Sydr-Fuzz: Continuous Hybrid Fuzzing and Dynamic Analysis for Security Development Lifecycle

Alexey Vishnyakov*, Daniil Kuts*, Vlada Logunova*‡, Darya Parygina*†,
Eli Kobrin*†, Georgy Savidov*† and Andrey Fedotov*

*Ivannikov Institute for System Programming of the RAS

†Lomonosov Moscow State University

‡Moscow Institute of Physics and Technology

Moscow, Russia

{vishnya, kutz, vlada, pa_darochek, kobrineli, avgor46, fedotoff}@ispras.ru

Abstract—Nowadays automated dynamic analysis frameworks for continuous testing are in high demand to ensure software safety and satisfy the security development lifecycle (SDL) requirements. The security bug hunting efficiency of cutting-edge hybrid fuzzing techniques outperforms widely utilized coverageguided fuzzing. We propose an enhanced dynamic analysis pipeline to leverage productivity of automated bug detection based on hybrid fuzzing. We implement the proposed pipeline in the continuous fuzzing toolset Sydr-Fuzz which is powered by hybrid fuzzing orchestrator, integrating our DSE tool Sydr with libFuzzer and AFL++. Sydr-Fuzz also incorporates security predicate checkers, crash triaging tool Casr, and utilities for corpus minimization and coverage gathering. The benchmarking of our hybrid fuzzer against alternative state-of-the-art solutions demonstrates its superiority over coverage-guided fuzzers while remaining on the same level with advanced hybrid fuzzers. Furthermore, we approve the relevance of our approach by discovering 85 new real-world software flaws within the OSS-Sydr-Fuzz project. Finally, we open Casr source code to the community to facilitate examination of the existing crashes.

Index Terms—dynamic analysis, hybrid fuzzing, continuous fuzzing, crash triage, dynamic symbolic execution, DSE, error detection, security development lifecycle, SDL, computer security

I. Introduction

Modern industrial software becomes more and more complicated. It pervades almost all the spheres of our life from relatively insignificant to critically important. Introducing the security development lifecycle (SDL) [1–3] becomes a natural thing in the majority of software development companies. Hybrid fuzzing [4–12] is one of the widely applied analysis techniques for searching errors in binary code. Its popularity is caused by the highly efficient combination of fuzzing and dynamic symbolic execution (DSE) where the tools work together and share obtained results to help each other. Launching fuzzing together with DSE outperforms coverage-guided

fuzzing [13]. Fuzzing can quickly increase the code coverage by overcoming simple constraints but fails at exploring complex code parts. DSE, on the contrary, copes well with non-trivial branch constraints yet performs slower analysis. We develop new hybrid fuzzing tool that is based on our symbolic execution tool Sydr [14]. We integrate Sydr with two state-of-the-art fuzzers, AFL++ [15] and libFuzzer [16], and evaluate our tool's efficiency compared to existing hybrid fuzzers.

Within the modern rapidly progressing industry, it is crucial not only to find bugs in software but also to report and fix them in adequate time. Integrating a variety of tools into one tool can increase program analysis efficiency by orders of magnitude. Based on this idea, we create dynamic analysis toolset *sydr-fuzz* that unites the hybrid fuzzing, corpus minimization, security predicates checking, crash triaging, and coverage collection. *Sydr-fuzz* implements a convenient and productive dynamic analysis pipeline. Running sequential *sydr-fuzz* pipeline stages allows to maximize the profit from hybrid fuzzing-based dynamic analysis.

The hybrid fuzzing itself is performed at the beginning pipeline stage. It results in a corpus of input test cases that provide some new coverage and may potentially lead to previously unknown errors. As the corpus may contain lots of seeds that discover the same coverage or errors, it is a good point to prune redundant seeds from further analysis. Corpus minimization tries to delete as much test cases as possible while saving the same code coverage, thus keeping the most profitable seeds.

After the first two steps, we receive the corpus of adequate size containing test cases set that can be then processed in many ways. *Sydr-fuzz* suggests three strategies that allow getting various information from the hybrid fuzzing results. The first one is error detection via applying symbolic security predicates. This technique is based on dynamic symbolic

© 2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

execution with additional constraints aimed at detecting four error kinds: null pointer dereference, division by zero, integer overflow, and out of bounds access. Some error kinds are related to multiple CWEs. The second strategy is collecting the code coverage provided by the corpus. And the third one includes crash triaging with the help of *Casr* [17] tools. These tools allow to generate crash reports for errors triggered by the corpus seeds, then deduplicate and cluster these reports. After this stage, the results are represented in a form of clusters for potentially different bugs accompanied by the corresponding test cases.

This paper makes the following contributions:

- We design Continuous Hybrid Fuzzing Infrastructure for efficient dynamic program analysis. We unite hybrid fuzzing [4–12], corpus minimization, symbolic security predicates [18], coverage collection, and crash triaging [17] stages into sydr-fuzz and propose a dynamic analysis pipeline to maximize its profitability. We present OSS-Sydr-Fuzz [19] repository inspired by OSS-Fuzz [20] and adapted to hybrid fuzzing with sydr-fuzz.
- We develop new hybrid fuzzer based on DSE tool Sydr [14]. We integrate Sydr with AFL++ [15] and libFuzzer [16] (which is the first integration between a DSE-tool and libFuzzer). We combine the power of our dynamic symbolic executor Sydr with the state-of-the-art fuzzers. We implement some profitable features in Sydr that help reach better evaluation results. We introduce symbolic pointers reasoning during hybrid fuzzing [21].
- We evaluate *sydr-fuzz* on Google FuzzBench [22] against state-of-the-art coverage-guided and hybrid fuzzers. We show that *sydr-fuzz* outperforms coverage-guided fuzzers and proves to be comparable to hybrid fuzzers, gaining a significant profit from its symbolic executor Sydr [23].
- We open source *Casr* [17] for crash reports clustering, deduplication, and severity estimation at https://github.com/ispras/casr.

II. RELATED WORK

A. Hybrid Fuzzing

Hybrid fuzzing is the state-of-the-art technique for detecting software bugs. Its power comes from the lightweight and fast fuzzing and accurate symbolic execution. Fuzzing helps quickly discover new paths, while DSE is responsible for systematic code exploration.

1) QSYM: The hybrid fuzzer QSYM [7] became one of the first tools that showed the effectiveness of hybrid fuzzing. Yun et al. implemented a hybrid fuzzer that is lightweight enough to allow DSE and fuzzer to work in parallel (while in Driller [6] DSE is launched for a short period to help fuzzer when it stops opening new coverage). QSYM utilizes Dynamic Binary Translation to reduce the number of symbolically emulated instructions, and refuses to use intermediate representation to eliminate additional overhead. The authors proposed two optimization techniques to increase analysis efficiency. Firstly, basic block pruning allows to skip some block

emulation if it has been executed too frequently. Secondly, optimistic solving assumes solving only the target constraint if the whole path predicate is unsatisfiable. These techniques do not provide sound analysis but help invert more symbolic branches per time unit. Another useful technique suggested by QSYM is cache for inverted branches with two caching modes. The static mode means that every symbolic branch is inverted only once, while the context mode allows to consider the depth and the set of the previously executed symbolic branches. QSYM also proposes handling of symbolic addresses [4] by simply fuzzing them. It searches minimum and maximum address values with SMT-solver and produces new seed on every invocation. As for the hybrid fuzzing, QSYM launches the fuzzer in parallel to the symbolic executor and lets them exchange new test inputs. DSE prefers such input files that have discovered the new coverage recently and at the same time have smaller size.

