Lec 25: Fuzzing

CSED415: Computer Security
Spring 2025

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Administrivia

- Lab 05 is due by the end of Friday, May 23
  - Attend office hours for help!
    - TA: Mondays and Thursdays 7-8 PM
    - Prof: Thursdays 1-2 PM

Administrivia

- Project presentations – Next week
  - Each team: 15-minute presentation + 5-minute Q&A (20 minutes total)
    - Three teams will present on Tue, May 27
    - The other three teams will present on Thu, May 29
  - Presentation must include a demonstration (live or recorded)
  - All teams MUST submit their slides, code and/or binary, and report by **May 26**
    - Check PLMS assignment for details

Administrivia

- Final exam:
  - Time: Thursday, June 5, 2:00-3:15 PM (75 minutes)
  - Location: Classroom (Science Building II, Room #106)
  - Format: Closed book, closed notes, no electronic devices allowed
    - Allowed: One-page (US letter- or A4-sized) double-sided handwritten cheat sheet
  - Structure: 6 main questions (each may have sub-questions)
  - Scope: Lectures 15-26, Labs 03-05

Program Analysis for Bug Finding

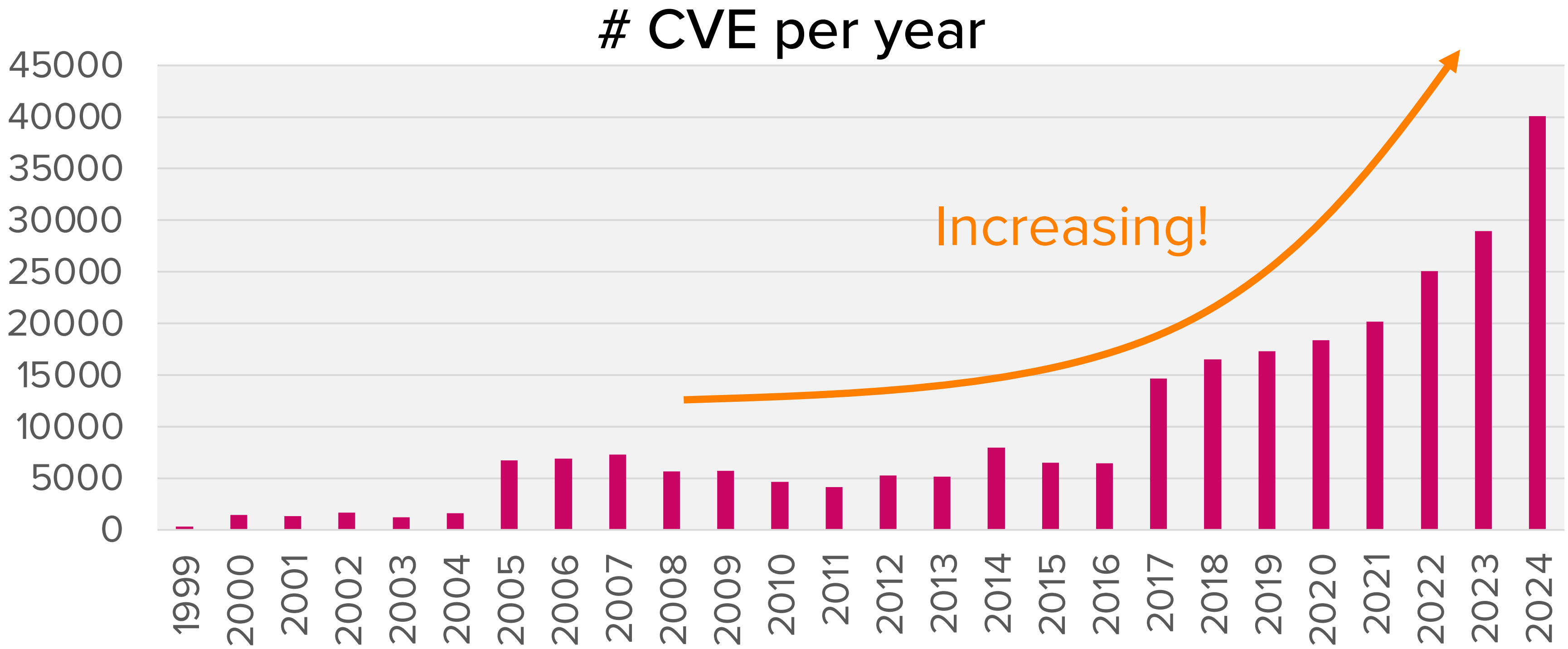
Motivation

- There are many bugs in the wild
  - Some bugs are security vulnerabilities that are exploitable by attackers

If we eliminate bugs, we can prevent attacks

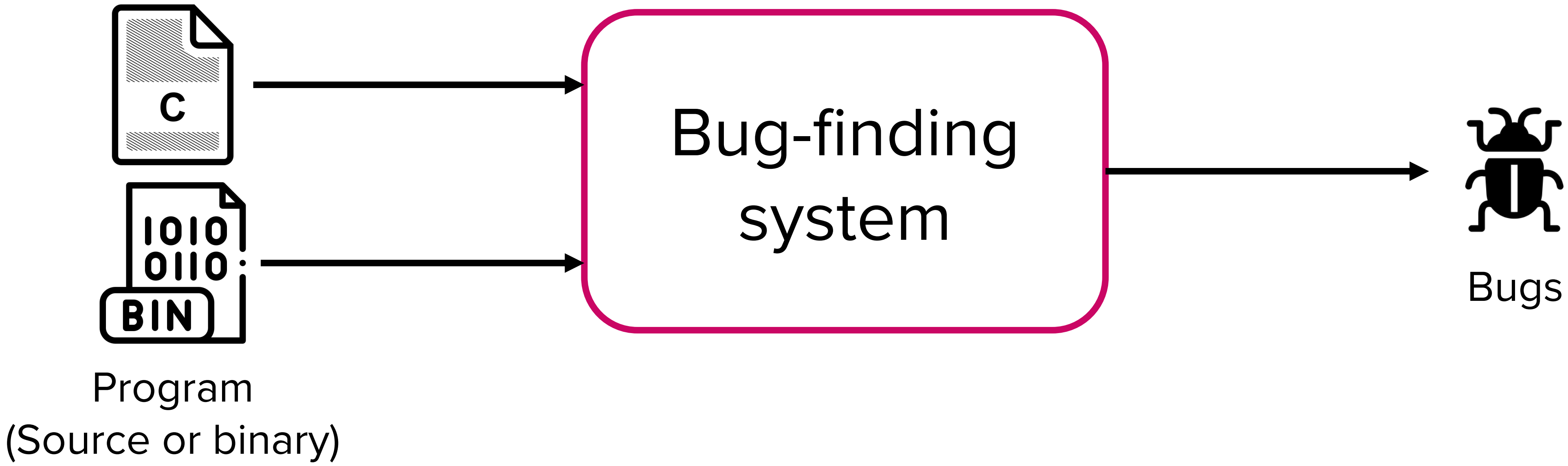
Motivation

- CVE (Common Vulnerability Enumeration)
  - CVE is an indentifier assigned to publicly disclosed vulnerabilities
  - # vulnerabilities keeps increasing - The attack surface is growing!



Key question

- Can we build a system that automatically finds bugs?



