Program Analysis

Random Testing and Fuzzing (Part 3)

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Outline

- **Introduction**
- **Randoop**
  - Based on *Feedback-Directed Random Test Generation*, Pacheco et al., ICSE 2007
- **Greybox fuzzing in AFL** ←
  - Based on

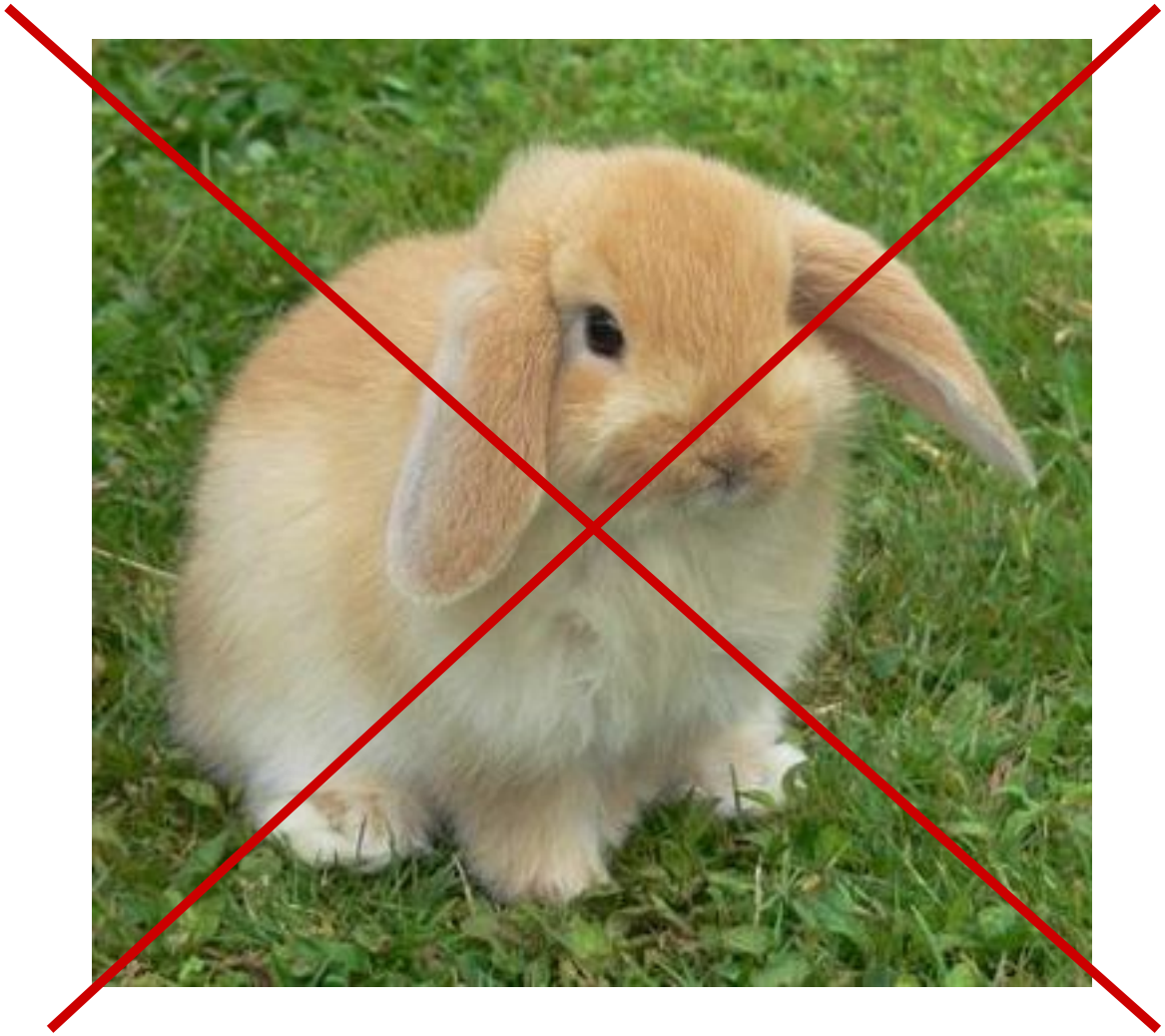
    https://lcamtuf.coredump.cx/afl/technical_details.txt

Greybox Fuzzing

- **Guide input generation toward a goal**
  - Guidance based on lightweight program analysis
- **Three main steps**
  - Randomly generate inputs
  - Get feedback from test executions: What code is covered?
  - Mutate inputs that have covered new code