2) SymCC, SymQEMU: SymCC [8] developed a new compilation-based symbolic execution technique. The instrumentation code for concolic execution is inserted into the target application code, hence compiled binary file can be executed without switching between program code execution and interpreter. The code for updating symbolic state and handling symbolic computations is generated only once at compile time. This method also benefits from the ability to apply all the LLVM IR and CPU optimizations. SymCC bundles the symbolic backend into the libraries used by the target program. Concreteness checks allow to significantly reduce the number of symbolically processed computations.

As a continuation of SymCC, the authors presented SymQEMU [9] that proposed applying compilation-based symbolic execution to binary files in the absence of source code. Such method combines high analysis speed with architecture-independence. SymQEMU was built on top of QEMU by extending its TCG component so that symbolic handling code is inserted into the TCG ops IR before compiling it to the host machine code. The symbolic analysis stops at the system-call boundary that allows to achieve better performance. SymQEMU also implements symbolic expression garbage collector for effective memory management.

Both SymCC and SymQEMU support AFL++ [15] integration in the way similar to QSYM.

3) FUZZOLIC: Borzacchiello et al. [10] suggested an approach similar to SymQEMU. They greatly increased symbolic execution efficiency due to the fast analysis built on top of QEMU, and the new Fuzzy-Sat [24] solver that utilizes fuzzing for query solving. FUZZOLIC performs JIT compilation to add instrumentation code at runtime. It compiles each basic block only once and benefits from inserting instrumentation code into the target program code. FUZZOLIC is composed by the tracer and the solver that run in distinct parallel processes, and that is the first important difference from SymQEMU. The tracer executes the program and generates symbolic expressions that are sent to the solver responsible for the queries solving. The processes communicate through the shared memory. Also, unlike SymQEMU, FUZZOLIC injects

symbolic instrumentation into the target code after QEMU has generated the basic block TCG. It allows to take advantage of TCG optimizations at the level of the entire basic block. The last significant difference is that SymQEMU handles only architecture-independent TCG instructions, while FUZZOLIC can insert symbolic instrumentation for a large number of architecture-dependent TCG native helpers for the x86 and x86_64 platforms. The hybrid fuzzing scheme in FUZZOLIC is similar to QSYM. It takes seeds mutated by AFL++, while the fuzzer takes interesting seeds provided by the symbolic executor.

- 4) PASTIS: David et al. [12] presented an automated testing infrastructure combining fuzzing and DSE to validate the alerts received from some static analysis tool and trigger the bugs if possible. The information provided by SAST tool is used to add intrinsic functions to the target code. All the code variants are compiled and sent to the PASTIS broker that performs all the communication between the testing engines. On the one side, Honggfuzz [25] represents the fuzzing toolkit, while on the other side Triton DSE framework [26] is responsible for symbolic execution.
- 5) SymSan, Jigsaw: The main insight of SymSan [11] lies in building a concolic executor as a special form of dynamic data flow analysis. SymSan performs compile-time symbolic instrumentation of the code in LLVM IR [27]. The use of the highly-optimized infrastructure from DFSAN [28] helps reduce the overhead of storing and retrieving symbolic expressions which form is also optimized. SymSan proposes using an AST table along with a special AST node design for storing symbolic expressions. In combination with simple forward allocation of new nodes, it allows to significantly decrease performance overhead while handling symbolic expressions. Additionally, SymSan implements deduplication of the stored AST nodes and simplifying load and store operations.

The authors implemented a hybrid fuzzer based on SymSan and Angora [29]. They also proposed a novel design to improve the search throughput and incorporated it into the Jigsaw [30] prototype that is utilized as a solver for the hybrid fuzzer. The approach essence is evaluating newly generated seeds with JIT-compiled path constraints. Jigsaw compiles preprocessed AST sub-tasks into LLVM IR functions, uses LLVM's JIT engine to compile the IR into a native function, and searches for a satisfying solution using gradient-guided search.

B. Continuous Fuzzing

The convergence of secure development and fuzzing is becoming an industry standard [2, 3] like unit testing enforcement. Continuous fuzzing is an approach to organize automated fuzz testing as a routine, e.g. by incorporating it into CI/CD pipeline. Continuous fuzzing infrastructure can be a part of organization internal workflow scenario [31, 32] or appear in a form of fuzzing-as-a-service tool [19, 33–36]. The existing solutions include simple fuzz job launchers as well as large frameworks encompassing enhanced functionality for

scalable and ensemble [12, 37, 38] fuzzing, discovered flaws analysis and reporting, regression commit bisecting, etc.

- 1) OSS-Fuzz & ClusterFuzz: Although automated fuzztesting is not a silver bullet, it is quite efficient at discovering bugs and reducing human analytics required. For instance, ClusterFuzz [39] has already found over 25,000 bugs in Google-developed products and more than 43,500 bugs [40] in open-source software included in OSS-Fuzz. OSS-Fuzz project [33] selectively provides open-source community with access to scalable ClusterFuzz infrastructure capacities running on Google Cloud Platform [41]. ClusterFuzz is designed to automatically handle any task within fuzzing lifecycle except for fuzz target writing and bug fixing. This involves planning and launching fuzzing jobs, collecting statistics, new crashes deduplication and triage, test case minimization, bisection of commit introducing regression and bug fix verification. ClusterFuzz supports multiple coverage-guided fuzzing engines [15, 16, 25], black box fuzzing, and a range of sanitizers. As ClusterFuzz does not possess a build infrastructure, a typical set of a project to participate in OSS-Fuzz includes a docker image, build configuration, and at least one fuzz target. For now, over 650 critical and widely-used open-source projects are continuously fuzzed by OSS-Fuzz.
- 2) OneFuzz: Another continuous fuzzing framework One-Fuzz [31] was open-sourced by Microsoft. Similar to ClusterFuzz, OneFuzz is currently applied to Microsoft software (Windows, Edge, etc.) and is tied to corporate cloud environment Azure [42]. The supported fuzzing engines are libFuzzer [16], AFL++ [15], and Radamsa [43]. OneFuzz provides an opportunity to benefit from built-in templates as well as creation of customized fuzzing pipeline is possible. Discovered flaws are classified by reproduction stability and deduplicated. Furthermore, OneFuzz enables crash live debugging and fuzzing workflow monitoring by configurable web hook events.
- 3) Grizzly: FirefoxCI TaskCluster utilizes Grizzly [32] a scalable browser-specific fuzzing framework. Grizzly invokes browser and fuzzing engine independently, manages data transferring between them during analysis, and performs test case reduction. The two main interfaces, Target and Adapter, are responsible for desired browser and fuzzer combination deployment but the framework is primarily oriented on black box fuzzing techniques.
- 4) Fuzzit: Incorporated into Gitlab [44] service Fuzzit [34] was designed for fuzzing integration into project continuous build system. It constitutes runners for a collection of coverage-guided fuzzing engines to fuzz different programming languages (for instance, in case of C/C++ possible options are libFuzzer and AFL++) and is capable of regression testing.
- 5) syzbot: Continuous Linux kernel fuzzing system syzbot [45] consistently produces structured reports on detected kernel crashes. In addition to searching for bugs, the system monitors bug obsoletion and verifies fixed issues. After conducting patch testing syzbot validates that corresponding commit reached kernel builds for all tracked branches to close

bug report. Similar-looking crashes can be separately reported thereupon instead of being merged into existing issue.

III. HYBRID FUZZING

The statistics show that hybrid fuzzing engines, combining the power of the symbolic execution and the fuzzing, can reach higher coverage than two simultaneously working fuzzers [13]. Based on this idea, we implement our hybrid fuzzing tool, combining Sydr [14] with two most popular and powerful open-source fuzzers: libFuzzer [16] and AFL++ [15]. There are two main tasks to achieve the goal of making an effective hybrid fuzzing engine. Firstly, we develop different heuristics to make Sydr work as effective as it can in combination with fuzzer. Secondly, we implement Sydr and fuzzers integration, such as inter communication and seed scheduling for Sydr.