Informal proof

- Define a function `is_buggy`
  - Input: A program
  - Output: `1` if the program has at least one bug, `0` if not

```
def is_buggy(prog):
    # test prog and return 1 or 0
```

Informal proof

- Write a program `buggy_prog`

```
# buggy_prog.py

if is_buggy("buggy_prog.py"):
    return # do nothing

else:
    corrupt_memory()
    launch_root_shell()
    return
```

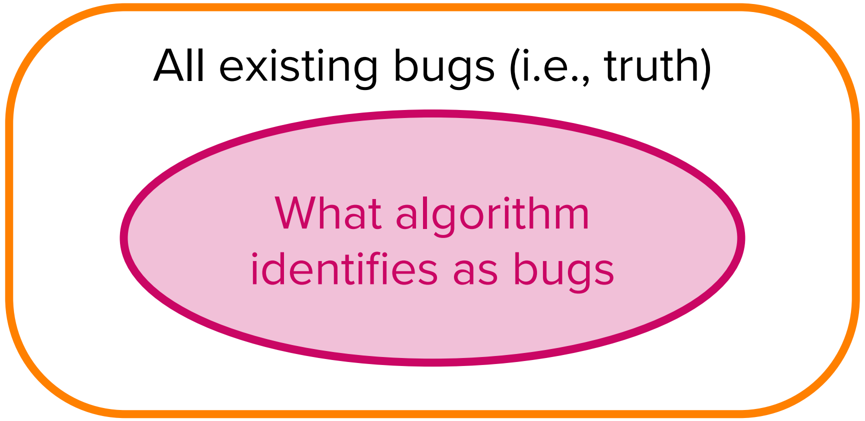
Self-contradictory! (Similar to the case of anti-virus)

Back to the question..

- Can we build a system that automatically finds bugs?
  - A a perfect bug-finding system cannot exist
- Therefore, we use best-effort approaches for partial bug identification
  - Bounded model checking
  - Static analysis
  - Dynamic analysis
  - etc.

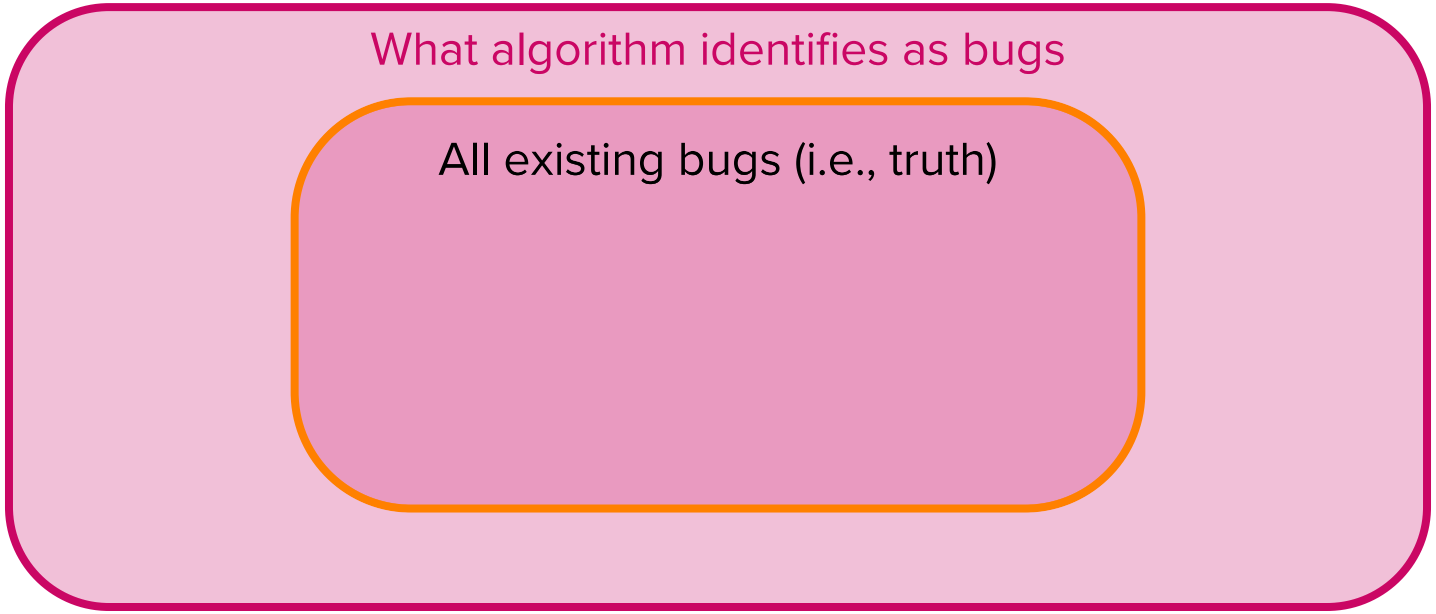
Definition of "partial"

- Soundness vs Completeness
  - An algorithm is sound if every result it produces is in fact true
    - Every reported bug is real if algorithm is sound
    - Soundness guarantees that there is no false positive
      - A sound algorithm never misclassifies a non-bug as bug



Definition of “partial”

- Soundness vs Completeness
  - An algorithm is complete if it can derive all truths
    - Every real bug is reported if algorithm is complete
    - Completeness guarantees that there is no false negative
      - A complete algorithm never misclassifies a bug as non-bug



Perfect analysis

- Soundness vs Completeness
  - Perfect algorithm is sound and complete
    - Very challenging to achieve in practice

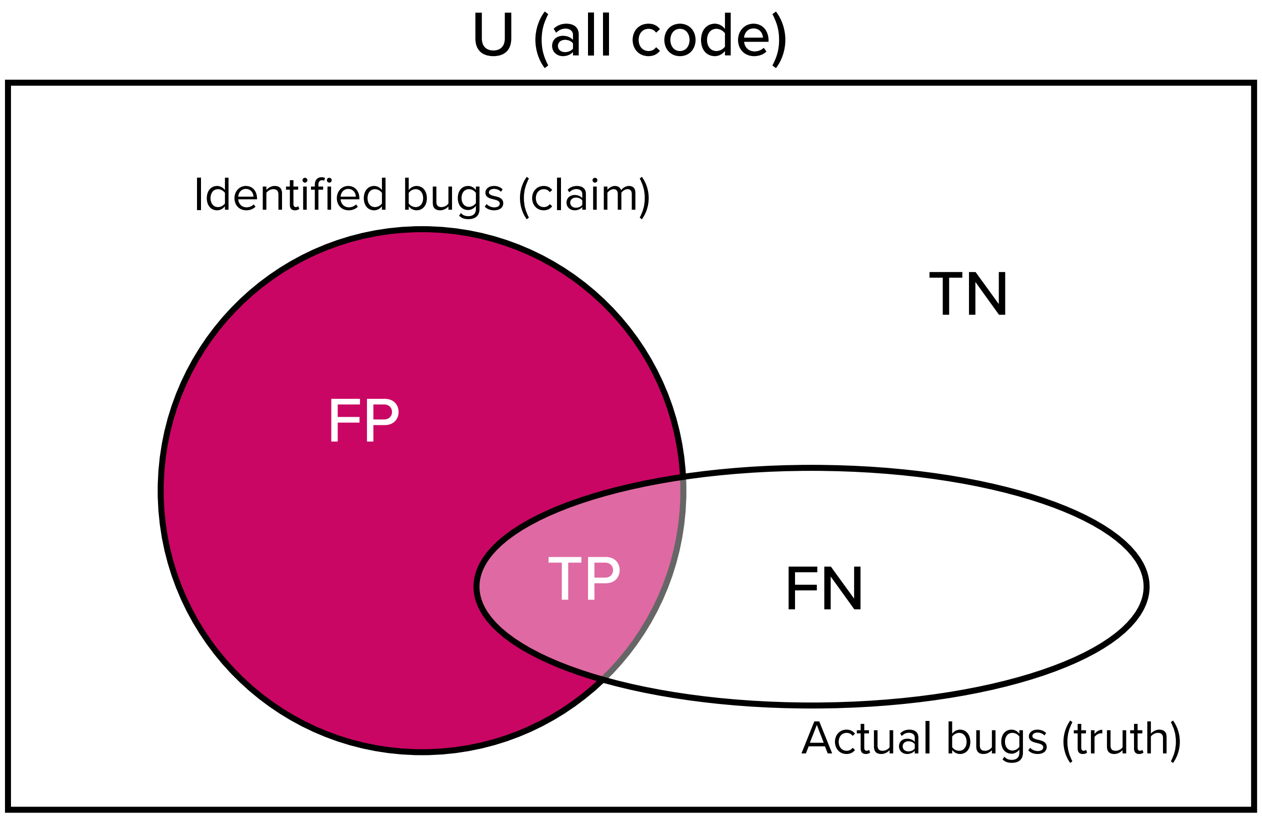
All existing bugs (i.e., truth)

