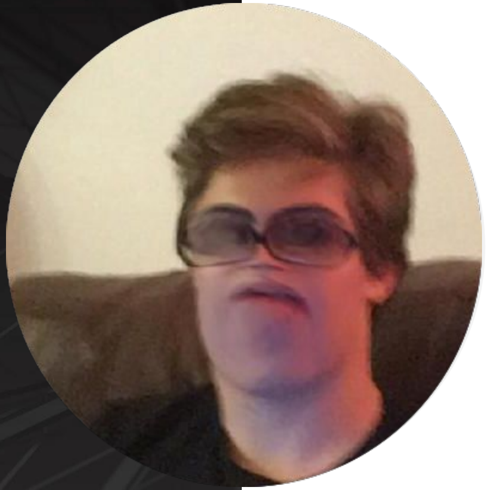
Fuzzing 101

UMD-CSEC



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Agenda

- About Trail of Bits
- What is fuzzing?
- Current techniques
- Versus other approaches to automated test generation
  - Ongoing work at Trail of Bits
- Research developments

About Trail of Bits

- **Information security, founded in 2012**
- **About 50 employees**
  - Half remote, half in NYC office
- **Research, assurance, and engineering practices**
  - Clientele: DARPA, Facebook, Google, LM, Airbnb
- **Open source bounties**

What is fuzzing?

- **An approach to *automated test generation***
  - Humans are bad at writing tests/thinking about invariants
  - Have the machine write and perform them for us!
- **Fuzzing randomly tests the *input space* of a program (or a function)**
  - Given a function `basename(char *str)`:
    - What happens when `str=NULL`?
    - ...when `strlen(str) >= MAX_PATH`?
    - ...when `str` isn't valid ASCII/UTF8?
      - Fuzzing can help us cover these cases without having to write specific tests!*

Fuzzing from 1000 feet

- Goal 1: Generate lots of inputs, as fast as possible
  - Subgoal: inputs should be diffuse, to avoid duplicating work
- Goal 2: Generate *high-quality* inputs
  - Inputs are *high-quality* if they activate novel behavior in the program
- Goal 3: Keep track of inputs that cause crashes, and what kinds of crashes they cause
  - Subgoal: *deduplicate* crashes that are caused by the same bug but different inputs
  - Subgoal: *minimize* inputs to make eventual triage/remediation simpler

Which goal(s) do we prioritize?

Fuzzing techniques: black-box

- **Black-box fuzzers operate with no knowledge of the target program**
  - Prioritize goal #1: since we don't know anything about the target, blast it with as many inputs as possible!
- **Examples:**
  - `radamsa`, `zzuf`
  - `while true; do program < /dev/urandom; done`
- **Pros:**
  - We spend most of our time actually running the program, not doing bookkeeping
  - We don't need our target's source code (or even to be on the same machine!)
  - Claim: Quantity compensates for quality in terms of empirical results
- **Cons:**
  - We spend most of our time running the program, but with boring test cases
  - Claim: We get stuck in a local maxima, and discover only "shallow" bugs

Black-box strengths and weaknesses

```
int main(void) {
    int x = getw(stdin);

    if (x > 100) crash();
    else whatever();
}
```

```
int main(void) {
    int x = getw(stdin);

    if (x == 0xFEEDFACE) crash();
    else whatever();
}
```

- Which of these programs is the black-box fuzzer going to crash first?
- What would happen if our crash conditions were more complex, or involved nested conditionals?
    - What about multiple distinct crashes, at different levels?