American Fuzzy Lop

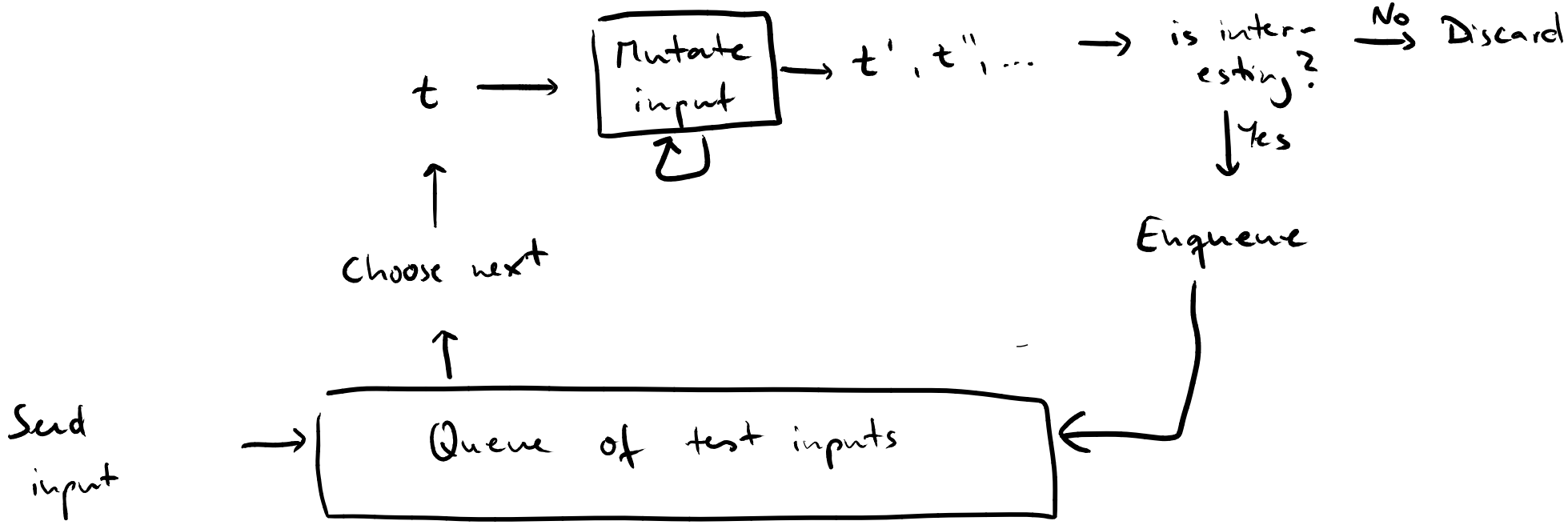
American Fuzzy Lop



American Fuzzy Lop

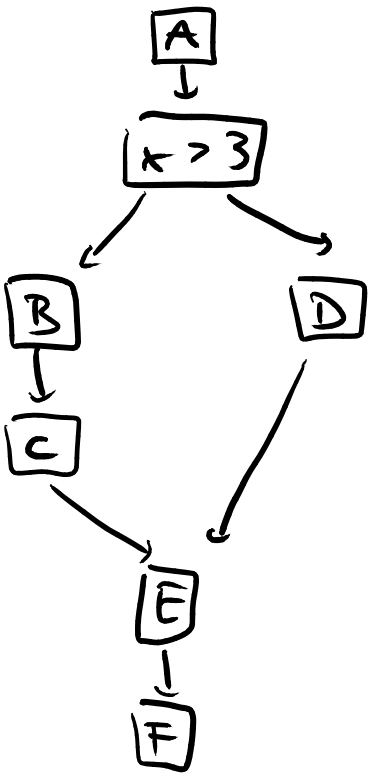
- **Simple yet effective fuzzing tool**
  - Targets C/C++ programs
  - Inputs are, e.g., files read by the program
- **Widely used in industry**
  - In particular, to find security-related bugs
  - E.g., in OpenSSL, PHP, Firefox