=

What algorithm identifies as bugs

Metrics to evaluate a bug finding algorithm

- Precision, recall, and accuracy



- Precision: Quality of identification
  = TP / (TP + FP)
- Recall: Quantity of identification
  = TP / (FN + TP)
- Accuracy
  = (TP + TN) / U

Static vs Dynamic analysis

- Static analysis:
  - Examine program (binary or code) without running it
  - Examples:
    - Decompilation
    - Pointer analysis
    - Symbolic execution (Next topic)
- Dynamic analysis:
  - Monitor program's runtime behavior during execution
  - Examples:
    - Fuzzing (Today's topic)
    - Concolic execution

Fuzzing

Fuzzing (or fuzz-testing)

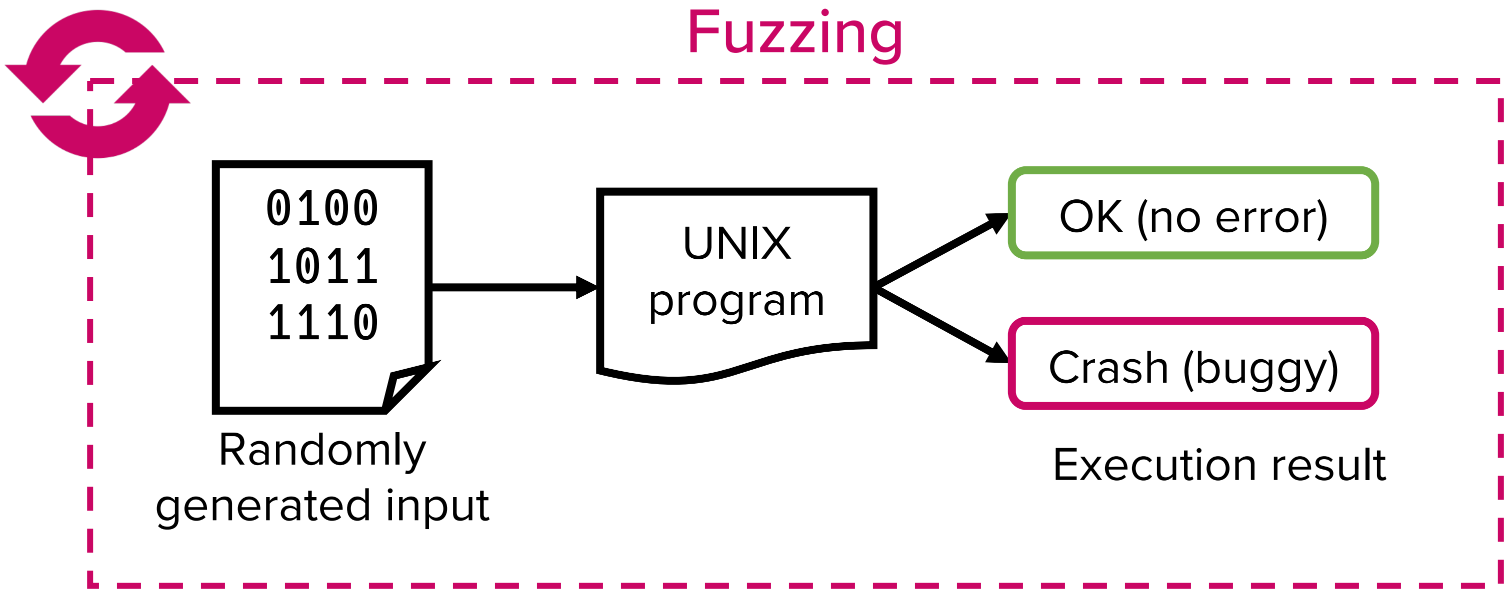
- Definition
  - Automated testing technique that feeds invalid/unexpected/random inputs to a program under test (PUT)
  - During the process, the program is monitored for anomalous behaviors
    - Crash, hang, memory leak, etc.
  - Goal is to uncover as many bugs (and vulnerabilities) as possible

Origin of fuzzing

- Experience of Barton Miller in 1990
  - He was logged on to his workstation through a modem (dial-up line)
  - Due to a storm there were a lot of line noise (i.e., line was fuzzy)
  - The noise kept generating spurious characters on the line
  - Programs on the workstation kept crashing due to the junk characters
  - He coined the term “fuzzing” from the experience

Early days of fuzzing

- Paper: Barton Miller, et al.,
  "*An Empirical Study of the Reliability of Unix Utilities*",
  Communications of the ACM, 1990



Early days of fuzzing

- Effectiveness
  - Tested 90 Unix utility programs
    - awk, cat, cc, diff, emacs, grep, …
  - The fuzzer crashed 36 utilities!
    - Due to various bugs including unbounded pointer/array accesses, overflows, race conditions, …
    - Randomly generated inputs were strikingly effective in triggering the bugs within poorly-written Unix programs of 1980s

Experiment

- Let's put Miller's fuzzer to the test with a simple program
  - Target program reads 4 bytes from stdin
  - If the four bytes are `0xde 0xad 0xbe 0xef`, it crashes by raising segmentation fault signal

```c
#include <signal.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

void bug(void) {
  printf("bug!\n");
  raise(SIGSEGV);
}

int main(void) {
  setvbuf(stdout, NULL, _IONBF, 0);
  setvbuf(stdin, NULL, _IONBF, 0);

  char in[16];
  FILE *fp = fopen("/dev/stdin", "rb");
  fread(&in, 4, 1, fp);
  if (in[0] == '\xde')
    if (in[1] == '\xad')
      if (in[2] == '\xbe')
        if (in[3] == '\xef')
          bug();
  fclose(fp);
  return 0;
}
```

target.c

Experiment

- Let's put Miller's fuzzer to the test with a simple program
  - Fuzzer: Brute-force 4-byte random inputs until the target crashes
  - Let's check the result at the end of today's lecture

```python
import os
import subprocess as sp

if __name__ == "__main__":
    trials = 0
    while True:
        _input = os.urandom(4)

        p = sp.Popen(["./target"], stdout=sp.PIPE, stdin=sp.PIPE, stderr=sp.PIPE)
        out, err = p.communicate(input=_input) # send _input to stdin and read stdout
        if b"bug!" in out:
            print(f"found in {trials} trials")
            print(f"Test input: {_input}")
            exit(0)

        print(trials)
        trials += 1
```

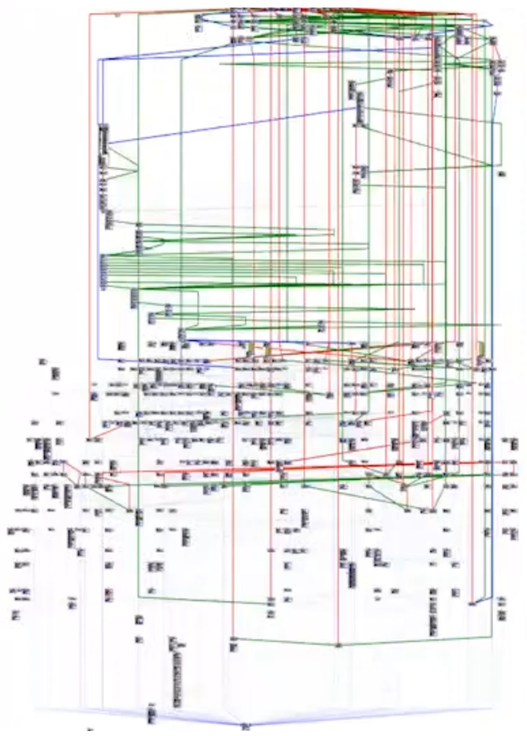
fuzz.py

Interpretation of Miller's success

- Fuzzing is simple, yet effective. Why?
  - Recall the software bugs we covered in this course
    - Many attacks originate from unsanitized user inputs
      - e.g., buffer overflow, control flow hijacking, authentication bypass, DoS, SQL injection, …
    - Fuzzing is a way to "simulate" hostile input with minimal effort

Is fuzzing still effective against modern software?