It is necessary to build the target binary in two versions to run *sydr-fuzz* in hybrid fuzzing mode. The first one must be built with sanitizers and fuzzing instrumentation to be used by the corresponding fuzzer. The second binary must be built without any instrumentation — it will be used by Sydr.

We implement various heuristics and features to make Sydr find new interesting seeds faster and work more effective in combination with fuzzers. For example, we implement cache in Sydr, that works quite same as QSYM cache, to save time from trying to invert same symbolic branches. The core idea is that unique hash is evaluated for every branch and is used as the index in bitmap. Every single branch corresponds to a byte which is a counter representing how many times the attempt to invert branch was proceeded. Moreover, we save an execution context for every branch, which represents what branches were met during execution before the considered one. If the context changes (i.e. Sydr reaches the branch with the different execution path), we try to invert the branch. Otherwise we attempt to invert a single branch when corresponding counter equals 0, 2, 4, 8, and so on (power of two) until it equals 255, and after that we stop the specific branch inversion.

Slicing [14] is another heuristic to fasten the symbolic execution. Every time we attempt to invert a branch, we apply the slicing algorithm to its path predicate. The idea of the algorithm is that we leave only those path constraints in path predicate which are data dependent on the target branch. Other path constraints are eliminated, input data for them is taken from the original program seed.

We implement optimistic and strong optimistic solving [46] to avoid formulas under- and overconstraint. Thus, Sydr inverts more branches and generates more seeds. The core idea is following. When the original sliced predicate is not satisfiable, we construct the optimistic predicate consisting of only the target branch constraint. If it is satisfiable, we construct strong optimistic predicate that is obtained from original sliced predicate by eliminating some irrelevant path constraints based on program call stack and branch control dependency analysis. If strong optimistic predicate matches optimistic predicate or is unsatisfiable, we save the optimistic seed. If they don't match and strong optimistic predicate is satisfiable, we save both generated seeds.

We implement function semantics to fasten the symbolic execution for standard library functions. Instead of stepping into the standard library functions (such as strto*1, *alloc, strcmp, etc.) and executing their bodies symbolically, we construct symbolic formulas for their return values, which helps fasten symbolic execution and avoid overconstraint.

We limit the time that Sydr worker can solve a single query and the total time that it can spend solving queries to avoid situations when SMT-solver is stuck solving complicated queries. Moreover, we set the timeout for the total time that single Sydr process can be executed to avoid program freeze.

It is also worth mentioning that Sydr have functionality to invert jump tables (switch statements) and handle symbolic addresses. There are two ways to handle symbolic addresses in Sydr: complete symbolic pointers processing and symbolic address fuzzing. Full support for symbolic pointers [21] drastically overloads symbolic engine, leading to worse fuzzing results. However, this mode still allows symbolic engine to successfully discover new unique coverage. Therefore, the optimal strategy is to enable this mode periodically instead of using it every Sydr run. When Sydr runs without symbolic pointers handling enabled, it performs SMT-fuzzing for all symbolic addresses. It is lightweight but less accurate method, that iterates over possible symbolic address values using an SMT-solver.

Before starting the hybrid fuzzing process, the initial corpus is automatically minimized to leave only those seeds that bring any new coverage.

A. Sydr and libFuzzer Integration

libFuzzer [16] is an open-source state-of-the-art coverage-guided fuzzer, which allows to fuzz libraries and applications effectively. It is integrated into the Clang C compiler and can be enabled with just setting a compile flag -fsanitize=fuzzer and adding a fuzzing target into the project code. We implement Sydr and libFuzzer integration and some interaction features to make them work better together.

All libFuzzer workers, that are executed simultaneously, store their test cases in the same corpus directory. So, in libFuzzer integration Sydr takes seeds to modify and puts generated seeds into the same corpus directory. This allows libFuzzer to immediately load seeds generated by Sydr into the memory and use them for further mutations. We measure Sydr contribution to the hybrid fuzzing process in the following way. We made a patch [47] to libFuzzer that counts the number of times it reloaded files that were generated by Sydr, so, we can learn how many interesting seeds Sydr stores to the corpus directory. All Sydr test cases that were not reloaded by libFuzzer are regularly removed from corpus directory.

Other important detail of Sydr and libFuzzer interaction is scheduling seeds for Sydr. We range every file in corpus comparing the following parameters in the order they are listed: 1) whether the seed discovered new function; 2) whether the seed brought new coverage; 3) whether the seed caused libFuzzer features increase; 4) $t_{creation}/S_{seed}$ value, where

 $t_{creation}$ is the time when the seed was created and S_{seed} is the size of the seed.

Thus, firstly, we compare the fact whether the seed brought new coverage. If two seeds brought new coverage, we compare whether they caused any features increase. If both of them brought new coverage and cause features increase, we prioritize them based on $t_{creation}/S_{seed}$ value: the seed has higher priority than the other one if it is newer and its size is smaller [7].

B. Sydr and AFL++ Integration

AFL++ [15] is a widely used state-of-the-art fuzzer, that has sound interface for configuring and combining with other fuzzing tools. We run Sydr as a fake secondary AFL worker to organize hybrid fuzzing with AFL++. That is, the Sydr worker directory is created in a common output directory for all AFL++ workers. It contains queue subdirectory so that main AFL worker is able to scan it and import useful seeds to its own corpus.

Sydr-fuzz retrieves seeds for Sydr launching from main AFL worker queue. These seeds are prioritized according to certain strategy [7] in order to improve the hybrid fuzzing efficiency. Seeds are scheduled according to the following criteria (in order of importance):

- 1) *New coverage* Seeds that discover new program coverage have the highest priority.
- Seed input Seeds from initial corpus often increase coverage as well, but they are labeled differently by AFL++.
- 3) *File size* Smaller seed size is better as it results in faster and more efficient symbolic execution.
- 4) *File name* Since file name in AFL++ starts with id, this ordering allows to select a newer file. Newer seeds are more promising to explore new coverage before it's done by fuzzer.

All seeds generated by Sydr are passed through a minimization step before being added to the Sydr worker queue [10]. We use a global bitmap to determine whether seed opens new program coverage, that hasn't been discovered by symbolic engine yet. The afl-showmap utility is used to collect a bitmap for every seed that Sydr is launched with. These seed bitmaps are merged into global bitmap for setting initial coverage. Sydr stores all generated seeds in the intermediate directory. Periodically, the afl-showmap utility runs on the whole directory and collects the set of bitmaps, which are sequentially merged into global bitmap. If global bitmap gets updated during merge, the corresponding seed is moved to the Sydr worker queue directory. If program crash was detected during aff-showmap run, the crashing seed is saved in crashes directory instead of queue. All other seeds are considered uninteresting and removed. Thus, only files with unique coverage are saved to the *sydr-fuzz* queue.

Sydr-fuzz is also capable of running AFL++ in parallel mode. It launches the specified amount of AFL workers, guided by recommendations in fuzzer tutorial [48]. There is

always one main AFL instance, the rest are secondaries. Options such as power schedule, MOpt, and old queue cycling are mutated between secondary workers. The queue of scheduled seeds for Sydr is synchronized only with main AFL worker. Seeds generated by all running Sydr instances are saved in single Sydr worker directory during *sydr-fuzz* minimization stage.

AFL++ measures assistance from other fuzzing instances by counting files imported from their queues. The number of files in main worker queue that were imported from Sydr worker is used to evaluate Sydr contribution to hybrid fuzzing. This may be done by using AFL++ statistics (in case of single AFL instance running) or by counting files in main AFL worker queue with corresponding synchronization tag.

