Fuzzing for Automated Vulnerability Discovery

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Outline

1. Motivation
2. What is fuzzing? (35 years ago)
3. Mutational fuzzing (10 years ago)
4. Research topics in fuzzing (to present)

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1. **Motivation**
2. What is fuzzing? (35 years ago)
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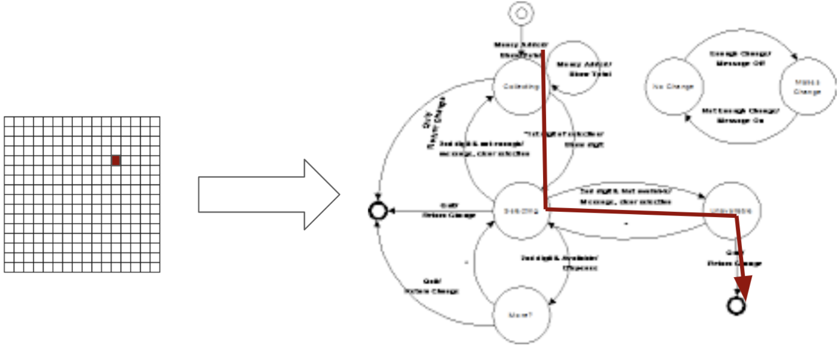
What are the components of a program?

- Input drawn from some input space (e.g., stdin, network state)
- States + transitions between them
- Outputs and/or side effects
- Termination conditions



Software security in a nutshell

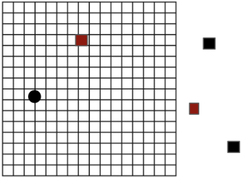
Two important questions:

1. What inputs cause “bad” behavior?
2. When is a state “bad”?

Security engineering (simplified)

Unrestricted input

- Anything can happen
- Minimal understanding of what code "should" do



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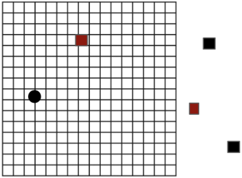
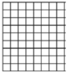


Option 1: Restrict inputs

- Typed language
- Delete code
- Privilege separation



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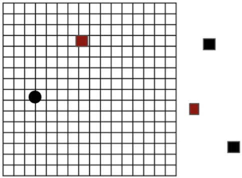

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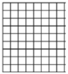
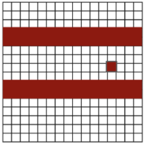


Option 2: Test inputs

- Unit tests
- Fuzzing
- Property tests



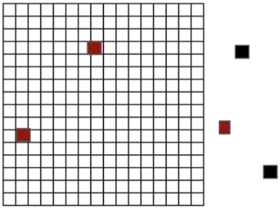
Levels of testing maturity

Level 0: No tests

- Developers think really hard and don't introduce bugs into the codebase!

Level 1: Try a few inputs

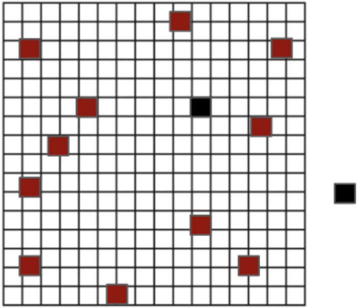
- Developers enumerate some common-sense checks and write unit tests.



Levels of testing maturity

Level 2: Try lots of random inputs

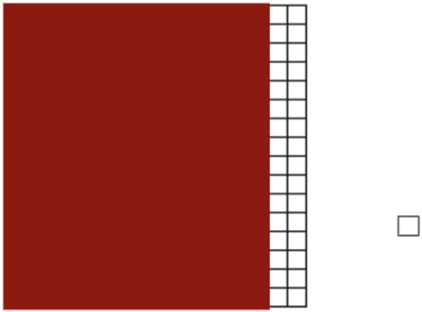
- Fuzzers, property-based testing
- Tons of papers, talks, and libraries
- Surprisingly effective [Din18]
- Fuzzing is gaining industry acceptance



Phases of testing maturity

Level 3: Test all the inputs

- Verification, symbolic execution
- Endgame, but not a cure-all
- Mostly rejected as impractical
- Incredible when it works



Outline

1. Motivation
2. **What is fuzzing? (35 years ago)**
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It was a dark and stormy night...