- Modern software have become very large and complex
  - Chromium browser codebase has 28 million lines of code (LoC)
  - Linux kernel comprises over 27 MLoC
  - FFmpeg has 1.4 MLoC
- Manual review of every code path is impractical
  - Imagine manually analyzing a program with the control flow graph (CFG) displayed on the right
  - Time consuming, error-prone, and hardly scalable



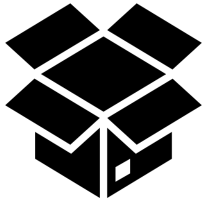
Is fuzzing applicable to large and complex programs?

Evolution of fuzzing

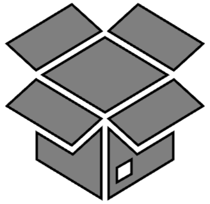
- Types of fuzzing
  - Blackbox, greybox, and whitebox fuzzing
  - Mutation-based vs generation-based fuzzing

Greybox Fuzzing

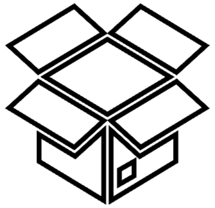
Overview of Black, grey, and whitebox fuzzing



- Generates random inputs
- Fuzzer has no knowledge of program's code and internal states
- The approach of Miller et al.
- Pros:
  - Extremely fast
  - Easy to use
  - Scalable
- Cons:
  - Poor effectiveness
  - Poor code coverage



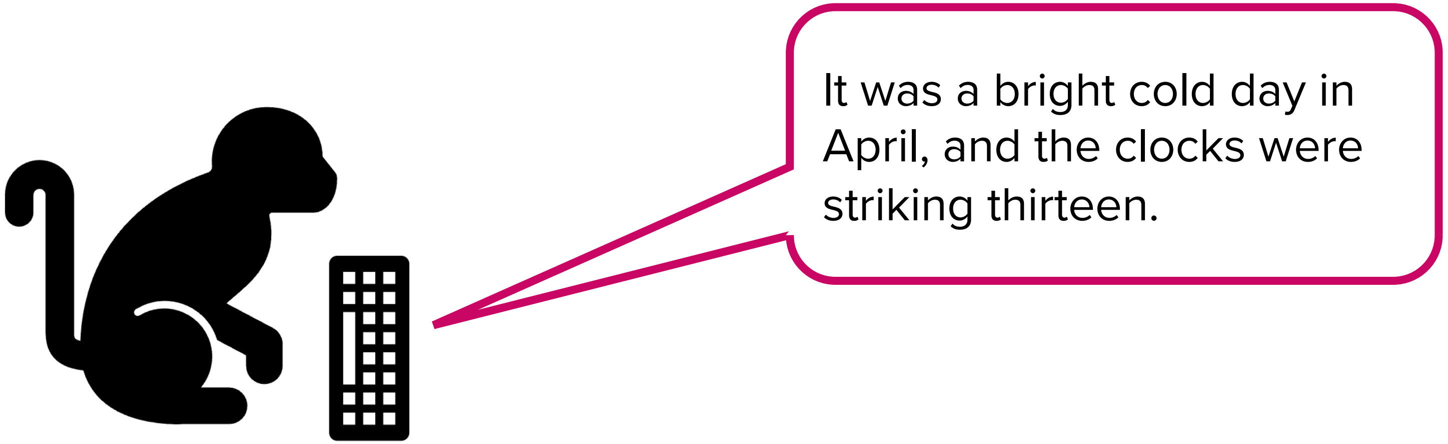
- Relies on "lightweight" instrumentation of the program under test
- Fuzzer has some knowledge of the program internals during fuzzing
  - Generates semi-random inputs based on the knowledge
- Pros: Best of both worlds
  - Scalable
  - Relatively fast
  - Decent code coverage



- Fuzzer has full knowledge of the program internals and code
- Solves path constraints to generate concrete inputs for all program branches
- Pros:
  - High code coverage
- Cons:
  - Complex
  - Slow
  - Not scalable

Breakdown of fuzzing efficiency

- A typing monkey problem
  - Given infinite amount of time, can a monkey, hitting keys at random on a keyboard, type a full sentence?

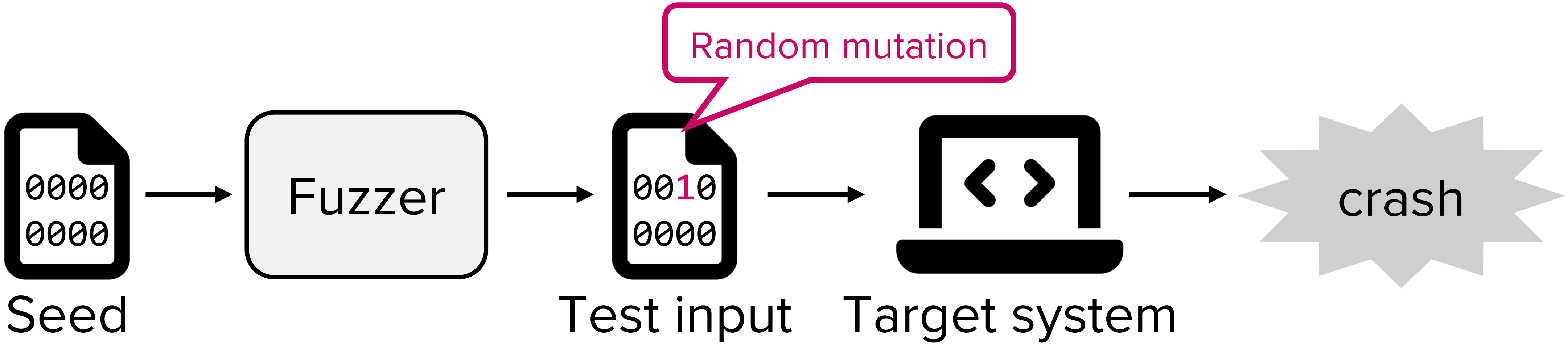


The possibility is non-zero; the monkey will "almost surely" type any given sentence

However, it will take astronomical amount of time

Breakdown of fuzzing efficiency

- Blackbox fuzzing



Target

```
x = input()

if x[0] == 'H':
  if x[1] == 'A':
    if x[2] == 'R':
      if x[3] == 'D':
        crash()
```

