

Scalable Fuzzing of Program Binaries with E9AFL

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Abstract—Greybox fuzzing is an effective method for software testing. Greybox fuzzers, such as AFL, use instrumentation that collects path coverage information in order to guide the fuzzing process. The instrumentation is usually inserted by a modified compiler toolchain, meaning that the program must be recompiled in order to be compatible with greybox fuzzing. When source code is unavailable, or for projects with complex build systems, recompilation is not always feasible. In this paper, we present E9AFL, a fast and scalable tool that automatically inserts AFL instrumentation to program binaries. E9AFL is built on top of the E9Patch static binary rewriting tool. To combat the overhead caused by binary instrumentation, E9AFL develops a set of optimization strategies. Our evaluation results show that E9AFL outperforms existing binary instrumentation tools and achieves comparable performance with the compile time instrumentation.

Open source tool: <https://github.com/GJDuck/e9afl>

Tool demo video: <https://youtu.be/bVyADCgzlnw>

Index Terms—Fuzzing, binary rewriting

I. INTRODUCTION

Greybox fuzzing is a proven and effective method for software testing. Popular greybox fuzzing tools, such as AFL [1], work by inserting instrumentation into the program in order to collect path coverage information for guiding the fuzzing process. The instrumentation is usually inserted at compile-time using a specially modified compiler (e.g., `afl-gcc`). However, in scenarios where the source code is unavailable, compile-time instrumentation is not possible. An alternative approach is to directly instrument binary code, i.e., binary instrumentation. Existing techniques instrument the binary as the program executes, such as with AFL-qemu [2], or use binary rewriting, such as with AFL-dyninst [3]. However, each approach has its drawbacks. For example, AFL-qemu is based on emulation, which may incur high overheads (up to 5× in our experiments). Static binary instrumentation may also be inaccurate and introduce errors, which can manifest as false positives during the fuzzing process. Either way, binary instrumentation tends not to scale for large/complex software.

To address the above limitations, we propose E9AFL—a fast and scalable binary AFL instrumentation tool. E9AFL is based on E9Patch [4], which is a scalable static binary rewriting system that can rewrite large/complex stripped binaries without relying on assumptions or heuristics. Specifically,

E9Patch uses a trampoline-based rewriting methodology, in combination with *instruction punning* [5] and extensions [4], in order to insert instrumentation into arbitrary locations. However, this methodology may incur significant overheads, since trampoline-based binary rewriting breaks code contiguity. To alleviate the overhead, E9AFL introduces three core optimization strategies: *Trampoline ordering*, *Instruction selection* and *Bad block elimination*. We evaluate E9AFL against select subjects from the FuzzBench [6] benchmark suite. Our experimental results show that E9AFL runs at 77.0% of the speed of `afl-gcc` with comparable code coverage, which outperforms the existing AFL-qemu and AFL-dyninst tools. Finally, we demonstrate the scalability of E9AFL by fuzzing the Google Chrome [7] binary.

II. TOOL USAGE

The E9AFL tool is designed for ease-of-use. Most binaries can be instrumented using a simple command:

```
$ e9afl program
```

This will generate an instrumented `program.afl` binary that can be fuzzed using the standard AFL toolchain. For example, we can instrument and fuzz the `readelf` binary as follows:

```
$ e9afl readelf
```

```
$ afl-fuzz -i in/ -o out/ -- ./readelf.afl -a @@
```

No other additional step or special set up is required.

We note the ease-of-use compared to AFL’s source-level instrumentation. To instrument a program at source-level, it is necessary to create a correct compiling environment and build using a specially modified compiler (e.g., `afl-gcc`). For software with complex build systems, e.g., Chrome, creating a compilation environment and modifying the build system can be a non-trivial task. In contrast, E9AFL is “push-button”, and can instrument pre-built binaries via a single command.

III. TOOL DESIGN

E9AFL is built on top of the E9Patch [4] static rewriting system for Linux x86_64 binaries. E9Patch uses a *trampoline-based* rewriting methodology, meaning that selected instructions are replaced by jumps to “trampolines” that implement the AFL instrumentation. An example is illustrated in Figure 1. Here, selected instructions (highlighted in Figure 1 (a)) are replaced by jump instructions that divert control to the trampolines illustrated in Figure 1 (b). The trampolines implement the instrumentation (as well as displaced instruction),

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before returning control-flow back to the main program. For short instructions <5 bytes (the size of a `jmpq` instruction), E9Patch uses *instruction punning* [4] to insert the jump. The trampoline-based methodology of E9Patch is general purpose and highly scalable, and is able to rewrite large/complex software such as Chrome with a >100MB binary size.