IV. SECURITY PREDICATES

We propose security predicates — a method for accurate bug detection based on dynamic symbolic execution — as a part of *sydr-fuzz*. We implement automated security predicates checking with further verification and deduplication of seeds generated by security predicates to reveal errors.

Security predicate is a boolean predicate that holds true if program instruction (or function) triggers an error [18]. Security predicates implementation is a part of Sydr [14] that is based on the following idea. We execute a program symbolically with the seed that does not lead to an error. Every time we execute instruction that operates on symbolic data, we construct corresponding security predicate to check for the certain error type. Then we conjunct security predicate with the sliced branch constraints from the path predicate and pass resulting predicate to SMT-solver, i.e. Bitwuzla [49], to generate a seed that will reproduce the error. If the predicate is satisfiable, we save the seed and report the error. There are several types of weaknesses security predicates can detect: null pointer dereference, division by zero, integer overflow, and out of bounds access.

Null pointer dereference and division by zero security predicates work in similar way. In the first case we construct the security predicate to check whether symbolic address may equal to zero every time we execute the instruction where the memory access occurs. In the second case we construct the security predicate to check whether symbolic divisor may equal to zero every time we execute division instruction such as div or idiv during symbolic execution.

For out of bounds access error we construct security predicate every time we execute instruction with memory access. This security predicate holds true if the symbolic address can be less than the array lower bound or greater than the array upper bound. To detect array's bounds we maintain shadow stack and shadow heap during symbolic execution. We save information about the array bounds allocated on heap every time we meet the *alloc function call and remove it when free is called. We change shadow stack according to call stack, because we consider the upper bound of array allocated on stack as the function frame beginning address. For arrays allocated on heap we learn their bounds from shadow heap.

For arrays allocated on stack we consider the upper bound as the current function call site and compute the lower bound heuristically.

Every time we execute arithmetical instruction during symbolic execution we construct security predicate for integer overflow error. This predicate holds true if CF or OF equals to 1 after instruction execution. If the result is signed, we check only OF flag, and CF otherwise. The signedness is learnt from previously met conditional instructions, which use at least one operand same as the analyzed instruction uses. For example, JL points that the result is signed and we must check only OF flag. The principal difference between this security predicate and the others is that we separate the meanings of error source (the arithmetical instruction where error may occur) and error sink (the place where error can be used), and check security predicate for the error source only when error sink that uses this error source is found. We distinguish the following error sinks types: branch instructions, address dereference instructions, and function arguments [50].

We implement automated security predicates checking in sydr-fuzz. Security predicates search for errors only on the path that is defined by the given seed. Thus, we need to achieve the maximum coverage with the minimum number of seeds. Firstly, we run hybrid fuzzing to achieve great coverage. Then we run corpus minimization to leave the minimum number of files, which achieve the same coverage as before the minimization. After corpus minimization security predicates checking starts. Security predicates results often appear to be false positive, so, we implement automatic verification of security predicates results. We run target binary built with sanitizers on seed generated by security predicates. If any sanitizer reports the error in the place that was reported as error source by security predicates, we consider this seed as verified. Otherwise, we run sanitizers-build binary with the seed from corpus, which was used for security predicates checking, and if seed generated by security predicates brings new sanitizer warnings, we consider this seed as verified. Sydrfuzz deduplicates verified security predicates results based on source file, line, and column of code where error was detected to ease the process of analyzing security predicates results.

V. CRASH TRIAGING

Crash triaging is an important step in dynamic analysis, including fuzzing or hybrid fuzzing. The number of crashes that a fuzzer produces could be significant. One can spend a long time to figure out which crashes represent the same error. We propose an approach that should help developers spend less time analyzing and fixing various bugs and issues. Our Casr [17] tools allow one to create crash reports, deduplicate, and cluster them. The main stages of sydr-fuzz casr are the following:

- casr-san runs an instrumented binary on all seeds that potentially cause crashes and generates crash reports based on sanitizer reports (with gdb help if needed).
- casr-cluster runs deduplication algorithm on Casr reports received from casr-san. Deduplication is based

- on the stack trace: each frame is hashed, then the hash of the entire stack trace is added to the hash set. As a result, only unique reports will remain in the hash set (details [17]), the rest will be removed from the casr directory.
- 3) casr-cluster starts hierarchical clustering of Casr reports. The distance between crashes is calculated based on the stack trace [17].
- casr-gdb generates crash reports for non-instrumented target binaries based on the clusters obtained from the third step.

As a result, we get clusters containing potentially different bugs (in the form of Casr reports). Along with each report there is the corresponding seed that leads to this crash. Some steps (3, 4) can be skipped by setting the appropriate options.

Crash report contains information about crash such as OS and package versions, executed command line, stack trace, open files and network connections, register state, part of the source code that caused the crash, with the corresponding crash line, etc. So, the developer does not need to run the gdb and analyze crash manually, all the necessary information is already in the report.

Also, our Casr tools allow one to estimate crash severity. We divide them into three broad classes (just like in gdb exploitable [51]): exploitable, probably exploitable, and not exploitable. The classes include various errors that may occur during the program execution, such as stack overflow, double free, and others. Crash class is determined based on the stack trace, disassembly of the code section that caused the exception, the signal that came to the program, and some other information. Classified crashes help developers understand which ones should be analyzed and fixed first.

VI. DYNAMIC ANALYSIS PIPELINE

We present a novel dynamic analysis framework *sydr-fuzz* that comprises a toolkit for hybrid fuzzing orchestration, corpus minimization, error detection, crash triaging, and coverage collection. The functionality is divided into separate tasks implemented by simple CLI that can be effortlessly integrated into continuous build system. The following pipeline is proposed to leverage analysis profitable impact.

A. Hybrid Fuzzing (sydr-fuzz run)

First of all, hybrid fuzzing session is launched. After merging and minimizing initial corpus directories into a single project directory, the fuzzing process starts. While the corpus of an individual worker (Sydr or fuzzer instance) is evolving, the orchestrator evaluates new seeds and spreads the most beneficial ones to other workers. The session is halted according to configurable parameters like quantity of discovered crashes, session timeout, and coverage growth stagnation timeout. The last one, named *exit-on-time*, sets the fuzzing time-limit when the coverage increase stops.

B. Corpus Minimization (sydr-fuzz cmin)

The next step consists in extracting the most useful seeds by corpus minimization. This reduces examination of seeds that cause equivalent program behaviour during the next stages.

C. Security Predicates (sydr-fuzz security)

Then security predicate checkers are applied to minimized corpus directory. In order to limit time consumption of this step for the large corpus, there is a fixed number of random seeds to be analyzed. As the project corpus is retained for the next continuous fuzzing iterations, eventually, an extensible proportion of thoroughly examined seeds will be accumulated. After conducting results verification and detected error deduplication, the summary is reported for unique flaws triggered by checkers.

D. Crash Triaging (sydr-fuzz casr)

At the moment when crash triggering seeds are gathered, Casr crash triage is employed to alleviate potential flaws investigation. During this phase crash reports are automatically created and distilled into clusters classified by severity of potential bug. Commonly, the number of issues to be manually analyzed decreases by orders of magnitude. The result report contains a list of cluster summaries that include number of united crashes, target application source code line where the crash occurs, crash triggering seed, error type and severity.

E. Coverage Collecting (sydr-fuzz cov-report)

Finally, corpus coverage is collected as standard fuzzing metrics. There are several possible *sydr-fuzz cov-** options which conform to the corresponding llvm-cov [52] commands.