Seed `x = "LIFE"`

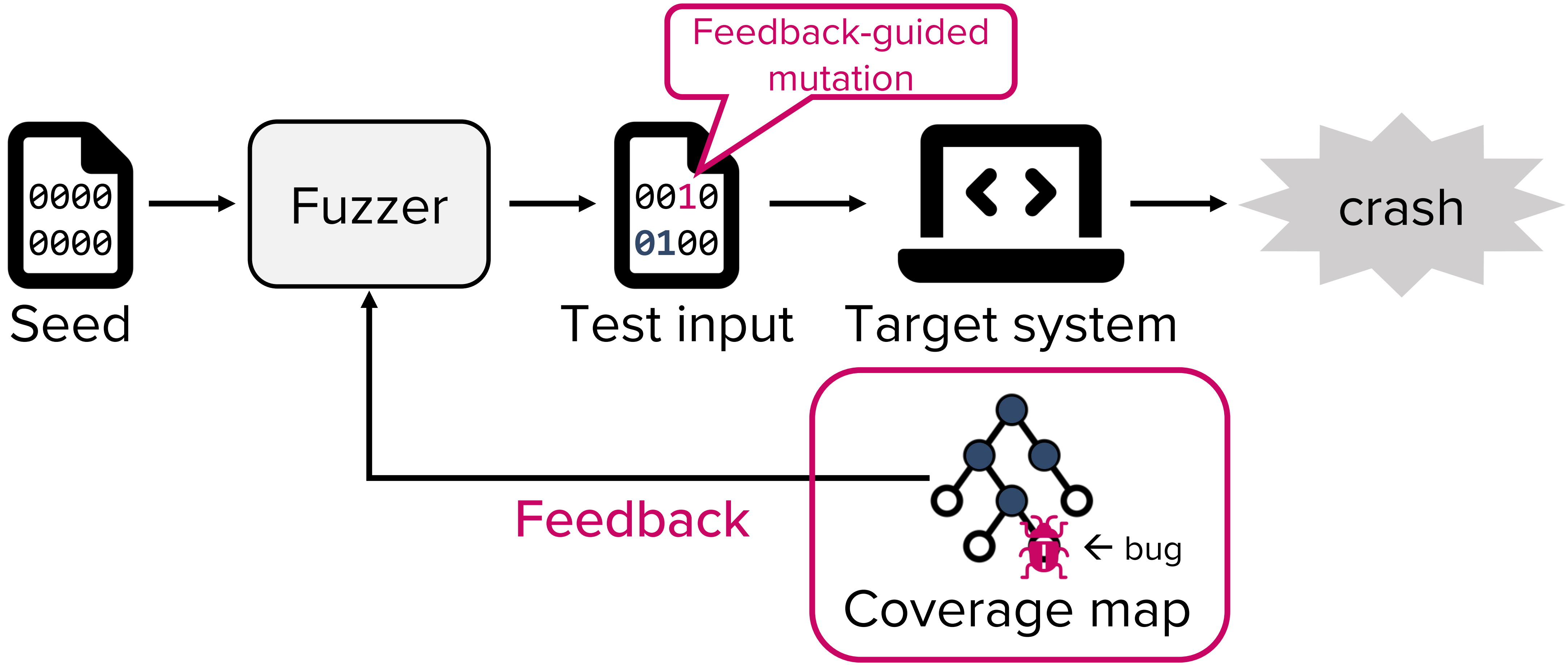
Test input

`x = "LIFO"`	`x = "5IFE"`	`x = "L0VE"`
`x = "HEFE"`	`x = "DOVE"`	`x = "LIFF"`

→ $P(\text{crash}) = \frac{1}{2^{32}}$

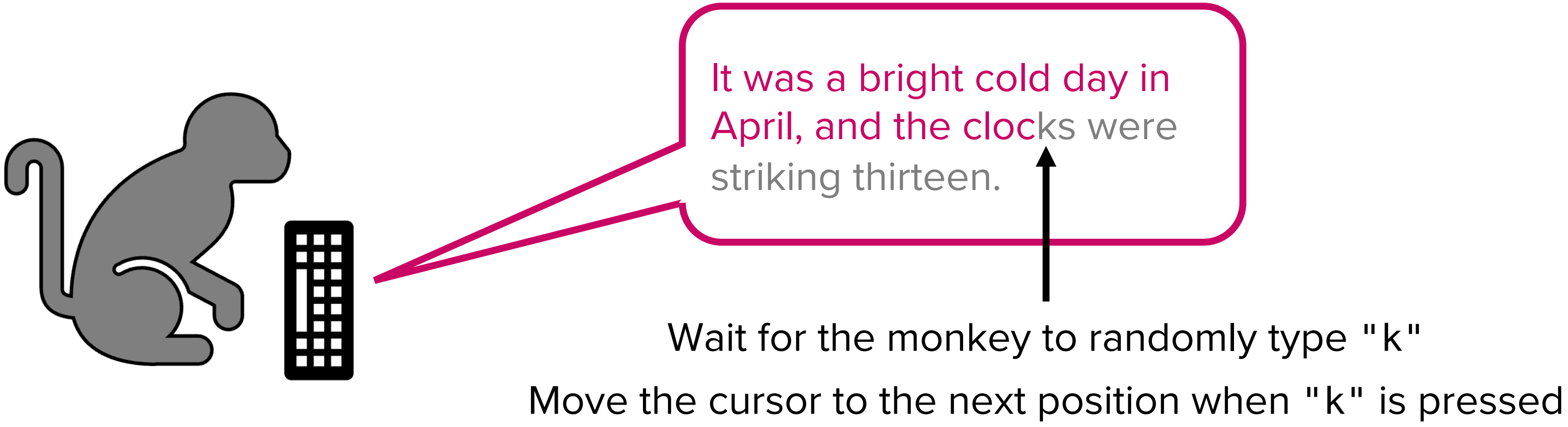
Recent breakthrough

- Greybox fuzzing with code coverage feedback



Breakdown of fuzzing efficiency

- A typing monkey problem (Greybox edition)
  - Keep the typed letters that are correct
  - Restart typing from the next position



Breakdown of fuzzing efficiency

- A typing monkey problem (Greybox edition)
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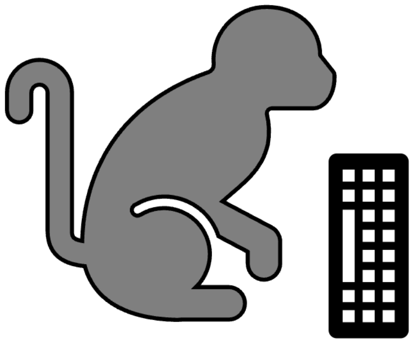

It was a bright cold day in April, and the clocks were striking thirteen.

Repeat for the rest of the sentence

The possibility is dramatically increased

Coverage feedback leads to better exploration

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Target

```
x = input()

if x[0] == 'H':
  if x[1] == 'A':
    if x[2] == 'R':
      if x[3] == 'D':
        crash()
```

Seed `x = "LIFE"`

Test input `x = "LIFO"` `x = "5IFE"` `x = "L0VE"`

`x = "HEFE"` New branch. Interesting!

New seed `x = "HEFE"`

Test input `x = "LEFE"` `x = "HAVE"` New branch. Interesting!

New seed `x = "HAVE"`

⋮

$$\rightarrow P(\text{crash}) = \frac{1}{2^8} \times \frac{1}{4} = \frac{1}{2^{10}} > \frac{1}{2^{32}}$$

Get correct byte

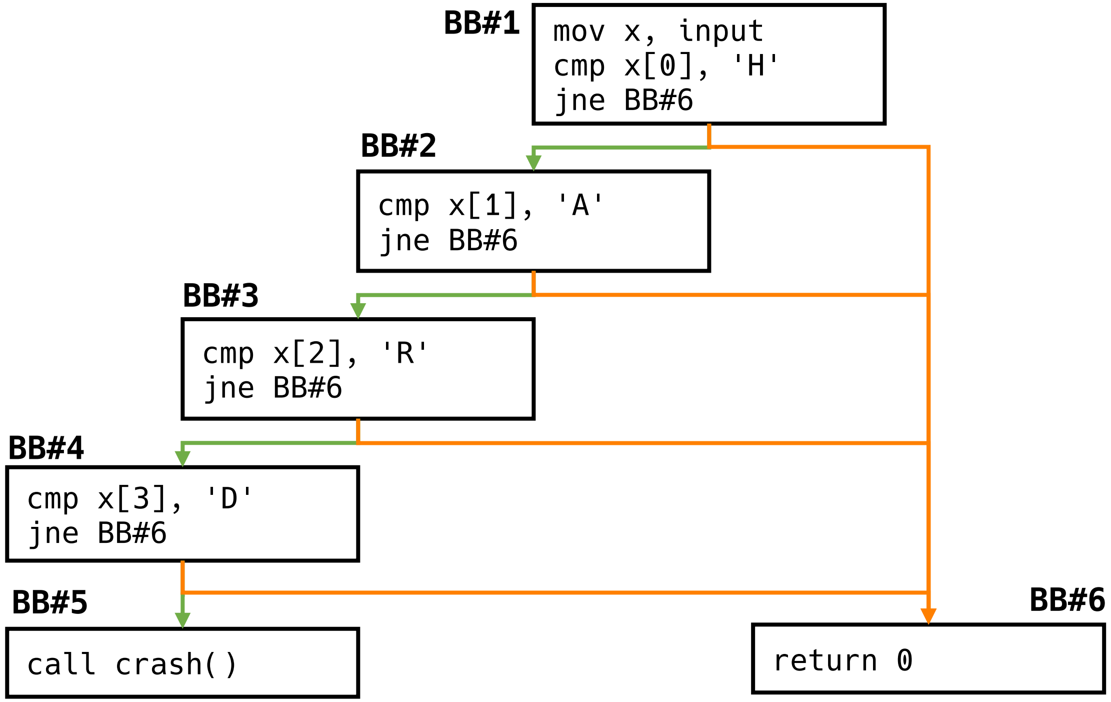
Select right position

How to track code coverage?