Demo: Radamsa

Fuzzing techniques: white-box

- **White-box fuzzers operate with (some) knowledge of the target program**
- **Some potential sources of knowledge:**
  - Source: which functions do I/O, touch memory, rely on undefined behavior?
  - Static analysis: does the program link to libraries that contain known vulnerabilities?
  - Specifications: if the program is specified, can we use the spec for counterexamples?
- **Example: american fuzzy lop*, SAGE***
- **Pros:**
  - We can discover "deep" bugs that random inputs would take much longer to hit
  - Claim: Quality compensates for quantity in terms of empirical results (goal #2)
- **Cons:**
  - We need access to the program's source or specification

White-box fuzzing: static analysis

What's (potentially) wrong with these functions?

```
typedef struct {
  int foo;
  int size;
} blob;

void* copy(blob* obj) {
  blob* dup = malloc(sizeof(obj));
  memcpy(dup, obj, sizeof(obj));

  return dup;
}
```

```
typedef struct {
  int foo;
  int size;
} blob;

void* copy(blob* obj) {
  blob* dup = malloc(obj->size);
  memcpy(dup, obj, obj->size);

  return dup;
}
```

Which of these functions is interesting to a fuzzer?

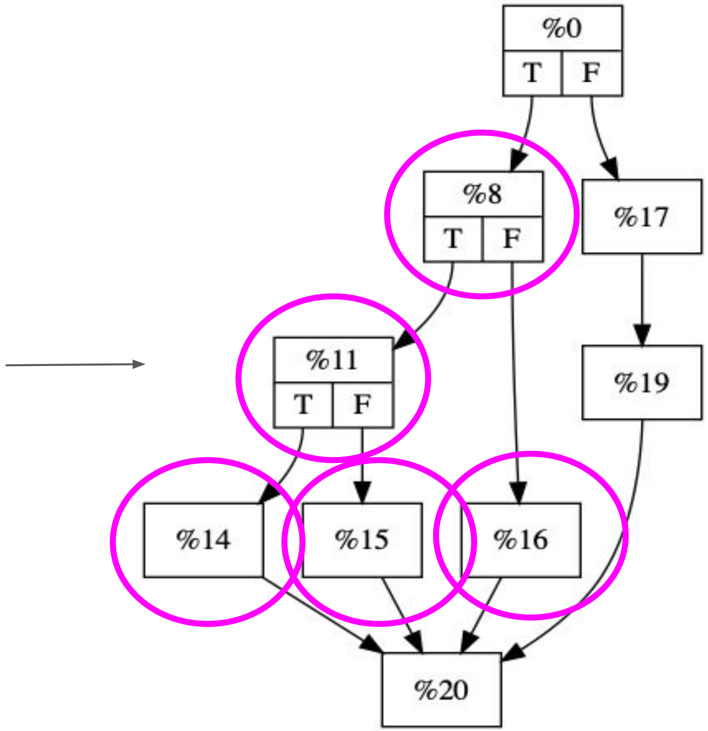
Fuzzing techniques: grey-box

- **Grey-box fuzzers use *dynamic instrumentation* to gain knowledge of the target program**
- **Things we can instrument:**
  - Basic blocks/CFG edges: does a given input cause us to execute unique BBs/edges? How does the tuple of all BBs/edges change as we mutate an input?
- **Examples: american fuzzy lop*, libFuzzer (LLVM)**
- **Pros:**
  - We can approximate the benefits of white-box fuzzing without needing source code
  - Claim: With lightweight instrumentation (AFL), we get empirically better/more results than either white or black-box fuzzers
- **Cons:**
  - Instrumentation adds runtime overhead, requires that we modify the program being tested (either at compile or runtime), introduces correctness concerns*

Grey-box fuzzing: basic block instrumentation

```
int main(void) {
  int x = getw(stdin);
  int y = 0;

  if (x > 10) {
    y = 1;
    if (x > 100) {
      y = 10;
      if (x > 1000) {
        y = 100;
        crash();
        return 3;
      }
      return 2;
    }
    return 1;
  }
  else {
    puts("nope!");
  }
  return 0;
}
```



CFG for 'main' function

Use changes to the activated basic blocks to search the program space:

1. Given an input, can we *minimize* it and produce the same chain of basic blocks?
2. Once minimized, can we activate *new* basic blocks along the same chain?

Demo: AFL

How effective is fuzzing?

