Symbolic Execution in Fuzzing — A Survey

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Contents

1 Related Work

Article Title	Paper	Cit#	Date
Symbolic execution for software testing in practice: preliminary assessment[1]	Conference on Software Engineering	492	05/2011
Fuzzing: The State of the Art[2]	DSTO Defence Science and Technology Organisation Australia	98	02/2012
Symbolic execution for software testing: three decades later[3]	ACM Computing Surveys	1035	02/2013
Network protocol fuzz testing for information systems and applications: a survey and taxonomy[4]	Multimedia Tools and Applications	21	11/2016
A systematic review of fuzzing techniques[5]	Science Computers & Security	112	06/2018
Fuzzing: A Survey[6]	Open Access	242	06/2018
Fuzzing: State of the Art[7]	IEEE Transactions on Reliability	196	06/2018
Evaluating Fuzz Testing[8]	CCS SIGSAC	561	10/2018
Fuzzing: hack, art, and science[9]	Comms of the ACM	113	01/2020
A Systematic Review of Search Strategies in Dynamic Symbolic Execution[10]	Computer Standards & Interfaces	7	10/2020
Fuzzing the Internet of Things: A Review on the Techniques and Challenges for Efficient Vulnerability Discovery in Embedded Systems[11]	IEEE IoT Journal	23	02/2021
Fuzzing: Challenges and Reflections[12]	IEEE Software	96	05/2021
Firmware Fuzzing: The State of the Art[13]	ACM Internetware	5	07/2021
Research on Fuzzing Technology for JavaScript Engines[14]	ACM CSAE	3	10/2021
The Art, Science, and Engineering of Fuzzing: A Survey[15]	IEEE Transactions on Software Engineering	395	11/2021
Fuzzing: A Survey for Roadmap[16]	ACM Computing Surveys	81	09/2022

Article Title	Paper	Cit#	Date
Fuzzing vulnerability discovery techniques: Survey, challenges and future directions[17]	Science Computers & Security	16	09/2022
Fuzzing of Embedded Systems: A Survey[18]	ACM Computing Surveys	11	07/2023
Demystify the Fuzzing Methods: A Comprehensive Survey[19]	ACM Computing Surveys	0	10/2023
A systematic review of fuzzing[20]	Application of soft computing	0	10/2023

2 Authors

Author	Works	Review Papers
Cristian Cadar	KLEE[21], EXE[22]	[3]
Koushik Sen	DART[23], CUTE[24]	[3]

3 Review Papers

3.1 Symbolic execution for software testing: three decades later

- [3]
- Cristian Cadar (KLEE[21], EXE[22]) and Koushik Sen (DART[23], CUTE[24])
- "Note that we do not aim to provide here a comprehensive survey of existing work in the area, but instead choose to illustrate some of the main challenges and proposed solutions by using examples from the authors' own work."[3]
- "A key disadvantage of classical symbolic execution is that it cannot generate an input if the symbolic path constraint along a feasible execution path contains formulas that cannot be (efficiently) solved by a constraint solver (for example, nonlinear constraints)."[3]
- Two techniques that alleviate this problem:
  - Concolic Testing (like DART[23]): Run concrete and symbolic execution at the same time, keep mapping between values, solve path constraint with one sub-constraint flipped to get input for an other path.
  - Execution-Generated Testing (EGT) (like EXE[22] and KLEE[21]): Only execute symbolically if any operands are symbolic
- These handle imprecision in symbex (like interaction with outside code (that is not instrumented for symbex), constraint solving timeouts, unhandled instructions (floating point), or system calls) by just using concrete values.
  - If none of the operands are symbolically, just use them
  - If any are, use the concrete values (direct in concolic, solution from path constraint in EGT)
- Downside: missing some feasible paths, and therefore sacrificing completeness.
- Challenges:
  - Path Explosion: program path count usually exponential in the number of static branches in the code.
    * Symbex helps by only looking at possible branches. Example: EXE[22] on `tcpdump`: only 42% of instructions contained symbolic operands, less than 20% of of symbolic branches have both sides feasible[22]
    * Prioritization of which path to explore next using heuristics (like statement or branch coverage (and using static analysis to guide), favouring statements that were run the fewest number of times, or random)
    * Interleave random and symbolic execution
    * Pruning redundant paths ("if a program path reaches the same program point with the same symbolic constraints as a previously explored path, then this path will continue to execute exactly the same from that point on and thus can be discarded."[25])
    * Lazy test generation
    * Static path merging
  - Constraint Solving: Dominates runtime