The main disadvantage of trampoline-based rewriting is performance, since the extra jumps to/from trampolines incur runtime overheads. An alternative is “inline” binary rewriting, which attempts to insert the instrumentation directly into the existing instruction stream [8], [9]. However, inline rewriting has known limitations, such as requiring jump/call offsets to be corrected in the rewritten binary—which is an undecidable problem in the general case.

E9AFL is implemented as a plugin to the E9Patch frontend. The E9AFL plugin takes the disassembly of the input binary as input (from the frontend), and outputs an AFL instrumentation trampoline template, the AFL runtime, and a set of instrumentation locations. This information is then passed to E9Patch, which then generates the AFL instrumented binary.

Trampoline template: The basic trampoline template used by E9AFL is as follows:

```
...                # Save state
mov  prev_loc,%eax  # Load prev_loc
xor  $cur_loc,%eax
incb AREA(%eax)     # AREA[cur_loc~prev_loc]++
movl $cur_loc>>1,prev_loc # Set prev_loc
...                # Restore state
```

The trampoline template implements the classic AFL instrumentation (i.e., `AREA[cur_loc ~ prev_loc]++`). Here: `AREA` is the AFL shared trace map, `prev_loc` is the previous location (*Thread Local Storage*), and `cur_loc` is the current location (a trampoline-specific constant). The trampoline also includes some boiler-plate code for saving/restoring the CPU flags and the `%rax` register, which are used by the instrumentation. This boilerplate is similar to code inserted by `afl-gcc` for the same purpose. The instrumentation itself is essentially counting edge transitions (`prev_loc`→`cur_loc`). The counts are stored in the `AREA` trace map that is shared with `afl-fuzz`. This allows AFL to collect the *path coverage* information that is necessary for greybox fuzzing.

Runtime injection: The AFL runtime, including the fork server and `AREA` initialization, must also be injected into the instrumented binary. For this, we use an E9Patch feature that allows for user code to be injected into the rewritten binary during program initialization (i.e., before `main()` is called). The injected runtime is derived from the standard AFL runtime, with some minor modifications.

Determining instrumentation locations: As with source-level AFL, the instrumentation ought to be inserted once per basic-block. To find the set of basic-blocks, E9AFL implements a lightweight control-flow recovery analysis that finds all likely jump targets from the input binary, including all direct targets, and all likely indirect targets by analyzing the data segments for *jump tables* and *code pointers*.

The accurate recovery of control-flow information is an undecidable problem in the general case. However, for the

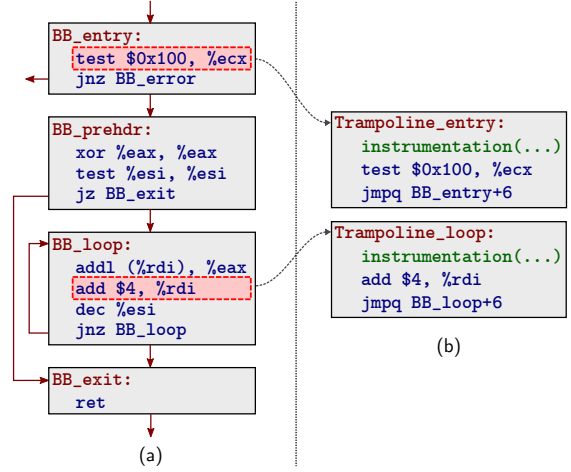


Fig. 1. Example of trampoline-based binary rewriting (a) original Control Flow Graph, and (b) *trampolines* that instrument selected instructions (highlighted).

application of AFL instrumentation, the recovered control-flow information need not be perfectly accurate. In the case of an *overapproximation* (i.e., superfluous jump targets), this may result in more instrumentation than is strictly needed, which may result in higher overheads but is otherwise harmless. In the case of an *underapproximation* (i.e., jump targets missed), this may result in less accurate coverage information being passed to the fuzzer, meaning that `afl-fuzz` may not detect some new paths that could be detected otherwise. Nevertheless, the fuzzing process can still generate useful results even with a slight loss of accuracy. E9AFL uses a heuristic-based control-flow recovery that is reasonably accurate for most programs compiled using standard compilers (e.g. `gcc`). In the case of *Position Independent Executables* (PIEs), the accuracy is further improved, as the analysis can use ELF *relocations* to accurately identify code pointers in data segments.