Extremely! Even black- and grey-box:

- Microsoft SAGE: Hundreds of bugs found in Windows 7 [1]
- AFL: Firefox, Safari, OpenSSL, OpenSSH, Android, glibc, many more [2]
- oss-fuzz (libFuzzer cluster): 1000 bugs in 47 projects (2017) [3]

How do black/white/grey box strategies stack up?

How do individual fuzzers compare?

- Not a lot of statistical research, or even standardized evaluation techniques!
    - Evaluating Fuzz Testing [4]

Other approaches to test generation

- **Formal verification and countermodeling**
  - Program's spec might be formally verified, but implementation may not be!
    - Generate test cases that should always fail, according to the formal spec
  - Grammar-based fuzzing
- **Symbolic and "concolic" (symbolic + concrete) execution**
  - Identify input-controlled variables and symbolize them, then do constraint solution
    - Apply an SMT solver like Z3! [5]
      - "Which values of variable `x` cause the program to take the `else` branch?"
    - If the input space is small, try all possible values of `x`!
- **No clear line between fuzzing and many other generation strategies**
  - SAGE is "white-box", but uses symbolic information for feedback
  - One property: fuzzing implies an element of randomness

Research developments

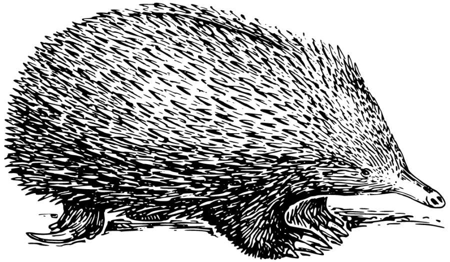
- **Hardware event-based feedback:**
  - Cache misses, page faults, instruction counts, time spent in kernel space, ...
  - Lower performance impact vs. coverage guidance, better results than black-box
- **Path and depth estimation**
  - “How much of the program’s (interesting) space have we covered so far?”
    - STADS: Software Testing as Species Discovery (Böhme, 2018)
- **CPU and kernel-space fuzzing:**
  - Undocumented isns, ring violations, kernel memory safety violations
  - CPU: sandsifter (Battelle)
  - Kernel: trinity, syzkaller (Google), kernel-fuzzers (Oracle), kAFL

XNU (iOS/macOS) Kernel RCE

https://lgtm.com/blog/apple_xnu_icmp_error_CVE-2018-4407

Ongoing work at Trail of Bits

- **Manticore: Symbolic execution for x86(_64), ARMv7, EVM bytecode [6]**
  - Input generation, instruction tracing
- **DeepState: Drop-in gtest compatible symbolic execution + fuzzing [7]**
- **Echidna: Grammar-based fuzzing/property testing for EVM [8]**
- **Sienna Locomotive: Coverage-guided black-box fuzzing for Windows**
  - Integrated crash triage and vulnerability estimation
- **Toolchain advancements:**
  - Etheno: JSON RPC multiplexer for running multiple Ethereum analysis tools [9]
  - McSema and remill: Binary lifting (assembly to LLVM) and translation [10, 11]
    - Can be used to make a binary compatible with libFuzzer!



Demo: Manticore

Sources

[1]: https://patricegodefroid.github.io/public_psfiles/SAGE-in-1slide-for-PLDI2013.pdf

[2]: http://lcamtuf.coredump.cx/afl/

[3]: https://opensource.googleblog.com/2017/05/oss-fuzz-five-months-later-and.html

[4]: https://arxiv.org/pdf/1808.09700

[5]: https://github.com/Z3Prover/z3

[6]: https://github.com/trailofbits/manticore

[7]: https://github.com/trailofbits/deepstate

[8]: https://github.com/trailofbits/echidna

[9]: https://github.com/trailofbits/etheno

[10]: https://github.com/trailofbits/mcsema

[11]: https://github.com/trailofbits/remill

Additional Resources

- "Super Awesome Fuzzing: Part One"
- https://github.com/CENSUS/choronzon
- https://github.com/MozillaSecurity/dharma
- https://github.com/aoh/blab

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