VII. CONTINUOUS HYBRID FUZZING INFRASTRUCTURE

The continuous fuzzing integration utilizing *sydr-fuzz* framework can be demonstrated with OSS-Sydr-Fuzz project [19]. OSS-Sydr-Fuzz is inspired by mentioned above OSS-Fuzz [33] and is intended to approve the power of hybrid fuzzing on real software. The corresponding trophy list [53] is presented in Section IX.

The required sources include code of the project to be tested and an additional OSS-Sydr-Fuzz [19] fuzzing repository. The repository contains a range of manually prepared facilities to configure and run hybrid fuzzing session. The key tasks to start one are project code building, fuzzing tools deployment, and fuzz target preparation. Consequently, the standard OSS-Sydr-Fuzz project package involves build script, Dockerfile instructions, composed fuzz targets, and hybrid fuzzing configuration file for each fuzz target. Moreover, the repository may provide extra materials like initial seed corpus, dictionaries, etc.

Depicted on the scheme (Fig. 1) fuzzing CI workflow is implemented on GitLab platform [54]. The system applies dynamic analysis pipeline introduced in the previous section. The fuzzing is launched when an external trigger event occurs. Currently, it is run manually for the selected project and branch. Alternatively, it could be organized as a scheduled routine or triggered by new commits as well.

Before starting the chosen project analysis, fuzzing job launcher activates docker builder task. First of all, the builder checks on the up-to-date commit and requests the container registry whether a docker image from the previous iteration exists and can be reused. The obtained or rebuilt container

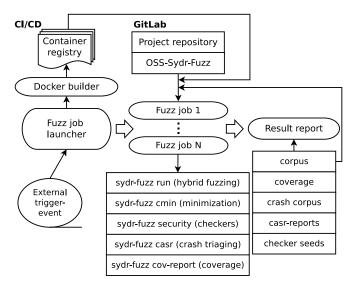


Fig. 1: OSS-Sydr-Fuzz CI Architecture.

is utilized for all project fuzz targets. Every fuzz target has an individual corpus and a separate fuzzing job that sequentially launches the analysis pipeline stages. In addition, there is an option to extend the initial seed corpus with seeds gained during previous fuzzing sessions. Apart from logs and analysis statistics, fuzzing job output includes resulting corpus, coverage information, Casr reports, and error triggering seeds.

VIII. IMPLEMENTATION

Sydr-fuzz is a Rust-written tool that configures, launches, and manages other tools to organize the entire dynamic analysis workflow. Crash triaging implemented as a set of tools written in Rust. It includes casr-san binary for crash report generation, casr-gdb binary for generating detailed crash reports without sanitizers, and casr-cluster for crashes deduplication and clustering. casr-cli binary represents the generated crash reports in a human readable format.

Sydr-fuzz uses Sydr as symbolic execution engine. Sydr workflow consists of two processes for symbolic and concrete execution running in parallel. Concrete executor is build on top of DynamoRIO [55] framework, and symbolic executor utilizes Triton [26] framework. We also extend Triton to support Bitwuzla [49] SMT-solver for constraint solving.

The efficiency of symbolic engine is extremely important when organizing hybrid fuzzing. We implement several enhancements for Sydr to improve its performance. One of the main features is asynchronous solving of SMT-queries. It moves branch inversion routine into a separate thread, that does not interact with symbolic and concrete execution processes. Whenever new symbolic branch is encountered during the analysis, the corresponding branch inversion job is pushed to the queue. One or several solving threads retrieve jobs from this queue and process them. Asynchronous solving allows to generate new seeds almost immediately after analysis startup avoiding long interruptions of program analysis caused by comlicated SMT-queries solving.

Another major improvement is suspending path predicate building if there are too many branches to invert. Usually branches get discovered by symbolic execution orders of magnitude faster than SMT-solver processes them. We suspend concrete executor process if queue of symbolic branches to invert reaches a certain threshold. Suspending concrete executor allows to keep the size of the path predicate appropriately to the seed generation rate and save computational resources. Concrete executor resumes when solving queue is emptied.

By default Sydr creates output directory with a certain structure, that allows convenient storing of different informational files for inverted symbolic branches. However, such structure turned out to be ineffective for hybrid fuzzing organization. Most of informational files are redundant and having multiple subdirectories only complicates the analysis. So, we implemented a flat output directory structure in Sydr for hybrid fuzzing mode, that contains only set of generated files. In this case Sydr generates unique filenames itself and places new seeds directly to libFuzzer corpus (or to intermediate directory for AFL++). A flat output directory allows *sydr-fuzz* to skip traversing Sydr directory and copying seeds, which improves hybrid fuzzing efficiency.

A hybrid fuzzing implementation differs for libFuzzer and AFL++. AFL++ stores all information about analysis in special files in its output directory. Information about generated seeds contained directly in their filenames. Therefore, sydr-fuzz only needs to parse corresponding files and check proper directories (queue, crashes, hangs) to synchronize tools and track the state of fuzzing process. On the contrary, libFuzzer only prints all information about analysis to log. Therefore, sydr-fuzz parses libFuzzer logs to retrieve information required for seeds prioritization and exit-on-time functionality. Only one libFuzzer log is parsed at a time even when there are several fuzzing jobs running. Due to the single corpus directory we assume that all libFuzzer workers are synchronized immediately, so parsing one log file is sufficient to get actual information. If a bug is found and currently parsed log is finished, then we select next log file to parse from all active libFuzzer workers.

Security predicates are implemented as part of Sydr and represented as SMT-solving job similar to branch inversion job. Security predicates could be checked during a symbolic execution together with path exploration. However, security predicate checking is a complex task for SMT-solver, so it is better to separate it from regular branch inversion tasks in order to keep Sydr performance for seed generation. We implemented a special mode in Sydr that allows to run symbolic execution only for security predicates checking.

IX. EVALUATION

We continuously use *sydr-fuzz* to perform program analysis. The OSS-Sydr-Fuzz repository [19] contains the list of tested projects and their build instructions, configuration setup for the environment and fuzzing process. During one year of *sydr-fuzz* usage, 85 previously unknown defects were discovered in 22 open source projects [53]. Of these, 13 errors were found by security predicates implemented in Sydr.

We used Google FuzzBench framework [22] to compare *sydr-fuzz* with modern state-of-the-art fuzzing tools. The FuzzBench experiments were deployed on the server with 256Gb RAM and two AMD EPYC 7702 CPUs (64 cores each). *Sydr-fuzz* was sequentially tested against 4 fuzzers: libFuzzer [16], AFL++ [15], SymQEMU [9], and FUZZOLIC [10]. We selected 15 targets from FuzzBench intended for coverage evaluation. Experiment was configured to perform 10 trials per fuzzer and target combination, each trial ran on a single CPU core for 23 hours. Due to the limited server resources we divided each *sydr-fuzz* testing in two packs of targets. Results of our FuzzBench experiments are publicly available [23].

During evaluation the following sydr-fuzz configuration was used. Hybrid fuzzing was performed with one instance of fuzzer and one running Sydr instance at a time. Sydr inverted branches in direct order with one solving thread. A 10 second limit was used for solving a single SMT-query, and 60 seconds — for the total solving time. Every Sydr run was limited to 2 minutes. A cache was used to prevent Sydr inverting the same branches. Strong optimistic solutions and symbolic address fuzzing were enabled for Sydr. Every symbolic address was fuzzed up to 10 different models. Symbolic addresses fuzzing was stopped for current Sydr run when 1000 such models were generated. Every 25th launch of Sydr a full symbolic pointers handling mode was enabled instead of symbolic addresses fuzzing. The path predicate building process was suspended after 300 branch inversion jobs were scheduled during symbolic execution. The memory usage for Sydr was limited by 8Gb. When this limit is exceeded, the program execution is terminated and only branch inversion continues.

