeping files reasonably
     small. */
41          case 13:
42            /* Clone bytes (75%) or insert a block of constant bytes
    (25%). */
43          case 14:
44            /* Overwrite bytes with a randomly selected chunk (75%) or
     fixed bytes (25%). */
45
46            /* Values 15 and 16 can be selected only if there are any
    extras present in the dictionaries. */
47          case 15:
48            /* Overwrite bytes with an extra. */
49          case 16:
50            /* Insert an extra. Do the same dice-rolling stuff as for
    the previous case. */
51        }
52      }
53      /* Write a modified test case, run program, process results.
    Handle error conditions, returning 1 if it's time to bail out.
    This is a helper function for fuzz_one(). */
54    }
```

Listing 6.1: Random havoc stage

6.B FuzzBench

We have reviewed the recipe for adding Waffle to FuzzBench in this section.

6.B.1 builder.Dockerfile

Builds Waffle for the usage in FuzzBench.

The `parent_image` is an image instance with premitive configurations, and is on `ubuntu:xenial` OS. Building Python, installing python requirements, and installing the `google-cloud-sdk`, are the operations applied on the `parent_image`.

```
ARG parent_image
FROM $parent_image

RUN apt-get clean
RUN apt-get update --fix-missing
RUN apt-get -y install wget git build-essential software-properties-common apt-transport-https --fix-missing

# The llvm we are looking for
RUN wget -O - https://apt.llvm.org/llvm-snapshot.gpg.key | apt-key add -
RUN add-apt-repository ppa:ubuntu-toolchain-r/test && echo $(gcc -v)
RUN apt-add-repository "deb http://apt.llvm.org/xenial/ llvm-toolchain-xenial-6.0 main" -y
RUN apt-get update
RUN apt-get install -y gcc-7 g++-7 clang llvm

# Clone and build the repository for Waffle
RUN git clone -b waffle --single-branch https://github.com/behnamarbab/memlock-waffle.git /source_files
RUN cd /source_files/waffle && \
    unset CFLAGS CXXFLAGS && \
    AFL_NO_X86=1 make && \
    cd llvm_mode && make

#  Install the driver for communicating with FuzzBench
RUN wget https://raw.githubusercontent.com/llvm/llvm-project/5feb80e748924606531ba28c97fe65145c65372e/compiler-rt/lib/fuzzer/afl/afl_driver.cpp -O /source_files/afl_driver.cpp  && \
    cd /source_files/waffle && unset CFLAGS CXXFLAGS && \
    clang -Wno-pointer-sign -c /source_files/waffle/llvm_mode/afl-llvm-rt.o.c -I/source_files/waffle/ && \
    clang++ -stdlib=libc++ -std=c++11 -O1 -c /source_files/
```

```
    afl_driver.cpp  && \
27   ar r /libAFL.a *.o
```

Listing 6.2: Recipe for building Waffle FuzzBench

6.B.2 fuzzer.py

This python program specifies the sequence of the actions Waffle takes, in order to start fuzzing and use the benchmark as the target program. This program modifies the file located in {FUZZBENCH_DIR}/fuzzers/AFL/fuzzer.py. As Waffle is based on AFL, this program can start the process same as the AFL's fuzzer.py.

```
1  """Integration code for Waffle fuzzer."""
2
3  import json
4  import os
5  import shutil
6  import subprocess
7
8  from fuzzers import utils
9
10
11 def prepare_build_environment():
12     """Set environment variables used to build targets for AFL-based
13     fuzzers."""
14     cflags = ['-fsanitize-coverage=trace-pc-guard']
15     utils.append_flags('CFLAGS', cflags)
16     utils.append_flags('CXXFLAGS', cflags)
17
18     os.environ['CC'] = 'clang'
19     os.environ['CXX'] = 'clang++'
20     os.environ['FUZZER_LIB'] = '/libAFL.a'
21
22
23 def build():
24     """Build benchmark."""
25     prepare_build_environment()
26
27     utils.build_benchmark()
28
29     print('[post_build] Copying waffle-fuzz to $OUT directory')
30     # Copy out the waffle-fuzz binary as a build artifact.
31     shutil.copy('/source_files/waffle/waffle-fuzz', os.environ['OUT'
       ])
32
33
```

```
34 def get_stats(output_corpus, fuzzer_log):  # pylint: disable=unused-
   argument
35     """Gets fuzzer stats for Waffle."""
36     # Get a dictionary containing the stats Waffle reports.
37     stats_file = os.path.join(output_corpus, 'fuzzer_stats')
38     with open(stats_file) as file_handle:
39         stats_file_lines = file_handle.read().splitlines()
40     stats_file_dict = {}
41     for stats_line in stats_file_lines:
42         key, value = stats_line.split(': ')
43         stats_file_dict[key.strip()] = value.strip()
44 
45     # Report to FuzzBench the stats it accepts.
46     stats = {'execs_per_sec': float(stats_file_dict['execs_per_sec'
   ])}
47     return json.dumps(stats)
48 
49 
50 def prepare_fuzz_environment(input_corpus):
51     """Prepare to fuzz with AFL or another AFL-based fuzzer."""
52     # Tell AFL to not use its terminal UI so we get usable logs.
53     os.environ['AFL_NO_UI'] = '1'
54     # Skip AFL's CPU frequency check (fails on Docker).
55     os.environ['AFL_SKIP_CPUFREQ'] = '1'
56     # No need to bind affinity to one core, Docker enforces 1 core
   usage.
57     os.environ['AFL_NO_AFFINITY'] = '1'
58     # AFL will abort on startup if the core pattern sends
   notifications to
59     # external programs. We don't care about this.
60     os.environ['AFL_I_DONT_CARE_ABOUT_MISSING_CRASHES'] = '1'
61     # Don't exit when crashes are found. This can happen when corpus
       from
62     # OSS-Fuzz is used.
63     os.environ['AFL_SKIP_CRASHES'] = '1'
64 
65     # AFL needs at least one non-empty seed to start.
66     utils.create_seed_file_for_empty_corpus(input_corpus)
67 
68 
69 def run_waffle_fuzz(input_corpus,
70                     output_corpus,
71                     target_binary,
72                     additional_flags=None,
73                     hide_output=False):
74     """Run the fuzzer"""
75     # Spawn the waffle fuzzing process.
76     print('[run_waffle_fuzz] Running target with waffle-fuzz')
77     command = ['./waffle-fuzz', '-i', input_corpus, '-o',
   output_corpus, '-d', '-m', 'none', '-t', '1000']
78     if additional_flags:
79         command.extend(additional_flags)
80     dictionary_path = utils.get_dictionary_path(target_binary)
81     if dictionary_path:
```

```
82          command.extend(['-x', dictionary_path])
83      command += [
84          '--',
85          target_binary,
86          # Pass INT_MAX to afl the maximize the number of persistent
    loops it
87          # performs.
88          '2147483647'
89      ]
90      print('[run_waffle_fuzz] Running command: ' + ' '.join(command))
91      output_stream = subprocess.DEVNULL if hide_output else None
92      subprocess.check_call(command, stdout=output_stream, stderr=
    output_stream)
93
94
95  def fuzz(input_corpus, output_corpus, target_binary):
96      """Run waffle-fuzz on target."""
97      prepare_fuzz_environment(input_corpus)
98
99      run_waffle_fuzz(input_corpus, output_corpus, target_binary)
```

Listing 6.3: Recipe for running fuzzing with Waffle on a target