Prof. Barton Miller, UWM [Mil88, MFS90]

Exercise

Adapted from Zeller et al.'s "The Fuzzing Book" [ZGB+24].

In Python 3,

1. Write a function that generates a random string of up to N ASCII characters.
2. Generate a random string, send it to the `bc` utility, and obtain the results.
3. Run 100 trials of the previous step. What do you observe about the results?

Discussion

Thinking about probability

- How likely is it to get a valid input for `bc` with the input generation method we used?

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Program outputs and side effects

- Return code semantics are not universal.

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- Return code semantics are not universal.
- Suppose we fuzz `rm -R`. What is the probability of generating an input that deletes the entire filesystem?

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Program outputs and side effects

- Return code semantics are not universal.
- Suppose we fuzz `rm -R`. What is the probability of generating an input that deletes the entire filesystem?
- Inconsistency in observed behavior for a given input across campaigns might indicate that there are changes in some uninstrumented state upon which the program depends.

Congratulations, you've written your first fuzzer!

What are the components of a fuzzer?

- Input generation
- Harness: some way of sending those inputs to the program or library under test
- Instrumentation: some way to collect data about the program execution for a given input
- Some way to decide whether a particular (input, execution) pair is "interesting"
- (Maybe) some way to track the progress of data collection (e.g., coverage)

Outline

afl [Zal13a]

[1]

- Released by Michał Zalewski in November 2013 (aka lcamtuf; formerly of Google, now at Snap)
- “a de-facto standard for fuzzing” ([FMMB23])
- Bundled with tools to help monitoring fuzzing campaigns and analyze results

[1] https://en.wikipedia.org/wiki/File:Conejillo_de_indias.jpg

afl: input generation

Strategy: genetic algorithm

Define a fitness function over (input, execution) pairs.
Given a corpus containing at least one sample input to the program under test, add all inputs to a queue.

1. Load next test case from the queue.
2. Minimize the test case:
   - Remove bytes from input
   - Check if trimmed input has equal fitness
   - If fitness preserved, discard original input and save trimmed input in queue
3. Mutate test case. Add mutants with greater fitness to the queue. Save mutants resulting in crashes or hangs.
4. If campaign termination conditions (e.g., timeout) not met, return to Step 1.

afl: input generation

Mutation

1. Deterministic stage:
   - Flip 1+ bits
   - Increment / decrement {8, 16, 32}-bit integers in {little, big}-endian encodings
   - Overwrite input chunks with "interesting" values (e.g., zero, {max, min} (u)int{8, 16, 32} in {little, big}-endian encodings)
   - Replace parts of input with data from user-supplied dictionary and/or auto-detected tokens (e.g., magic bytes, keywords)

afl: input generation

Mutation

2. Havoc stage: Apply 2-128 mutations, including:
   - Deterministic mutations (above)
   - Random byte replacement
   - Bytestring of length N replaced by N repetitions of single byte
   - Bytestring deletion
   - Bytestring duplication
   - (As a last resort if queue exhausted without increasing fitness) Splice two inputs together

afl: harnessing

Two standard ways to feed inputs to program:

1. `stdin`
2. File

Vulnerability researcher's task: write a program that reads from stdin or a file, then passes the resulting input to the code you're interested in testing.

May need to mock/stub initial state - be careful about implicit assumptions!

afl: instrumentation

What is a graph?

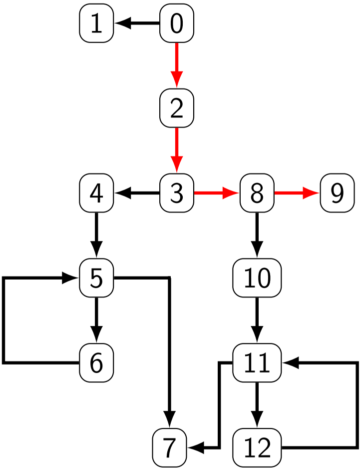
Definition

A **graph** is a pair G = (V, E) , where V is a set whose elements are called *vertices* and E is a set whose elements are paired vertices, called *edges*. If the elements of E are ordered pairs, we call the graph *directed*; otherwise, we call it *undirected*.