A. Sydr-fuzz vs Fuzzers

Firstly, we compared *sydr-fuzz* with two state-of-the-art fuzzers to prove the advantages of utilizing symbolic engine. We tested AFL++ [15] and libFuzzer [16] against *sydr-fuzz* configured with corresponding fuzzer. The same versions of libFuzzer (de5b16d) and AFL++ (8fc249d) were used in *sydr-fuzz* and FuzzBench for evaluation. Also, an identical fuzzer configuration was used in all tools. Because *sydr-fuzz* has two instances running (fuzzer and Sydr) on single CPU core in trial, we configured FuzzBench to launch two workers of libFuzzer (-workers=2) and two instances of AFL++ (main and secondary nodes).

The results of *sydr-fuzz* and libFuzzer comparison are shown in Fig. 2 in Appendix. *Sydr-fuzz* outperformed libFuzzer by reached coverage on 9 out of 14 applications. From 5 applications where libFuzzer has better results, only sqlite3 has a strong advantage. For the rest 4 applications the final coverage differs slightly. Experiment was performed with two FuzzBench launches by 7 benchmarks each. *Sydr-fuzz* reached more coverage normalized score in both launches: 98.67% and 99.63% for *sydr-fuzz* against 96.51% and 98.33% for libFuzzer respectively.

Fig. 3 in Appendix shows the results of *sydr-fuzz* vs AFL++ experiment. *Sydr-fuzz* also showed the best results on 9 out of 14 applications in this experiment. As can be seen from Fig. 3, there is a huge margin between *sydr-fuzz* and AFL++ results on the most of applications in favor of both tools. For two packs of targets *sydr-fuzz* got a higher average coverage score: 98.75% and 99.19% for *sydr-fuzz* against 94.87% and 96.70% for AFL++ respectively.

Thereby, *sydr-fuzz* outperformed both libFuzzer and AFL++ on the most of evaluated benchmarks and reached a higher total coverage.

B. Sydr-fuzz vs Hybrid Fuzzers

On the next stage, we evaluated *sydr-fuzz* with modern hybrid fuzzers. We selected SymQEMU [9] and FUZZOLIC [10] because these tools also perform AFL++ [15] based hybrid fuzzing while symbolically executing binary code. We made sure that *sydr-fuzz* uses same AFL++ version (8fc249d) and settings as in these tools. The set of benchmarks slightly differs from those used for fuzzer evaluation due to inoperability of tested tools with some targets: both tools with libxslt and openssl, FUZZOLIC with woff2.

The results of *sydr-fuzz* and SymQEMU comparison are shown in Fig. 4 in Appendix. *Sydr-fuzz* was able to outperform SymQEMU on 7 out of 13 applications. The results are pretty close on the most benchmarks. From all benchmarks, where SymQEMU has the better results, only zlib_uncompress has a significant advantage over *sydr-fuzz*. Only 5 trials were launched for sqlite3 benchmark due to SymQEMU instability on this target. For two experiment packs *sydr-fuzz* reached a higher average coverage: 99.35% and 99.95% for *sydr-fuzz* against 97.03% and 99.67% for SymQEMU respectively.

The results of experiments with *sydr-fuzz* and FUZZOLIC are shown in Fig. 5 in Appendix. Only 12 targets were available for FUZZOLIC evaluation. *Sydr-fuzz* was able to outperform FUZZOLIC on 6 out of 12 benchmarks. Same as SymQEMU, the results are close in this experiment. FUZZOLIC reached significantly more coverage only on sqlite3 target. *Sydr-fuzz* outperformed FUZZOLIC with a big advantage on libjpeg_turbo and openthread targets. The rest benchmarks have very similar results on 23 hour distance. Nevertheless, *sydr-fuzz* was able to reach a little more average normalized score by coverage on the both experiment packs: 99.1% and 99.84% for *sydr-fuzz* vs 99.07% and 99.81% for FUZZOLIC respectively.

These results show that *sydr-fuzz* is on the same level with powerful state-of-the-art hybrid fuzzers and can outperform them in some cases. Also, *sydr-fuzz* was able to outperform all tested coverage-guided and hybrid fuzzers on 4 targets: freetype2, openthread, libxslt (SymQEMU and FUZZOLIC couldn't execute libxslt), and woff2 (FUZZOLIC failed to launch). There is also one target sqlite3 on which all other tools have better results than *sydr-fuzz*. This can be explained by the inefficient work of Sydr in

this particular example, as a result the fuzzer performance decreases.

TABLE I: Average Number of Useful Seeds Generated by Symbolic Engines

Application	Sydr	SymQEMU	FUZZOLIC
freetype2	307.8	90.8	241.9
harfbuzz	58.8	34.8	21.3
lcms	139.3	192.5	203.5
libpng	30.4	25.7	23.9
libjpeg-turbo	17.5	13.5	14.6
libxml2	34.8	41.9	26.9
mbedtls	17.1	18.0	31.0
openthread	59.3	38.1	72.9
re2	2.5	2.0	0.1
sqlite3	59.7	88.2	96.6
vorbis	3.1	3.5	2.2
woff2	24.9	13.0	_
zlib_uncompress	1.2	4.7	3.8

In addition, we compared the assistance of symbolic engines to the fuzzer. It can be measured with number of seeds generated by symbolic engine, that were imported by AFL++. The Table I contains an average number of imported files per 10 trials at the end of analysis. The results show that Sydr managed to generate more useful seeds than SymQEMU and FUZZOLIC on 6 out of 13 evaluated applications. On other examples the number of imported files is less but still on the same level, except <code>zlib_uncompress</code>. These statistics show that Sydr impact on the fuzzing process is comparable to the state-of-the-art symbolic engines.

X. CONCLUSION

We have presented Continuous Hybrid Fuzzing Framework *Sydr-Fuzz* for efficient dynamic program analysis during security development lifecycle. We have united hybrid fuzzing orchestration, corpus minimization, error detection, coverage collection, and crash triaging into a single powerful toolset. We have presented new hybrid fuzzing integration based on Sydr symbolic executor [14] and popular open-source fuzzers AFL++ [15] and libFuzzer [16]. We have created OSS-Sydr-Fuzz [19] repository with open-source software targets for *sydr-fuzz* and discovered 85 new bugs in 22 projects [53]. We have proposed dynamic analysis pipeline for *sydr-fuzz* to maximize the toolset profitable impact. We open source Casr tool for crash reports clustering and deduplication [56].

Our evaluation shows that, on the one hand, *sydr-fuzz* outperforms modern coverage-guided fuzzers AFL++ and lib-Fuzzer on the majority of estimated targets, and reaches a higher total coverage. On the other hand, *sydr-fuzz* proved to be comparable to powerful state-of-the-art hybrid fuzzers SymQEMU [9] and FUZZOLIC [10], and can even outperform them in some cases. The significant profit that *sydr-fuzz* gains from dynamic symbolic executor Sydr during the fuzzing process, therefore, demonstrates the relevance of utilizing cutting-edge hybrid fuzzers in dynamic analysis.

AVAILABILITY

The source code for Casr tool is publicly available at https://github.com/ispras/casr.

OSS-Sydr-Fuzz project can be found at https://github.com/ispras/oss-sydr-fuzz.

The FuzzBench results are available at https://sydr-fuzz.github.io/fuzzbench.

FUTURE WORK

As future directions, we consider the following issues:

- Implementing AARCH64 dynamic symbolic execution in Sydr and employing our dynamic analysis pipeline for AARCH64 applications.
- Supporting fuzzing, corpus minimization, crash triaging, and coverage collection for Python code. We plan to integrate Atheris [57] coverage-guided fuzzing engine from Google based on libFuzzer into *sydr-fuzz*.
- Varying AFL_SYNC_TIME [58] environment variable value to allow AFL++ observe Sydr-generated test cases more frequently.
- Parsing debug information, which can help us clarify array boundaries for symbolic pointers reasoning and security predicates.
- Developing seed scheduler for Sydr based on Katz graph centrality [59].
- Adding security predicate checkers for integer truncation, format string, and command injection errors.