Once all jump targets are identified, the set of basic-blocks can be derived. The instrumentation is inserted into each basic-block entry by issuing E9Patch instruction patching commands with the AFL instrumentation template. E9Patch completes the rewriting process and outputs the final instrumented binary.

IV. TOOL OPTIMIZATION

The basic E9AFL design will suffer from poor fuzzing throughput (execs/s), meaning that some optimization is necessary. We use insights from the recent FuZZan [10] work, namely, that fuzzing performance is dominated by startup/teardown costs after `fork()`, and optimize accordingly.

Startup/teardown costs: In normal operation, fuzzers such as AFL execute the target program multiple times—once for each generated test case. To do so, AFL uses a *fork server*, which is essentially a *Remote Procedure Call* (RPC) loop that is injected into the target program. Whenever a new test case is generated, `afl-fuzz` will instruct the target program (via a RPC) to make a copy of itself using the `fork()` system call. Here, `fork()` essentially duplicates the calling process into a

parent and child process.¹ The child process executes the test case, collects coverage information via AFL instrumentation, and either exits normally or abnormally (i.e., crashes). The parent process will wait for the child to complete, and then send the resulting exit status back to the main afl-fuzz process before waiting for the next RPC.

The `fork()` system call is a relatively slow operation and this one of the main bottlenecks for overall fuzzer throughput (execs/sec). Modern versions of Linux attempt to optimize `fork()` by avoiding the copying of memory, including page table entries, as much as possible. For example, any page table entry corresponding to a file mapping will not be explicitly copied during a `fork()` operation. Rather, only if the child process actually accesses the mapping, a *page fault* will be generated, allowing the kernel to set up the corresponding page table entries lazily. In the context of fuzz testing, these page faults are a major contributing factor to the *startup costs* of the child process, and this can be a dominant factor in overall fuzzer performance [10].

Trampolines and page faults: With these insights, we can optimize the basic E9AFL design. One of the major sources of page faults in the rewritten binary are the trampolines used to implement the AFL instrumentation. Thus, to minimize page faults, our strategy will be to (1) make trampoline memory as contiguous as possible, and (2) remove trampolines if possible. To do so, we implement three main optimizations:

- 1) *Trampoline ordering:* allocate trampolines in order;
- 2) *Instruction selection:* select instructions for instrumentation that allow for better trampoline ordering; and
- 3) *Bad block elimination:* attempt to eliminate redundant instrumentation that will likely cause page faults.

Trampoline ordering: The idea of trampoline ordering is very simple: we contiguously allocate trampolines in the same order as the corresponding patched instructions. Thus, the same code regions will be mapped to the same trampoline memory, minimizing page faults.

However, for short instructions <5 bytes, E9Patch uses *instruction punning* to insert the trampoline. This means that E9Patch does not have complete control over trampoline placement, meaning that some trampoline fragmentation is still likely to occur. To mitigate this, we can optimize which instructions are selected for instrumentation.

Instruction selection: Traditionally, the AFL instrumentation is inserted at the start of each basic block. However, the instrumentation can also be inserted elsewhere in the basic block and preserve the same functionality. E9AFL applies a simple *instruction selection* algorithm to choose an instruction with size ≥ 5 bytes if available, allowing the *trampoline ordering* optimization to be applied to more basic blocks.

Note, however, that not all basic blocks will have an instruction with size ≥ 5 bytes. We define these to be *bad blocks*, since the *trampoline ordering* optimization cannot be applied, meaning that the corresponding trampoline is more likely to generate a page fault and slow down fuzzing. To

mitigate this, we can attempt to eliminate the trampolines for bad blocks altogether.