Definition

A **path** in a graph is a sequence of edges which joins a sequence of (distinct) vertices. Paths in directed graphs have an added restriction: the edges must all be directed in the same direction.

afl: instrumentation



$$G = (V, E)$$

$$V = \{0, 1, ..., 12\}$$

$$E = \{(0,1), (0,2), (2,3), (3,4), (3,8), (8,9), (8,10), (10,11), (11,12), (12,11), (11,7), (4,5), (5,6), (6,5), (6,7)\}$$

Node 9 is **reachable** from node 0 by path $((0,2), (2,3), (3,8), (8,9))$.

afl: instrumentation

Control-flow graph:

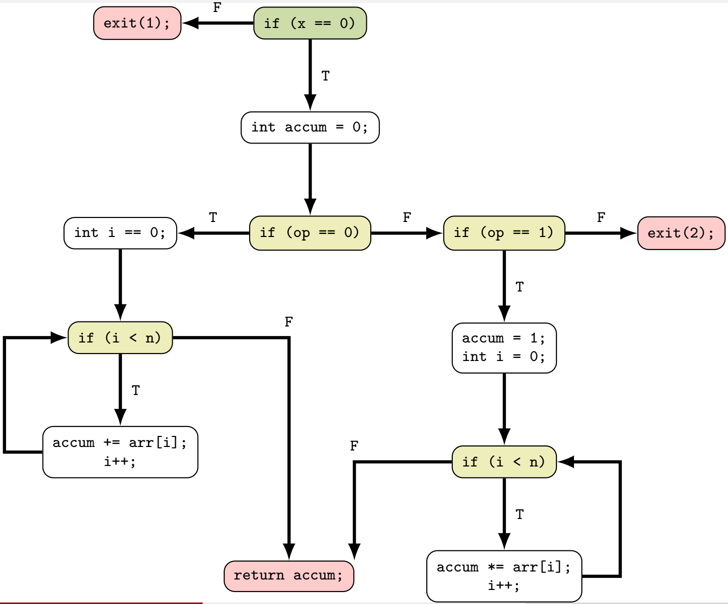
- Nodes - *basic blocks* of a program
- Edges - *control flow* between basic blocks

afl: instrumentation

```
foo:
.LFB6:
        .cfi_startproc
        endbr64
        push    rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        mov     rbp, rsp
        .cfi_def_cfa_register 6
        sub     rsp, 48
        mov     DWORD PTR -20[rbp], edi
        mov     DWORD PTR -24[rbp], esi
        mov     QWORD PTR -32[rbp], rdx
        mov     DWORD PTR -36[rbp], ecx
        cmp     DWORD PTR -20[rbp], 0
        jne     .L2
        mov     edi, 1
        call    exit@PLT
.L2:
        mov     DWORD PTR -12[rbp], 0
        cmp     DWORD PTR -24[rbp], 0
        jne     .L3
        mov     DWORD PTR -8[rbp], 0
        jmp     .L4
.L5:
        mov     eax, DWORD PTR -8[rbp]
        cdqe
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -32[rbp]
        add     rax, rdx
        mov     eax, DWORD PTR [rax]
        add     DWORD PTR -12[rbp], eax
```

```
        cmp     eax, DWORD PTR -36[rbp]
        jl      .L5
        jmp     .L6
.L3:
        cmp     DWORD PTR -24[rbp], 1
        jne     .L7
        mov     DWORD PTR -12[rbp], 1
        mov     DWORD PTR -4[rbp], 0
        jmp     .L8
.L9:
        mov     eax, DWORD PTR -4[rbp]
        cdqe
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -32[rbp]
        add     rax, rdx
        mov     eax, DWORD PTR [rax]
        mov     edx, DWORD PTR -12[rbp]
        imul    eax, edx
        mov     DWORD PTR -12[rbp], eax
        add     DWORD PTR -4[rbp], 1
.L8:
        mov     eax, DWORD PTR -4[rbp]
        cmp     eax, DWORD PTR -36[rbp]
        jl      .L9
        jmp     .L6
.L7:
        mov     edi, 2
        call    exit@PLT
.L6:
        mov     eax, DWORD PTR -12[rbp]
        leave
        .cfi_def_cfa 7, 8
```

afl: instrumentation



afl: instrumentation

- With source code: drop-in compiler replacement adds some code at each branch point to track edge coverage[2]
- Without source code: on-the-fly instrumentation via binary translator (e.g. QEMU, DynamoRIO, PIN)[3]
- NB: other tools (e.g., `afl-cov` [Ras15]) necessary for human-interpretable coverage reports from AFL results