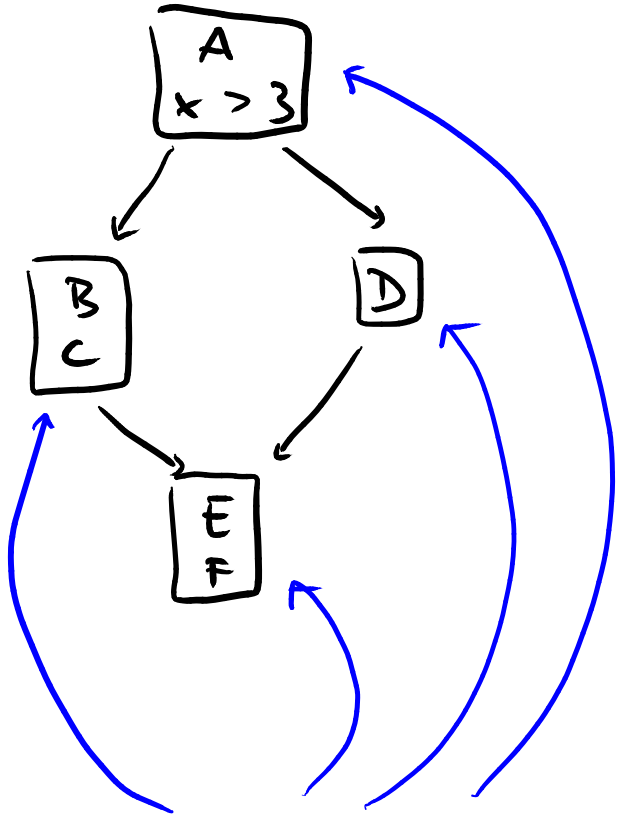
Overview


t
Mutate input
t', t'', ...
is interesting?
No
Discard
Yes
Enqueue
Choose next
Seed input
Queue of test inputs

Control Flow Graphs – Basic Blocks

```
A
if (x > 3) {
    B
    C
} else {
    D
}
E
F
```





Basic: Sequence of operations/stmts. always executed together (i.e. no branch in between)

Measuring Coverage

- **Different coverage metrics**
  - Line/statement/branch/path coverage
- **Here: Branch coverage**
  - Branches between basic blocks
  - Rationale: Reaching a code location not enough to trigger a bug, but state also matters
  - Compromise between
    - Effort spent on measuring coverage
    - Guidance it provides to the fuzzer

Example

Sequence of basic that are executed	Branches covered (i.e. edges in CFG)
A → B → C → D → E	AB, BC, CD, DE
A → B → D → C → E	AB, BD, DC, CE

Efficient Implementation

- **Instrumentation added at branching points:**

```
cur_location = /*COMPILE_TIME_RANDOM*/;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

Efficient Implementation

- **Instrumentation added at branching points:**

```
cur_location = /*COMPILE TIME RANDOM*/;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

Advantage:
Works well with separate compilation

Efficient Implementation

- **Instrumentation added at branching points:**

```
cur_location = /*COMPILE_TIME_RANDOM*/;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

Globally reachable memory location that stores how often each edge was covered

Efficient Implementation

- **Instrumentation added at branching points:**

```
cur_location = /*COMPILE_TIME_RANDOM*/;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

Combine previous and current block into a fixed-size hash

Efficient Implementation

- **Instrumentation added at branching points:**

```
cur_location = /*COMPILE_TIME_RANDOM*/;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

Shift to distinguish between "A" followed by "B" from "B" followed by "A"

Detecting New Behaviors

- **Inputs that trigger a new edge in the CFG: Considered as new behavior**
- **Alternative: Consider new paths**
  - More expensive to track
  - Path explosion problem

Example

Exec. 1: $A \to B \to C \to D \to E$ new

Exec. 2: $A \to B \to C \to A \to E$ new

Exec. 3: $A \to B \to C \to A \to B \to C \to A \to B \to C \to D \to E$ not new

Edge Hit Counts

- **Refinement of the previous definition of "new behaviors"**
- **For each edge, count how often it is taken**
  - Approximate counts based on buckets of increasing size
    - 1, 2, 3, 4-7, 8-15, 16-31, etc.
  - Rationale: Focus on relevant differences in the hit counts

Evolving the Input Queue

- **Maintain queue of inputs**
  - Initially: Seed inputs provided by user
  - Once used, keep input if it covers new edges
  - Add new inputs by mutating existing input
- **In practice: Queue sizes of 1k to 10k**

Mutation Operators

- **Goal: Create new inputs from existing inputs**
- **Random transformations of bytes in an existing input**
  - Bit flips with varying lengths and stepovers
  - Addition and subtraction of small integers
  - Insertion of known interesting integers
    - E.g., 0, 1, INT_MAX
  - Splicing of different inputs

More Tricks for Fast Fuzzing

- **Time and memory limits**
  - Discard input when execution is too expensive
- **Pruning the queue**
  - Periodically select subset of inputs that still cover every edge seen so far
- **Prioritize how many mutants to generate from an input in the queue**
  - E.g., focus on unusual paths or try to reach specific locations

Real-World Impact

- **Open-source tool maintained mostly by Google**
  - Initially created by single developer
  - Various improvements proposed in academia and industry
- **Fuzzers regularly check various security-criticial components**
  - Many thousands of compute hours
  - Hundreds of detected vulnerabilities