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- ∗ Irrelevant constraint elimination: Generally, we go from a solvable constraint set (namely the current execution with the solution being the current concrete values) to one where only one constraint changes (the one we flipped). Typically, major major parts of the constraint set are not influenced by the change and can be excluded from what is passed to the solver. We can then just use the values from the previous iteration.
- ∗ Incremental solving: Reuse the results of previous similar queries, because subsets of the constraints are still solved by the same results and supersets often do not invalidate existing solutions.
- Memory Modeling: Things like modelling `int`s as mathematical integers being imprecise since it ignores over-/underflows, and pointers being hard to deal with. "On the one end of the spectrum is a system like DART[23] that only reasons about concrete pointers, or systems like CUTE[24] and CREST[26] that support only equality and inequality constraints for pointers, which can be efficiently solved.35 At the other end are systems like EXE[22], and more recently KLEE[21] and SAGE[27] that model pointers using the theory of arrays with selections and updates implemented by solvers like STP or Z3."[3]
- Handling Concurrency: Testing usually difficult because of the inherent non-determinism. "Concolic testing was successfully combined with a variant of partial order reduction to test concurrent programs effectively."[3]

4 Random notes

- "Today, testing is the primary way to check the correctness of software. Billions of dollars are spent on testing in the software industry, as testing usually accounts for about 50% of the cost of software development. It was recently estimated that software failures currently cost the US economy alone about $60 billion every year, and that improvements in software testing infrastructure might save one-third of this cost."[23]

- "The blackbox and whitebox strategies achieved similar results in all categories. This shows that, when testing applications with highly-structured inputs in a limited amount of time (2 hours), whitebox fuzzing, with the power of symbolic execution, does not improve much over simple blackbox fuzzing. In fact, in the code generator, those grammar-less strategies do not improve coverage much above the initial set of seed inputs."[28]

- "KLEE8 is a redesign of EXE"[3]

- I think the EXE paper also introduced STP

5 Primary Papers

5.1 An Empirical Study of the Reliability of UNIX Utilities (1990)

- [29]
- OG Fuzzing paper
- Started because in a stormy night, electrical interference on a dial-up connection
- Authors were surprised by amount of crashes, and artificially produced those.
- Generates random data (all chars/only printable chars, with or without NULL), throws them against a program
- Were able to crash or hang between 24 and 33% of programs on different UNIX systems
- Different error categories: pointer and array errors, unchecked return codes, input functions, sub-processes, interaction effects, bad error handling, signed characters, race conditions and undetermined.

5.2 DART (2005)

- [23]
- Automated extraction of interface and env based on static source-code parsing
- Starts with random input, then uses symbex (without calling it symbex) to choose a different path
- Introduces a lot of concepts that I understand to be base level for symbex
- Has a unclear distinction to symbex, argues that symbex is stuck at expressions that aren't an issue with the symbex I know
- Concolic execution, fallback on concrete value whenever stuck
- Works on C code
- Positioned against static code analysis, which produces a lot of false positives while errors reported by DART are "trivially sound"[23]
- Run on a Pentium III 800MHz
- "As illustrated by the examples in Section 2, DART is able to alleviate some of the limitations of symbolic execution by exploiting dynamic information obtained from a concrete execution matching the symbolic constraints, by using dynamic test generation, and by instrumenting the program to check whether the input values generated next have the expected effect on the program."[23]

5.3 SAGE (2008)

- [27]
- First Whitebox Fuzzing paper so far.
- Developed at Microsoft.
- Does minor optimization to be able to perform partial symbex

- New invention: "Generational Search" — flips every branching condition after a symbex run to test in the next run, thus requiring fewer symbex runs overall.

- Uses concolic symbex whenever it gets too complex (i.e. interaction with the environment). It then checks whether the expected execution path is actually chosen and if not recovers (so-called "divergence").

- Runs on x86, Windows, file-reading applications.

- Found some vulnerabilities in media parsing engines and Office 2007.