- Instrumentation: Modifying a program to enable analysis
  - For code coverage tracking, we want to record which branches of a program has been executed
  - We can instrument basic blocks
    - Basic block (BB): A sequence of code representing one branch of a software

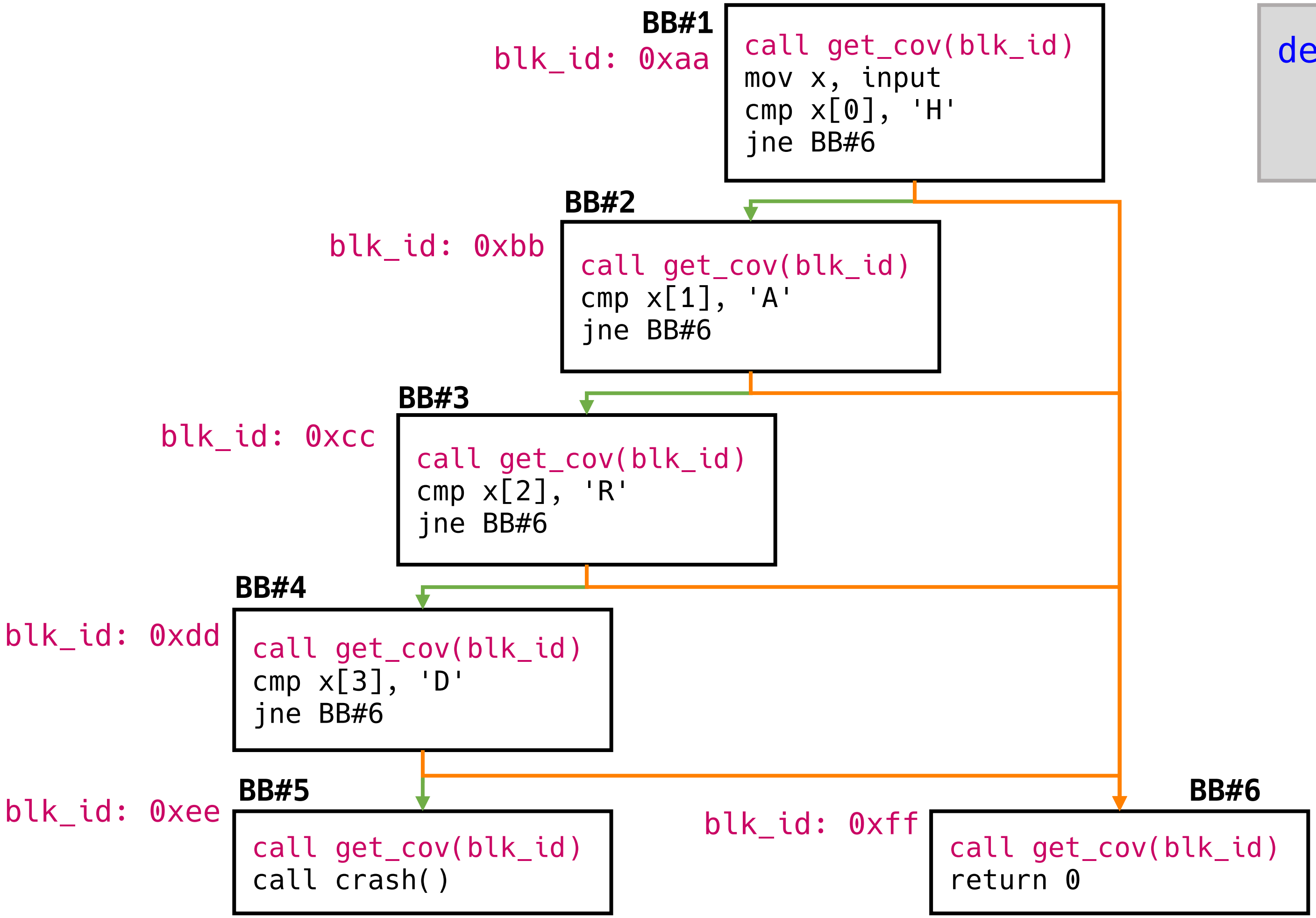
How to track code coverage?

- Control flow graph (CFG) of the "HARD" example
  - Consists of six basic blocks



How to track code coverage?

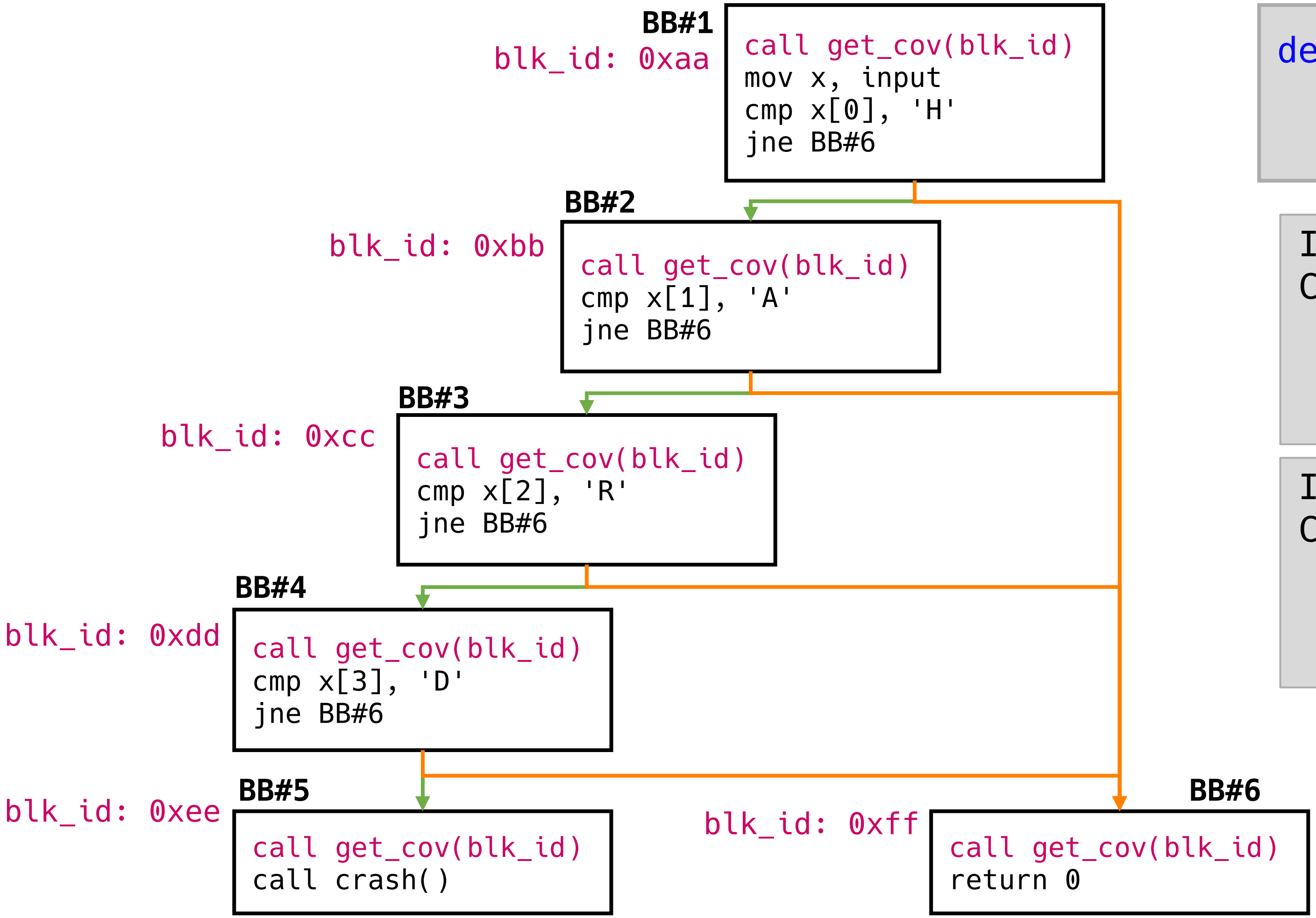
- Instrumentation for code coverage tracking




```
def get_cov(blk_id):
  global prev_blk_id
  record(prev_blk_id, blk_id)
```

How to track code coverage?