Bad block elimination: Sometimes the AFL instrumentation for a given basic-block is *redundant*, meaning that the instrumentation can safely be eliminated without affecting path coverage. For example, suppose that all paths through block *A* must pass through block *B*, and vice versa. Then only one of block *A* or *B* needs to be instrumented, since the path through one implies the path through the other. This can be generalized to the *path differentiation problem*, i.e., what is the minimum number of *Control Flow Graph* (CFG) vertices (i.e. blocks) that need to be marked (i.e. instrumented) such that all paths through the CFG can still be differentiated? Tools such as INSTRIM [11] use this idea to optimize fuzzing by removing as much instrumentation as possible (as much as 80% can be removed on average). However, in the E9AFL context, our main insight is that “quality” is more important than “quantity”. Specifically, we should preferentially eliminate instrumentation for *bad blocks* only, since this is the main source of additional page faults that slow down fuzzing.

The *bad block elimination* optimization uses an algorithm with similar aims to that of INSTRIM [11]. First, the algorithm builds the CFG from the recovered set of basic blocks. Next, the algorithm marks each block as either *optimized* or *unoptimized*, where *optimized* means that the block should not be instrumented. Initially, all blocks will be marked as follows:

- 1) Good blocks are initially marked as *unoptimized*.
- 2) Bad blocks that are potential indirect jump/call targets are also initially marked as *unoptimized*.
- 3) All other bad blocks are initially marked as *optimized*.

Here, 2) is a simplification that removes the need for paths to be traced over indirect jumps/calls. The remainder of the algorithm attempts to find a solution to the path differentiation problem, and works by constructing all sub-paths $\sigma = \langle A \rightarrow \dots \rightarrow B \rangle$ through the CFG such that (1) *A* and *B* are *unoptimized*, and (2) all intermediate blocks between *A* and *B* are *optimized*. Note that loops ($A=B$) are allowed, and *B* can be considered an *unoptimized* pseudo-block in the case where the last edge is an indirect call/jump, as per 2) from above. The path differentiation property is violated if there exists two (or more) distinct ($\sigma_1 \neq \sigma_2$) sub-paths:

$$\sigma_1 = \langle A \rightarrow \dots \rightarrow B \rangle \quad \text{and} \quad \sigma_2 = \langle A \rightarrow \dots \rightarrow B \rangle$$

for the same (*A*, *B*) pair. To restore the property, the algorithm will greedily mark an intermediate *optimized* block from σ_1/σ_2 as *unoptimized*. This process is repeated until no such sub-path pairs (σ_1, σ_2) exist.

Example: An example of optimized code is illustrated in Figure 1. Here, `BB_entry` is a good block (since the test instruction is ≥ 5 bytes) and is marked as *unoptimized*. The remaining `BB_prehdr/BB_loop/BB_exit` blocks are bad (since all other instructions are <5 bytes) and are initially marked as *optimized*. The path differentiation property is violated by

¹See the manpage of `fork`.

TABLE I

THE EXPERIMENTAL RESULTS. HERE *speed* IS THE FUZZING SPEED (EXECUTIONS PER SECOND) AND *cov* (%) IS THE LINE COVERAGE.

Subject	AFL-gcc		AFL-qemu		AFL-dyninst		E9AFL-00		E9AFL	
	speed	cov	speed	cov	speed	cov	speed	cov	speed	cov
FreeType	1148	35.6	279	31.3	647	34.8	71	30.2	745	35.8
libjpeg	1444	5.3	455	4.8	<i>n.r.</i>	<i>n.r.</i>	420	4.9	1273	5.1
libpng	1465	27.4	302	23.4	885	23.4	495	22.8	1262	23.4
libxml2	958	9.9	76	7.8	<i>n.r.</i>	<i>n.r.</i>	152	5.7	601	9.9
Vorbis	1032	30.3	252	27.7	582	30.1	300	29.8	905	30.2
G.Mean	100%	17.3	19.8%	15.0	-	-	19.5%	14.2	77.0%	16.6
Chrome	n/a	n/a	<i>n.r.</i>	<i>n.r.</i>	<i>n.r.</i>	<i>n.r.</i>	0.12	n/a	0.51	n/a

the following sub-paths:

$$\sigma_1 = \langle \text{BB_entry} \rightarrow \text{BB_prehdr} \rightarrow \text{BB_exit} \rangle$$

$$\sigma_2 = \langle \text{BB_entry} \rightarrow \text{BB_prehdr} \rightarrow \text{BB_loop} \rightarrow \text{BB_exit} \rangle$$

Path differentiation will be restored by the algorithm by marking BB_loop as *unoptimized*. The optimized Figure 1 code only uses two trampolines, whereas four (possibly non-contiguous) trampolines would be required under the basic unoptimized design (one for each basic block).