REFERENCES

- [1] M. Howard and S. Lipner, *The security development lifecycle*. Microsoft Press Redmond, 2006, vol. 8. [Online]. Available: http://msdn.microsoft.com/en-us/library/ms995349.aspx.
- [2] ISO/IEC 15408-3:2008: Information technology Security techniques Evaluation criteria for IT security Part 3: Security assurance components. 2008. [Online]. Available: https://www.iso.org/standard/46413.html.
- [3] GOST R 56939-2016: Information protection. Secure software development. General requirements. National Standard of Russian Federation, 2016. [Online]. Available: http://protect.gost.ru/document.aspx?control=7&id=203548.
- [4] S. K. Cha, T. Avgerinos, A. Rebert, and D. Brumley, "Unleashing Mayhem on binary code," in *Proceedings of the 2012 IEEE Symposium on Security and Privacy*, ser. SP '12, IEEE, 2012, pp. 380–394.
- [5] B. S. Pak, "Hybrid fuzz testing: Discovering software bugs via fuzzing and symbolic execution," M.S. thesis, School of Computer Science Carnegie Mellon University, 2012.
- [6] N. Stephens, J. Grosen, C. Salls, A. Dutcher, R. Wang, J. Corbetta, Y. Shoshitaishvili, C. Kruegel, and G. Vigna, "Driller: Augmenting fuzzing through selective symbolic execution," in NDSS, vol. 16, 2016, pp. 1–16.
- [7] I. Yun, S. Lee, M. Xu, Y. Jang, and T. Kim, "QSYM: A practical concolic execution engine tailored for hybrid fuzzing," in *27th USENIX Security Symposium*, 2018, pp. 745–761.

- [8] S. Poeplau and A. Francillon, "Symbolic execution with SymCC: Don't interpret, compile!" In *29th USENIX Security Symposium (USENIX Security 20)*, 2020, pp. 181–198.
- [9] —, "SymQEMU: Compilation-based symbolic execution for binaries," in *Proceedings of the 2021 Network and Distributed System Security Symposium*, 2021.
- [10] L. Borzacchiello, E. Coppa, and C. Demetrescu, "FUZZOLIC: Mixing fuzzing and concolic execution," *Computers & Security*, vol. 108, p. 102 368, 2021.
- [11] J. Chen, W. Han, M. Yin, H. Zeng, C. Song, B. Lee, H. Yin, and I. Shin, "SYMSAN: Time and space efficient concolic execution via dynamic data-flow analysis," in *31st USENIX Security Symposium (USENIX Security* 22), USENIX Association, 2022, pp. 2531–2548.
- [12] R. David, J. Salwan, and J. Bourroux, "From source code to crash test-cases through software testing automation," *Proc. of the 28th C&ESAR*, p. 27, 2021.
- [13] FuzzBench symbolic report, 2021. [Online]. Available: https://www.fuzzbench.com/reports/experimental/2021-07-03-symbolic/index.html.
- [14] A. Vishnyakov, A. Fedotov, D. Kuts, A. Novikov, D. Parygina, E. Kobrin, V. Logunova, P. Belecky, and S. Kurmangaleev, "Sydr: Cutting edge dynamic symbolic execution," in 2020 Ivannikov ISPRAS Open Conference (ISPRAS), IEEE, 2020, pp. 46–54.
- [15] A. Fioraldi, D. Maier, H. Eißfeldt, and M. Heuse, "AFL++: Combining incremental steps of fuzzing research," in 14th USENIX Workshop on Offensive Technologies (WOOT 20), 2020.
- [16] K. Serebryany, "Continuous fuzzing with libFuzzer and AddressSanitizer," in 2016 IEEE Cybersecurity Development (SecDev), IEEE, 2016, p. 157.
- [17] G. Savidov and A. Fedotov, "Casr-Cluster: Crash clustering for linux applications," in 2021 Ivannikov ISPRAS Open Conference (ISPRAS), IEEE, 2021, pp. 47–51.
- [18] A. Vishnyakov, V. Logunova, E. Kobrin, D. Kuts, D. Parygina, and A. Fedotov, "Symbolic security predicates: Hunt program weaknesses," in 2021 Ivannikov ISPRAS Open Conference, IEEE, 2021, pp. 76–85.
- [19] OSS-Sydr-Fuzz: Hybrid fuzzing for open source software. [Online]. Available: https://github.com/ispras/oss-sydr-fuzz.
- [20] OSS-Fuzz: Continuous fuzzing for open source software. [Online]. Available: https://github.com/google/oss-fuzz.
- [21] D. Kuts, "Towards symbolic pointers reasoning in dynamic symbolic execution," in 2021 Ivannikov Memorial Workshop (IVMEM), IEEE, 2021, pp. 42–49.
- [22] J. Metzman, L. Szekeres, L. Simon, R. Sprabery, and A. Arya, "FuzzBench: An open fuzzer benchmarking platform and service," in *Proceedings of the 29th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*, 2021, pp. 1393–1403.
- [23] FuzzBench results for Sydr-Fuzz. [Online]. Available: https://sydr-fuzz.github.io/fuzzbench.

- [24] L. Borzacchiello, E. Coppa, and C. Demetrescu, "Fuzzing symbolic expressions," in 2021 IEEE/ACM 43rd International Conference on Software Engineering (ICSE), IEEE, 2021, pp. 711–722.
- [25] R. Swiecki and F. Gröbert, *Honggfuzz*. [Online]. Available: https://github.com/google/honggfuzz.
- [26] F. Saudel and J. Salwan, "Triton: A dynamic symbolic execution framework," in *Symposium sur la sécurité des technologies de l'information et des communications*, ser. SSTIC, 2015, pp. 31–54.
- [27] C. Lattner and V. Adve, "LLVM: A compilation framework for lifelong program analysis & transformation," in *Proceedings of the 2004 International Symposium on Code Generation and Optimization (CGO'04)*, vol. 4, 2004, p. 75.
- [28] DataFlowSanitizer design document, 2018. [Online]. Available: https://clang.llvm.org/docs/DataFlowSanitizerDesign.html.
- [29] P. Chen and H. Chen, "Angora: Efficient fuzzing by principled search," in 2018 IEEE Symposium on Security and Privacy (SP), IEEE, 2018, pp. 711–725.
- [30] J. Chen, J. Wang, C. Song, and H. Yin, "JIGSAW: Efficient and scalable path constraints fuzzing," in 2022 *IEEE Symposium on Security and Privacy (SP)*, IEEE, 2022, pp. 1531–1531.
- [31] OneFuzz: A self-hosted fuzzing-as-a-service platform. [Online]. Available: https://github.com/microsoft/onefuzz.
- [32] *Grizzly browser fuzzing framework*. [Online]. Available: https://github.com/MozillaSecurity/grizzly.
- [33] K. Serebryany, "OSS-Fuzz Google's continuous fuzzing service for open source software," USENIX Association, 2017.
- [34] Fuzzit. [Online]. Available: https://github.com/fuzzitdev/fuzzit.
- [35] *cifuzz: Fuzz tests as easy as unit tests*. [Online]. Available: https://github.com/CodeIntelligenceTesting/cifuzz.
- [36] S. Warkentin, *Getting started using Mayhem with continuous integration*, 2020. [Online]. Available: https://www.brighttalk.com/webcast/17668/439580.
- [37] Y. Chen, Y. Jiang, F. Ma, J. Liang, M. Wang, C. Zhou, X. Jiao, and Z. Su, "EnFuzz: Ensemble fuzzing with seed synchronization among diverse fuzzers," in 28th USENIX Security Symposium (USENIX Security 19), 2019, pp. 1967–1983.
- [38] S. Österlund, E. Geretto, A. Jemmett, E. Güler, P. Görz, T. Holz, C. Giuffrida, and H. Bos, "Collabfuzz: A framework for collaborative fuzzing," in *Proceedings* of the 14th European Workshop on Systems Security, 2021, pp. 1–7.
- [39] J. D. DeMott, R. J. Enbody, and W. F. Punch, "Towards an automatic exploit pipeline," in 2011 International Conference for Internet Technology and Secured Transactions, IEEE, 2011, pp. 323–329.
- [40] OSS-Fuzz issue report tracker. [Online]. Available: https://bugs.chromium.org/p/oss-fuzz/issues/list?q=-