- Instrumentation for code coverage tracking




```
def get_cov(blk_id):
  global prev_blk_id
  record(prev_blk_id, blk_id)
```

```
Input: HASH
Coverage map:
  (0xaa,0xbb)
  (0xbb,0xcc)
  (0xcc,0xff)
```

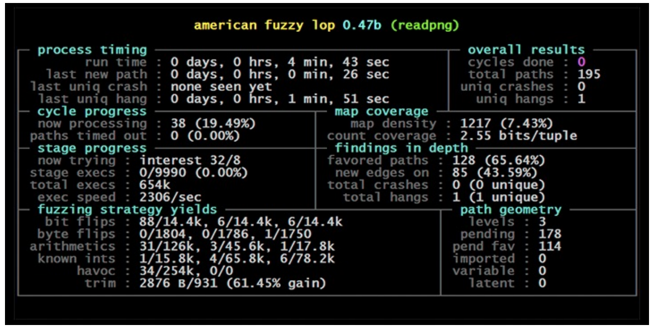
```
Input: HANK
Coverage map:
  (0xaa,0xbb)
  (0xbb,0xcc)
  (0xcc,0xff)
```

```
Input: HAND
Coverage map:
  (0xaa,0xbb)
  (0xbb,0xcc)
  (0xcc,0xff)
```

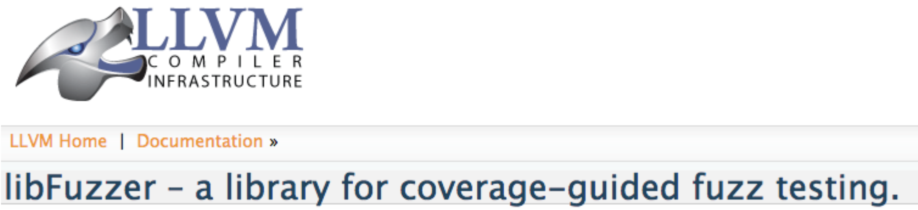
```
Input: HARM
Coverage map:
  (0xaa,0xbb)
  (0xbb,0xcc)
  (0xcc,0xdd)
  (0xdd,0xff)
```

New coverage found!

Feedback-driven greybox fuzzing is effective



AFL



libFuzzer

OSS-Fuzz

Discovered millions of <u>crashes</u> in complex software systems

Test Input Generation

Mutation- vs Generation-based fuzzing

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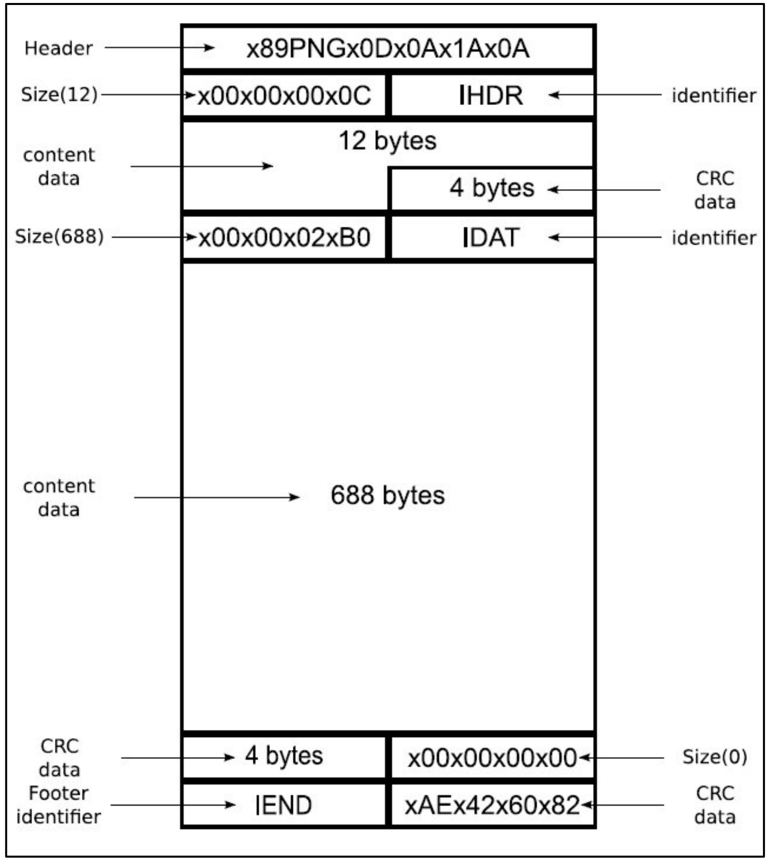
- Motivation: Randomly generated inputs are likely rejected by the program under test
  - e.g., When fuzzing a video player application, it is very unlikely that a fuzzer generates a properly formatted `mp4` file at random
- Two methods for better input generation
  - Mutation: Mutate a given seed to generate test inputs
    - Seed: A legitimate `mp4` file
  - Generation: Generate test inputs from an input model
    - Model: Specification of `mp4` file format

Mutation

- Frequently used mutation operators
  - Bit-flipping: Flip a randomly selected bit
    - e.g., `0xdead` (`0b1101 1110 1010 1101`) → `0xdeaf` (`0b1101 1110 1010 1111`)
  - Arithmetic operation: Select a byte and add/subtract a value
  - Randomization: Select a byte and randomize the value
  - Insertion and deletion: Add or remove bytes
  - Splicing: Crossover two test inputs
    - e.g., First half of input #1 + second half of input #2

Generation

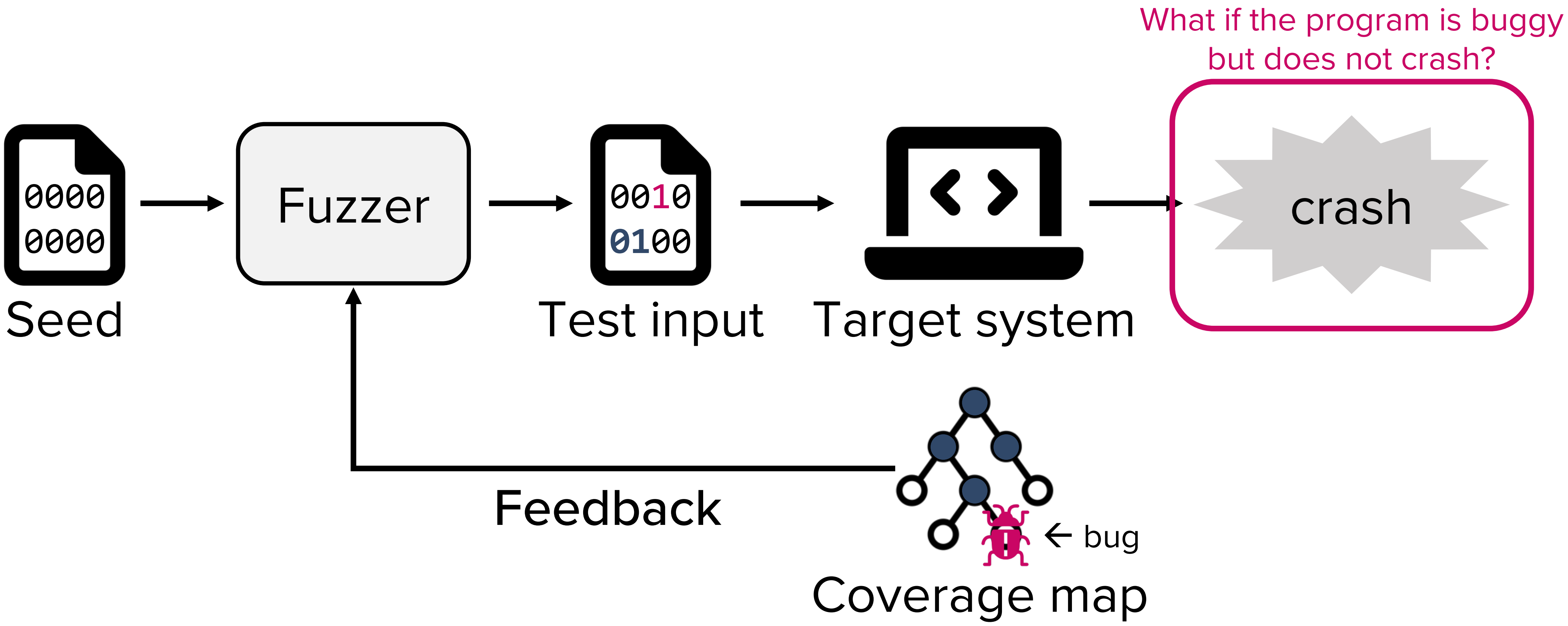
- Generate inputs that the program under test would accept
- A model describes the correct format
  - e.g., a grammar specifying the input format
    - PNG input has header and size fields
    - The header field must have the “magic number” of PNG in order for the input to be accepted by a PNG parser