- Further findings: symbex is slow (duh), at least two orders of magnitude compared to concrete execution.

- Divergences are common (60% of runs). This is because a lot of instructions were concretized to help with performance.

- No clear correlation between coverage and crashes, only weak effect when using a block coverage based heuristic to choose next execution.

- tl;dr: Runs concolic symbex, records run, flips every branch condition on its own, and solves the constraint formulas to generate inputs that choose a different path at each branch.

- Struggles with highly structured input like compilers and interpreters. Issue: "Due to the enormous number of control paths in early processing stages, whitebox fuzzing rarely reaches parts of the application beyond these first stages."[28].

- Also: Parsers sometimes use hash functions to match tokens, which make symbex impossible because they cannot be inverted.[28].

5.4   KLEE (2008)

- [21]

- Wide array of tests including GNU COREUTILS, BUSYBOX, MINIX, and HISTAR (430K LOC, 452 programs)

- Tests programs and OS Kernel (HISTAR)

- Found multiple high-profile errors (ten fatals in COREUTILS, three older than 15 years)

- Compares functionality of different implementations of the same specs

- Checks each error on the real binary, so no false positives theoretically (but because nondeterminism and bugs in KLEE there are some in practice)

- Works on LLVM basis (so not binary, doesn't work for projects where source code is unavailable)

- Extensive env modelling, including command line args, files, file metadata, env variables, failing system calls

- Path explosion combated with copy-on-write in state

- Performs query optimization (expression rewriting like mathematical simplifications, and using more efficient operations), constraint set simplification, constraint independence and a counter-example cache

- Alternates between random and coverage-optimized choice of next branch to execute

- New development: Better env modelling (not just dropping back on concrete values)
- "KLEE uses search heuristics on symbolic execution to achieve high code coverage."[5]

5.5   Grammar-based Whitebox Fuzzing (2008)

- [28]
- Follow-up to SAGE[27]
- SAGE struggled with highly structured inputs. Which is where this paper comes in.
- "We present a dynamic test generation algorithm where symbolic execution directly generates grammar-based constraints whose satisfiability is checked using a custom grammar-based constraint solver."[28]
- Two main parts:

  1. "Generation of higher-level symbolic constraints, expressed in terms of symbolic grammar tokens returned by the lexer, instead of the traditional symbolic bytes read as input."[28]
  2. "A custom constraint solver that solves constraints on symbolic grammar tokens. The solver looks for solutions that satisfy the constraints and are accepted by a given (context-free) grammar."[28]

- Basically wrote their own custom token-based (as opposed to bit/byte-based) symbex engine.
- Does not mark input bytes as symbolic, but the tokens returned by the tokenization function in the parser, implemented based on SAGE[27]

  - Also tries to only do this without using a grammar, so symbex based on tokens without pruning invalid inputs.

- When negating constraints allows to generate input that will be parsed (does not use *any* byte, but one that will conform to the manually provided context-free grammar).
- Also allows to quickly prove that flipping certain conditions isn't possible (while still conforming to the grammar) without even running the code.
- If the parser has more constraints than the context-free grammar provided (like basic type checks or, e. g. in network protocols, the number k followed by k records, which cannot be represented as context-free grammar), this makes the system less efficient, but the outputs are still complete.
- Requires no source modifications
- "We use the official JavaScript grammar. The grammar is quite large: 189 productions, 82 terminals (tokens), and 102 nonterminals."[28]
- Downside: Requires some domain knowledge:

  - Formal grammar structure (available for many input formats)
  - Identifying the tokenization function in the parser that needs to be instrumented (apparently usually fairly straight-forward, by looking for functions with names that contain *token, nextToken, scan* or something similar)

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– Creating a de-tokenization function to generate input byte strings from input token strings generated by a context-free constraint solver.