- status % 3AWontFix % 2CDuplicate % 20 component % 3AInfra&can=1.
- [41] *Google cloud platform*. [Online]. Available: https://github.com/GoogleCloudPlatform.
- [42] M. Copeland, J. Soh, A. Puca, M. Manning, and D. Gollob, "Microsoft azure," *New York, NY, USA:: Apress*, pp. 3–26, 2015.
- [43] *A crash course to Radamsa*. [Online]. Available: https://gitlab.com/akihe/radamsa.
- [44] Coverage-guided fuzz testing in GitLab. [Online]. Available: https://docs.gitlab.com/ee/user/application_security/coverage_fuzzing/.
- [45] D. Vyukov, *syzbot: Automated kernel testing*, 2018. [Online]. Available: https://lpc.events/event/2/contributions/237/attachments/61/71/syzbot_automated_kernel_testing.pdf.
- [46] D. Parygina, A. Vishnyakov, and A. Fedotov, "Strong optimistic solving for dynamic symbolic execution," in *Ivannikov Memorial Workshop (IVMEM)*, IEEE, 2022.
- [47] Patch for libFuzzer: Print reloaded file paths. [Online]. Available: https://reviews.llvm.org/D100303.
- [48] *AFL*++ *tutorial*. [Online]. Available: https://github.com/AFLplusplus/AFLplusplus/blob/stable/docs/fuzzing_in_depth.md.
- [49] A. Niemetz and M. Preiner, "Bitwuzla at the SMT-COMP 2020," *CoRR*, vol. abs/2006.01621, 2020. arXiv: 2006.01621. [Online]. Available: https://arxiv.org/abs/2006.01621.
- [50] T. Wang, T. Wei, Z. Lin, and W. Zou, "IntScope: Automatically detecting integer overflow vulnerability in x86 binary using symbolic execution," in *NDSS*, 2009.
- [51] *GDB 'exploitable' plugin*. [Online]. Available: https://github.com/jfoote/exploitable.
- [52] The LLVM compiler infrastructure. llvm-cov emit coverage information. [Online]. Available: https://llvm.org/docs/CommandGuide/llvm-cov.html.
- [53] *Sydr-Fuzz trophy list*. [Online]. Available: https://github.com/ispras/oss-sydr-fuzz/blob/master/TROPHIES.md.
- [54] *GitLab: The one devops platform.* [Online]. Available: https://about.gitlab.com/.
- [55] D. Bruening, "Efficient, transparent, and comprehensive runtime code manipulation," Ph.D. dissertation, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, 2004.
- [56] *CASR: Crash analysis and severity report.* [Online]. Available: https://github.com/ispras/casr.
- [57] Atheris: A coverage-guided, native Python fuzzer. [Online]. Available: https://github.com/google/atheris.
- [58] *AFL*++ *environment variables documentation*. [Online]. Available: https://github.com/AFLplusplus/AFLplusplus/blob/stable/docs/env_variables.md.
- [59] D. She, A. Shah, and S. Jana, "Effective seed scheduling for fuzzing with graph centrality analysis," in 2022 *IEEE Symposium on Security and Privacy (SP)*, IEEE, 2022, pp. 2194–2211.

APPENDIX

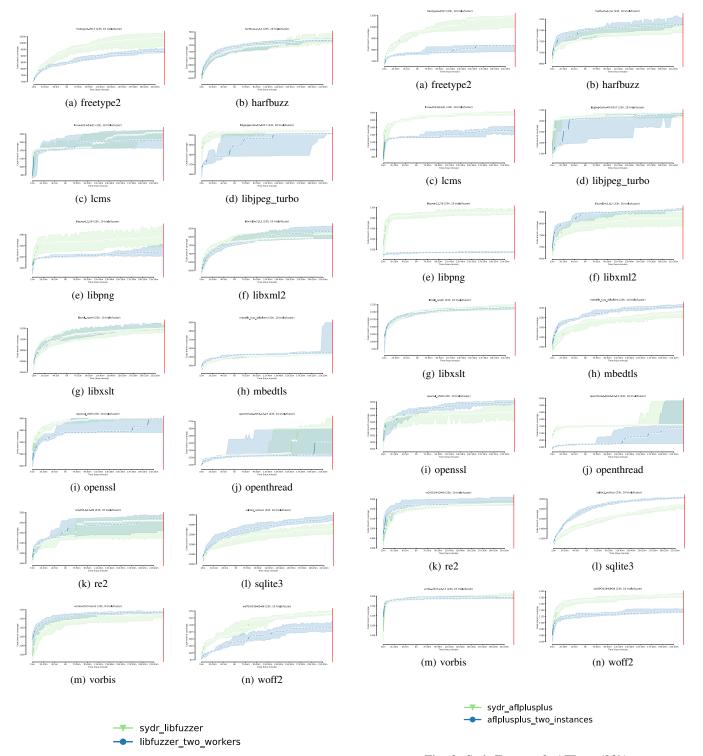


Fig. 2: Sydr-Fuzz vs 2xlibFuzzer (23h).

Fig. 3: Sydr-Fuzz vs 2xAFL++ (23h).

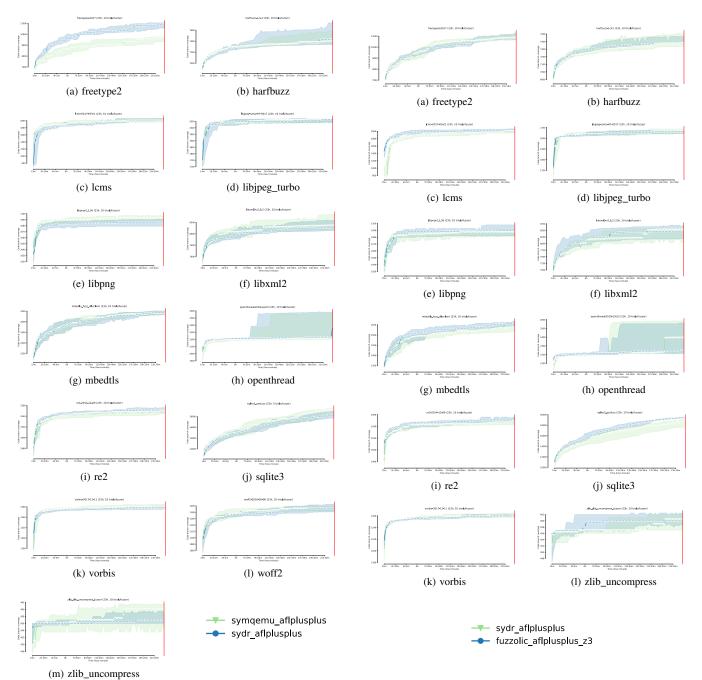


Fig. 4: Sydr-Fuzz vs SymQEMU (23h).

Fig. 5: Sydr-Fuzz vs FUZZOLIC (23h).