[2] See https://afl-1.readthedocs.io/en/latest/about_afl.html#coverage-measurements

[3] See https://afl-1.readthedocs.io/en/latest/about_afl.html#binary-only-instrumentation

afl: instrumentation

Sanitizers [Inc12]: compiler passes that insert instrumentation to detect bugs at run-time

Examples:

- Address sanitizer (ASAN): detects addressability issues, e.g., buffer overflows [4]
- Memory sanitizer (MSAN): detects use of uninitialized memory
- Undefined behavior sanitizer (UBSan)

Sanitizers can be used alone or in combination (see [Zal13b], [Mor20] for caveats)

[4] See https://github.com/google/sanitizers/wiki/AddressSanitizerAlgorithm

afl: interesting inputs

- Input causes a crash
- Input causes a hang
- Input causes a new edge to be covered

afl: campaign progress

- Edge coverage over time
- Unique crashes / hangs

Exercise

1. Run the buffer overflow example.
2. Run the Heartbleed example. Adapted from Michael Macnair's AFL workshop [Mac17].

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Input generation

Greybox fuzzing leverages lightweight instrumentation to prioritize further program exploration.

- "Shape aware"
- Novelty generally based on strategy for selecting next input
- Examples: AFL (new coverage), AFLFast [BPR16] (unusual path), AFLGo [BPNR17] (path close to uncovered basic blocks)

Input generation

Grammar-based fuzzing: Use specification for input language to produce syntactically valid inputs. Examples:

- CSmith [YCER11] for compilers
- Fuzzilli [GKB+23], LangFuzz [HHZ12] for JavaScript interpreters
- H26FORGE [VCS23] for video codecs
- Grammarinator [HKG18] for programs with `antlr`-specified grammars

Input generation

Fuzzing with the help of constraint solvers

Concolic fuzzing (“concrete + symbolic”)

- Accumulate constraints on inputs by tracking conditionals during execution
- Novelty generally based on strategy for appealing to the constraint solver
- Examples: DART [GKS05], SAGE [GLM12], CUTE [SMA05], EXE [CGP+08], Driller [SGS+16], MAYHEM [CARB12]

Harnessing

FUZZ ALL THE THINGS!

- Auto-harnessing via program synthesis techniques
- Handling non-standard inputs (e.g., firmware rehosting)

Instrumentation

- Source code available: program-specific sanitization
- Binary only: using dynamic binary instrumentation, binary lifting techniques to support new architectures, add finer-grained instrumentation
- Improving performance (executions/sec)
- Running fuzzers at scale (e.g., ClusterFuzz [Inc19])
- Running fuzzers in ensemble (e.g. EnFuzz [CJM+19], CollabFuzz [OGJ+21])

Interesting inputs, campaign progress

Directed (aka search-based) fuzzing: measuring novelty and/or progress via alternative metrics to coverage. Examples:

- IJON [ASAH20]
- FuzzFactory [PLS$^+$19]
- GOLLUM [HMK19]

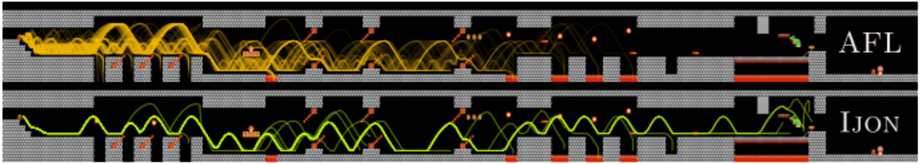

Fig. 1: AFL and AFL + IJON trying to defeat Bowser in Super Mario Bros. (Level 3-4). The lines are the traces of all runs found by the fuzzer.

Fuzzer evaluation

From an art to a science

- Reproducibility and statistical significance [KRC+18, HGM+21]
- Comparability: FuzzBench [MSS+21]
- Software engineering: libAFL [FM24]

Conclusion

What is the “best” fuzzer?

Conclusion

What is the "best" fuzzer?

The fuzzer that you've tailored
to the program under test
and your analysis objectives!

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