- This system doesn't check the lexer and parser for bugs, but one can just use traditional whitebox fuzzing (they say that coverage is similar to other approaches, but will likely not cover the error handling as well)
- Tested on IE7s JS engine

6 TODOs

6.1 Related

- AFLGo (Directed Greybox Fuzzing)[30] (follow-up to Grammar-based Whitebox Fuzzing I think)
- SAGE: Whitebox Fuzzing for Security Testing: SAGE has had a remarkable impact at Microsoft.[31]

6.2 New

- CUTE: a concolic unit testing engine for C (2005)[24] (discussed as early idea in [5])
- CREST: Heuristics for Scalable Dynamic Test Generation[26] (discussed in [3])
- TaintScope: A Checksum-Aware Directed Fuzzing Tool for Automatic Software Vulnerability Detection[32] (Tainting, discussed in [5] as improving the efficiency of fuzzing by reducing search space)
- BuzzFuzz: Taint-based directed whitebox fuzzing[33] (discussed in [5] as improving the efficiency of fuzzing by reducing search space, specifically library and system calls)
- Dowser: A Guided Fuzzer for Finding Buffer Overflow Vulnerabilities[34, 35] (discussed in [5])
- The BORG: Nanoprobing Binaries for Buffer Overreads[36]
- MoWF — Model-based whitebox fuzzing for program binaries[37]
- Driller: Augmenting Fuzzing Through Selective Symbolic Execution[38]
- ! S2E: a platform for in-vivo multi-path analysis of software systems[39]
- ! Mayhem: Unleashing MAYHEM on Binary Code[40]
- VUzzer: Application-aware Evolutionary Fuzzing[41]
- SYMFUZZ: Program-Adaptive Mutational Fuzzing[42]
- Improving Function Coverage with Munch: A Hybrid Fuzzing and Directed Symbolic Execution Approach[43]
- Magma: A Ground-Truth Fuzzing Benchmark[44]

6.3 Non-Symbex

- AFL++[45]
- Learn&Fuzz: Machine Learning for Input Fuzzing[46]
- T-Fuzz: fuzzing by program transformation[47]

References

[1] C. Cadar, P. Godefroid, S. Khurshid, C. S. Păsăreanu, K. Sen, N. Tillmann, and W. Visser, "Symbolic execution for software testing in practice: Preliminary assessment," in *Proceedings of the 33rd International Conference on Software Engineering*, ICSE '11, (New York, NY, USA), p. 1066–1071, Association for Computing Machinery, 2011.

[2] R. McNally, K. K.-H. Yiu, D. A. Grove, and D. Gerhardy, "Fuzzing: The state of the art," *DSTO Defence Science and Technology Organisation*, 2012.

[3] C. Cadar and K. Sen, "Symbolic execution for software testing: Three decades later," *Commun. ACM*, vol. 56, p. 82–90, feb 2013.

[4] T. L. Munea, H. Lim, and T. Shon, "Network protocol fuzz testing for information systems and applications: a survey and taxonomy," *Multimedia Tools and Applications*, vol. 75, pp. 14745–14757, Nov 2016.

[5] C. Chen, B. Cui, J. Ma, R. Wu, J. Guo, and W. Liu, "A systematic review of fuzzing techniques," *Computers & Security*, vol. 75, pp. 118–137, 2018.

[6] J. Li, B. Zhao, and C. Zhang, "Fuzzing: a survey," *Cybersecurity*, vol. 1, pp. 1–13, 2018.

[7] H. Liang, X. Pei, X. Jia, W. Shen, and J. Zhang, "Fuzzing: State of the art," *IEEE Transactions on Reliability*, vol. 67, no. 3, pp. 1199–1218, 2018.

[8] G. Klees, A. Ruef, B. Cooper, S. Wei, and M. Hicks, "Evaluating fuzz testing," in *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security*, CCS '18, (New York, NY, USA), p. 2123–2138, Association for Computing Machinery, 2018.

[9] P. Godefroid, "Fuzzing: Hack, art, and science," *Commun. ACM*, vol. 63, p. 70–76, jan 2020.

[10] A. Sabbaghi and M. R. Keyvanpour, "A systematic review of search strategies in dynamic symbolic execution," *Computer Standards & Interfaces*, vol. 72, p. 103444, 2020.

[11] M. Eceiza, J. L. Flores, and M. Iturbe, "Fuzzing the internet of things: A review on the techniques and challenges for efficient vulnerability discovery in embedded systems," *IEEE Internet of Things Journal*, vol. 8, no. 13, pp. 10390–10411, 2021.

[12] M. Boehme, C. Cadar, and A. ROYCHOUDHURY, "Fuzzing: Challenges and reflections," *IEEE Software*, vol. 38, no. 3, pp. 79–86, 2021.

