The Art, Science, and Engineering of Fuzzing: A Survey

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Fuzzing: Hack, Art, and Science*

Patrice Godefroid

Qiang Liu

EPFL

hexhive

Motivation

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Vibrant Fuzzing Community

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- Over a thousand public repos related to fuzzing on GitHub
- 112 fuzzers (big-4 security cons and three SE cons, from 08 to 19)
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- Terminology fragmentation -> Hinder knowledge progress
  - AFL: test case minimization, funfuzz: test case reduction

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We need to consolidate and distill the large amount of progress in fuzzing!

Outline

Three Parts

- Fuzzing Terminology
- A unified Fuzzing Model
- Stages in Fuzz Testing
  - Design Choices
  - Trade-offs

Fuzzing Terminology

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PUT: Program Under Test

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- Bug Oracle: A bug oracle is a program, perhaps as part of a fuzzer, that determines whether a given execution of the PUT violates a specific **correctness policy**.

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- Fuzz Configuration: A fuzz configuration of a **fuzz algorithm** comprises **the parameter value(s)** that control(s) the fuzz algorithm.

Model Fuzzer

Two parts

- Preprocess
- Fuzz Loop

Fuzzers

- Black-box Fuzzer (B)
- Grey-box Fuzzer (G)
- White-box Fuzzer (W)

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	B	G	W
Input/Output	Y	Y	Y
Internals	N	P	Y
Execution Feedback	N	P	Y

Preprocess

Instrumentation

Seed Selection

Seed Trimming

Driver Application

- Hard to directly fuzz
- Manual and one-time effort
  - FuzzGen (Sec'20)
  - WINNE (NDSS'21)
  - APICraft (Sec'21)
- Diverse in implementation

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Design Choices	Semantics Level	Overhead	Library
Static Instrumentation	Source Code, IR, Binary	Low	Separate
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Usage Scenarios

- Execution Feedback
  - BitMap: Direct -> Colliding
- Thread Scheduling
  - Romdon Scheduling: Effective

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  - In-Memory API Fuzzing
    - AFL Persistent Mode: Not Reproducible
    - **Delta Debugging (ViDeZZo)**

Preprocess Cont’d

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Seed Selection

- Minset: find a minimal set of seeds that maximizes a coverage metric
- Coverage metric

	Coverage Metric	Preference
AFL	branch cov with **logarithmic** counter	differ in orders of magnitude
Honggfuzz	# instr, # BB, # branch	longer executions

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Seed Trimming

- Smaller seeds: less memory and higher throughput
- Different intuitions

	Intuition
AFL	code coverage
USec’14	smaller size
MoonShine	dependency

Preprocess Cont'd

EPFL hexhive

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Both of them can be in ConfUpdate

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Fuzz Configuration Scheduling (FCS) Problem

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- Richer coverage
- Evolutionary Algorithm: Fitness

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AFL

- Fastest and Smallest

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AFLFast: FAST power schedule

- Start with a small “energy” value to **ensure initial exploration** among configurations and increase exponentially up to a limit to **quickly ensure sufficient exploitation**
- Normalize the energy by the number of generated inputs that exercise the same path, thus promoting explorations of **less-frequently** fuzzed configurations

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AFLGo

- Target specific program locations

Input Generation

Model-based (Generation)	Predefined Model	specs: tool-specific, grammar, protocol, syscall, file format	
	Inferred Model*	preprocessing	binary, seeds, API logs, …
		configuration updating	kinds of dynamic behaviors
	Encoder Model	MutaGen: Mutate the encoder program.	
Model-less (Mutation)	Bit-Flipping	# bits to flip; each PUT has a specific mutation ratio.	
	Arithmetic Mutation	integer i: i +/- r	
	Block-based Mutation	block: add, append, delete, replace, shuffle, crossover	
	Dictionary-based Mutation	“ELF\x00”	

*How to automate the generation of input grammars for complex formats, perhaps using machine learning, is another challenge.

Input Generation Cont’d

White-box Fuzzers

Dynamic Symbolic Execution	Expensive*	specify uninterested parts of a PUT
		alternate between concolic testing and grey-box fuzzing
Guided Fuzzing: costly program analysis + test case generation		hot bytes, control/data flow features
PUT Mutation: change PUT and recover		checksum, branches

* How to engineer exhaustive symbolic testing (that is, a form of verification) in a cost-effective manner is still an open problem for large applications.

Input Evaluation

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Bug Oracles

- Fatal Signals -> Sanitizers
- Memory and Type Safety (ASAN)
  - spatial and temporal memory safety, control flow integrity
- Undefined Behaviors (MSAN, UBSAN, TSAN)
  - uninitialized memory, misaligned pointers, division by zero, dereferencing null pointers, and integer overflow, data races
- Others
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  - Semantic Difference: differential testing: semantic bugs

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Execution Optimization

- Fork-server, In-memory Fuzzing, In-memory API Fuzzing

Input Evaluation Cont’d

Triage

Input Evaluation Cont’d

Triage

- Deduplication
  - Stack Backtrace Hashing
    - widely used
    - but “some crashes do not occur near the code that caused the crash“
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- Minimization
  - Delta-debugging, C-Reduced

Configuration Updating

ALGORITHM 1: Fuzz Testing

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Input: ℂ, t_limit
Output: 𝔹 // a finite set of bugs
1 𝔹 ← ∅
2 ℂ ← Preprocess(ℂ)
3 while t_elapsed < t_limit ∧ Continue(ℂ) do
4     conf ← Schedule(ℂ, t_elapsed, t_limit)
5     tcs ← InputGen(conf)
      // O_bug is embedded in a fuzzer
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7     ℂ ← ConfUpdate(ℂ, conf, execinfos)
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Maintaining a Minset

- Avoid creating too many confs
- Variants:
  - Completely remove useless configurations
  - A culling procedure to mark minset configurations as being favorable

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Conclusion

Summary

- Rich taxonomy
- A general purpose model fuzzer
- Design decisions in each stage

Hopefully help bring some more uniformity to future works, particularly in the terminology and in the presentation of fuzzing algorithms

Discussion

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Questions in presentation?

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When can/should we do a survey paper?

What are the generic steps to do a survey paper?

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Some new directions?

Discussion

New papers since 2020: https://wcventure.github.io/FuzzingPaper/

- Speed
  - Towards Systematic and Dynamic Task Allocation for Collaborative Parallel Fuzzing (ASE'21)
  - Hardware Support to Improve Fuzzing Performance and Precision (CCS'21)
- Benchmark
  - FuzzBench: An Open Fuzzer Benchmarking Platform and Service (FSE'21)
- New feedback
  - The Use of Likely Invariants as Feedback for Fuzzers (USec'21)
  - IJON: Exploring Deep State Spaces via Fuzzing (SP'20)
  - SAVIOR: Towards Bug-Driven Hybrid Testing (SP'20)
- Emerging PUTs
  - compiler, interpreter, database, library, kernel, Hypervisor, firmware, RTL design
  - distributed systems
  - commits