V. EXPERIMENTS

We evaluate the efficiency and effectiveness of E9AFL against five subjects (FreeType, libjpeg, libpng, libxml and Vorbis) selected from FuzzBench [6]. To test scalability, we also evaluate E9AFL against the Google Chrome binary [7]. Our evaluation considers three comparable techniques: AFL-gcc, the original compile time AFL instrumentation; AFL-qemu [2], a binary AFL implementation based on the QEMU emulator [12]; and AFL-dyninst [3], a binary AFL instrumentation based on the Dyninst [13] binary rewriting tool. In addition to E9AFL with full optimization enabled, we also evaluate E9AFL-00 with optimization disabled. Except for AFL-gcc, which requires source code, all other tools directly instrument binaries. All experiments are run on an Intel Xeon CPU E5-2660 2.00GHz processor with 64GB of memory. Each experiment uses a timeout of 24 hours.

Our evaluation is shown in Table I with the main result highlighted in **bold**. Here, *speed* is the number of executions per second, *cov* (%) is the line coverage, and *n.r.* (*no result*) means that the corresponding tool did not work correctly under our testing.

a) Fuzzing Efficiency: Overall we see that AFL-qemu is quite slow, and only runs at 19.2% of the speed (execs/s) of the baseline AFL-gcc. In contrast, with full optimization enabled, E9AFL runs at 77.0% of the speed of AFL-gcc. This means that E9AFL achieves nearly the same performance as AFL-gcc without the need for the program to be recompiled from source code. Finally, AFL-dyninst proved to be less reliable, with two test subjects not working (AFL-dyninst was unable to instrument libxml2, and the instrumented libjpeg would crash on benign inputs). Regardless, E9AFL still achieves a better performance than AFL-dyninst for the remaining working test subjects.

b) Fuzzing Effectiveness: In terms of effectiveness, AFL-gcc, AFL-qemu, and E9AFL achieve an overall 17.3%, 15.0%, and 16.6% line coverage, respectively. Our results show that E9AFL can generate comparable code coverage to that of AFL-gcc. Compared with the other binary-only instrumentation tools, including the working AFL-dyninst subjects, E9AFL achieves the overall best code coverage.

c) Scalability: For scalability, we find that E9AFL is the only tool that can successfully fuzz Chrome. Afl-gcc is not applicable since the source code of Chrome is unavailable (Chrome is closed source), AFL-qemu fails since the QEMU emulator does not support some syscalls used by Chrome, and AFL-dyninst failed to correctly disassemble the Chrome binary. E9AFL can successfully instrument the Chrome binary, which can then be fuzzed using AFL under *headless mode* (i.e., no user interface):

```
$ afl-fuzz ... -- ./chrome.afl --headless @@
```

We remark that Chrome is a large multi-threaded binary with high startup overheads, so it does not make an ideal fuzz target. Nevertheless, afl-fuzz can fuzz the instrumented Chrome with appropriate memory (-m) and timeout (-t) limits.

d) Optimization: Finally, we evaluate the fuzzing performance before/after the optimization has been applied. Here, the E9AFL-00 column from Table I represents the results before optimization. Overall, we see that E9AFL-00 runs at a mere 19.5% of the speed of AFL-gcc, which essentially replicates the slow performance of AFL-qemu. In contrast, the fully optimized E9AFL runs at 77.0% of the speed of AFL-gcc, or nearly 4× the performance of the unoptimized version. These results show that the optimization is not only effective, but is also essential for achieving a good fuzzing performance and code coverage result.

VI. CONCLUSION

Several AFL binary instrumentation tools have been proposed. Some tools are slow [2], use modified toolchains [14], have limited binary support (e.g., *position-independent-executable* only) [8], or may introduce false positives [3], [9]. In this paper we presented E9AFL, a new tool for automatically inserting AFL instrumentation into existing binary code using the E9Patch static binary rewriting system [4]. We show that E9AFL achieves 77.0% of the performance of AFL-gcc with comparable code coverage—all without the need for recompilation, nor the assumption of the availability of source code. Compared to other binary AFL solutions, E9AFL significantly improves the speed and code coverage, does not introduce false positives (or other rewriting errors), and can scale to very large programs such as Google Chrome [7].

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