[13] C. Zhang, Y. Wang, and L. Wang, "Firmware fuzzing: The state of the art," in *Proceedings of the 12th Asia-Pacific Symposium on Internetware*, Internetware '20, (New York, NY, USA), p. 110–115, Association for Computing Machinery, 2021.

[14] Y. Tian, X. Qin, and S. Gan, "Research on fuzzing technology for javascript engines," in *Proceedings of the 5th International Conference on Computer Science and Application Engineering*, CSAE '21, (New York, NY, USA), Association for Computing Machinery, 2021.

[15] V. J. Manès, H. Han, C. Han, S. K. Cha, M. Egele, E. J. Schwartz, and M. Woo, "The art, science, and engineering of fuzzing: A survey," *IEEE Transactions on Software Engineering*, vol. 47, no. 11, pp. 2312–2331, 2021.

[16] X. Zhu, S. Wen, S. Camtepe, and Y. Xiang, "Fuzzing: A survey for roadmap," *ACM Comput. Surv.*, vol. 54, sep 2022.

[17] C. Beaman, M. Redbourne, J. D. Mummery, and S. Hakak, "Fuzzing vulnerability discovery techniques: Survey, challenges and future directions," *Computers & Security*, vol. 120, p. 102813, 2022.

[18] J. Yun, F. Rustamov, J. Kim, and Y. Shin, "Fuzzing of embedded systems: A survey," *ACM Comput. Surv.*, vol. 55, dec 2022.

[19] S. Mallissery and Y.-S. Wu, "Demystify the fuzzing methods: A comprehensive survey," *ACM Comput. Surv.*, vol. 56, oct 2023.

[20] X. Zhao, H. Qu, J. Xu, X. Li, W. Lv, and G.-G. Wang, "A systematic review of fuzzing," *Soft Computing*, pp. 1–30, 2023.

[21] C. Cadar, D. Dunbar, and D. Engler, "Klee: Unassisted and automatic generation of high-coverage tests for complex systems programs," in *Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation*, OSDI'08, (USA), p. 209–224, USENIX Association, 2008.

[22] C. Cadar, V. Ganesh, P. M. Pawlowski, D. L. Dill, and D. R. Engler, "Exe: Automatically generating inputs of death," *ACM Trans. Inf. Syst. Secur.*, vol. 12, dec 2008.

[23] P. Godefroid, N. Klarlund, and K. Sen, "Dart: Directed automated random testing," in *Proceedings of the 2005 ACM SIGPLAN Conference on Programming Language Design and Implementation*, PLDI '05, (New York, NY, USA), p. 213–223, Association for Computing Machinery, 2005.

[24] K. Sen, D. Marinov, and G. Agha, "Cute: A concolic unit testing engine for c," *SIGSOFT Softw. Eng. Notes*, vol. 30, p. 263–272, sep 2005.

[25] P. Boonstoppel, C. Cadar, and D. Engler, "Rwset: Attacking path explosion in constraint-based test generation," in *Proceedings of the Theory and Practice of Software, 14th International Conference on Tools and Algorithms for the Construction and Analysis of Systems*, TACAS'08/ETAPS'08, (Berlin, Heidelberg), p. 351–366, Springer-Verlag, 2008.

[26] J. Burnim and K. Sen, "Heuristics for scalable dynamic test generation," in *2008 23rd IEEE/ACM International Conference on Automated Software Engineering*, pp. 443–446, 2008.

[27] P. Godefroid, M. Y. Levin, and D. A. Molnar, "Automated whitebox fuzz testing," in *Network and Distributed System Security Symposium*, 2008.

[28] P. Godefroid, A. Kiezun, and M. Y. Levin, "Grammar-based whitebox fuzzing," in *Proceedings of the 29th ACM SIGPLAN Conference on Programming Language Design and Implementation*, PLDI '08, (New York, NY, USA), p. 206–215, Association for Computing Machinery, 2008.

[29] B. P. Miller, L. Fredriksen, and B. So, "An empirical study of the reliability of unix utilities," *Commun. ACM*, vol. 33, p. 32–44, dec 1990.

[30] M. Böhme, V.-T. Pham, M.-D. Nguyen, and A. Roychoudhury, "Directed greybox fuzzing," in *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, CCS '17, (New York, NY, USA), p. 2329–2344, Association for Computing Machinery, 2017.

[31] P. Godefroid, M. Y. Levin, and D. Molnar, "Sage: Whitebox fuzzing for security testing: Sage has had a remarkable impact at microsoft.," *Queue*, vol. 10, p. 20–27, jan 2012.

[32] T. Wang, T. Wei, G. Gu, and W. Zou, "Taintscope: A checksum-aware directed fuzzing tool for automatic software vulnerability detection," in *2010 IEEE Symposium on Security and Privacy*, pp. 497–512, 2010.

[33] V. Ganesh, T. Leek, and M. Rinard, "Taint-based directed whitebox fuzzing," in *2009 IEEE 31st International Conference on Software Engineering*, pp. 474–484, 2009.

[34] I. Haller, A. Slowinska, M. Neugschwandtner, and H. Bos, "Dowsing for overflows: A guided fuzzer to find buffer boundary violations," in *Proceedings of the 22nd USENIX Conference on Security*, SEC'13, (USA), p. 49–64, USENIX Association, 2013.

[35] I. Haller, A. Slowinska, M. Neugschwandtner, and H. Bos, "Dowser: A guided fuzzer for finding buffer overflow vulnerabilities," *login Usenix Mag.*, vol. 38, 2013.

[36] M. Neugschwandtner, P. Milani Comparetti, I. Haller, and H. Bos, "The borg: Nanoprobing binaries for buffer overreads," in *Proceedings of the 5th ACM Conference on Data and Application Security and Privacy*, CODASPY '15, (New York, NY, USA), p. 87–97, Association for Computing Machinery, 2015.

[37] V.-T. Pham, M. Böhme, and A. Roychoudhury, "Model-based whitebox fuzzing for program binaries," in *Proceedings of the 31st IEEE/ACM International Conference on Automated Software Engineering*, ASE '16, (New York, NY, USA), p. 543–553, Association for Computing Machinery, 2016.

[38] N. Stephens, J. Grosen, C. Salls, A. Dutcher, R. Wang, J. Corbetta, Y. Shoshitaishvili, C. Krügel, and G. Vigna, "Driller: Augmenting fuzzing through selective symbolic execution," in *Network and Distributed System Security Symposium*, 2016.

[39] V. Chipounov, V. Kuznetsov, and G. Candea, "S2e: A platform for in-vivo multi-path analysis of software systems," *SIGPLAN Not.*, vol. 46, p. 265–278, mar 2011.

[40] S. K. Cha, T. Avgerinos, A. Rebert, and D. Brumley, "Unleashing mayhem on binary code," in *2012 IEEE Symposium on Security and Privacy*, pp. 380–394, 2012.

[41] S. Rawat, V. Jain, A. Kumar, L. Cojocar, C. Giuffrida, and H. Bos, "Vuzzer: Application-aware evolutionary fuzzing," in *Network and Distributed System Security Symposium*, 2017.

[42] S. K. Cha, M. Woo, and D. Brumley, "Program-adaptive mutational fuzzing," in *2015 IEEE Symposium on Security and Privacy*, pp. 725–741, 2015.

[43] S. Ognawala, T. Hutzelmann, E. Psallida, and A. Pretschner, "Improving function coverage with munch: A hybrid fuzzing and directed symbolic execution approach," in *Proceedings of the 33rd Annual ACM Symposium on Applied Computing*, SAC '18, (New York, NY, USA), p. 1475–1482, Association for Computing Machinery, 2018.

[44] A. Hazimeh, A. Herrera, and M. Payer, "Magma: A ground-truth fuzzing benchmark," *Proc. ACM Meas. Anal. Comput. Syst.*, vol. 4, jun 2021.

[45] 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)*, USENIX Association, Aug. 2020.

[46] P. Godefroid, H. Peleg, and R. Singh, "Learn&fuzz: Machine learning for input fuzzing," in *2017 32nd IEEE/ACM International Conference on Automated Software Engineering (ASE)*, pp. 50–59, 2017.

[47] H. Peng, Y. Shoshitaishvili, and M. Payer, "T-fuzz: Fuzzing by program transformation," in *2018 IEEE Symposium on Security and Privacy (SP)*, pp. 697–710, 2018.