PNG format

Bug Oracles

Mutation-based greybox fuzzing overview



A need for bug oracles

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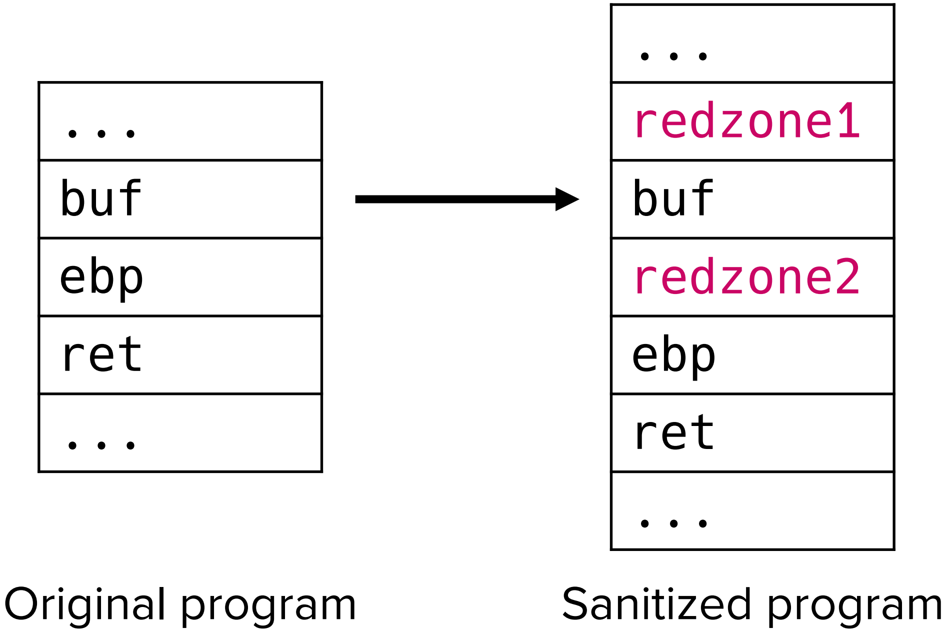
- What types of anomalous behavior do we want to find?
  - Crashes, but not all vulnerabilities lead to crashes (e.g., Lab 01)
  - Memory corruption: e.g., Use-After-Free (UAF) vulnerabilities
  - Hang: Program does not finish within a timeout period
  - Memory leaks, race conditions, specification violation, …
- A bug oracle detects any interesting behavior occurred during the execution of a program with the test input

Bug oracles in practice

- AddressSanitizer (ASan)
  - Detects buffer overflows and use-after-free
- ThreadSanitizer (TSan)
  - Detects data races
- MemorySanitizer (MSan)
  - Detects uses of uninitialized memory

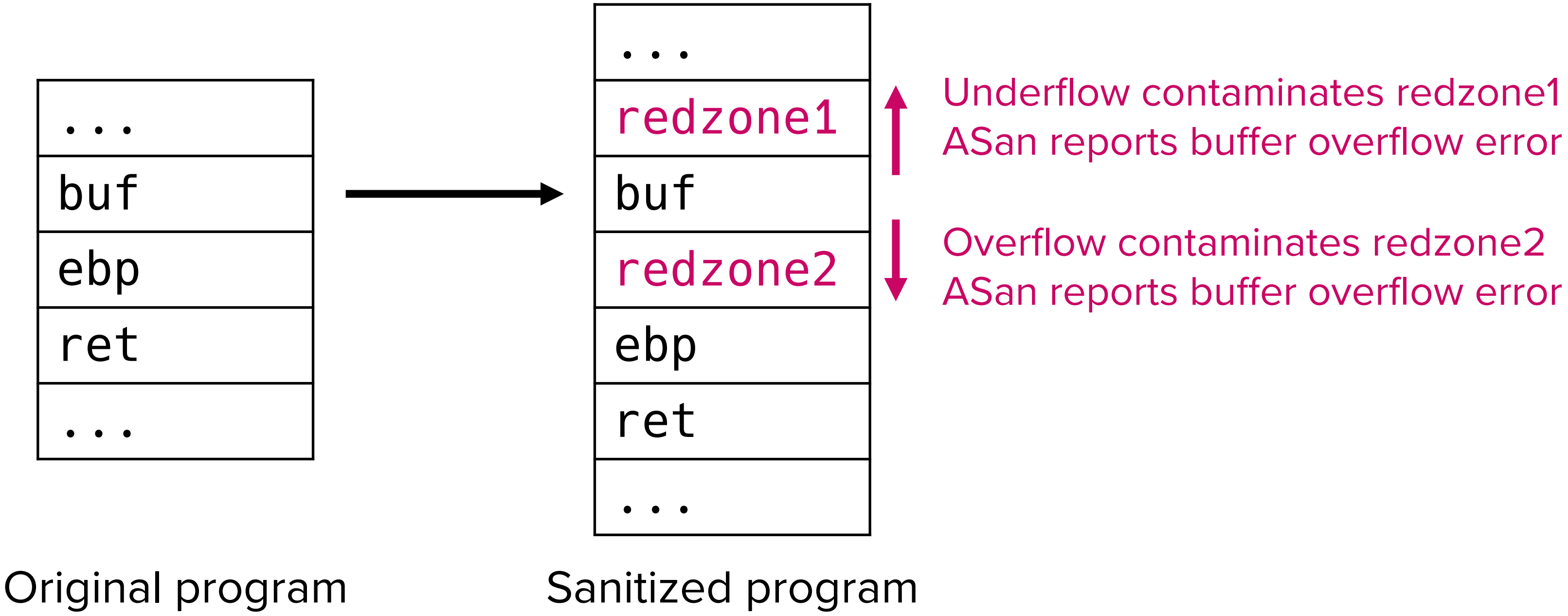
Address sanitizer

- Implemented as compiler module (available in clang and gcc)
  - Instruments all load and store instructions
  - Inserts redzones around each stack and global variable



Address sanitizer

- Runtime module checks whether redzones are touched when `buf` is read or something is written to `buf`



Address sanitizer in action

- Without ASan

```c
// oob.c
#include <stdio.h>
int numbers[] = { 1, 2, 3 };
int main() { /* classic out of bounds read error. */
  printf("The 4th number in my array is: %i\n", numbers[4]);
}
```

```
$ gcc oob.c -o oob
```

```
$ ./oob
The 4th number in my array is: 0
```

The bug is missed

Address sanitizer in action

- With ASan

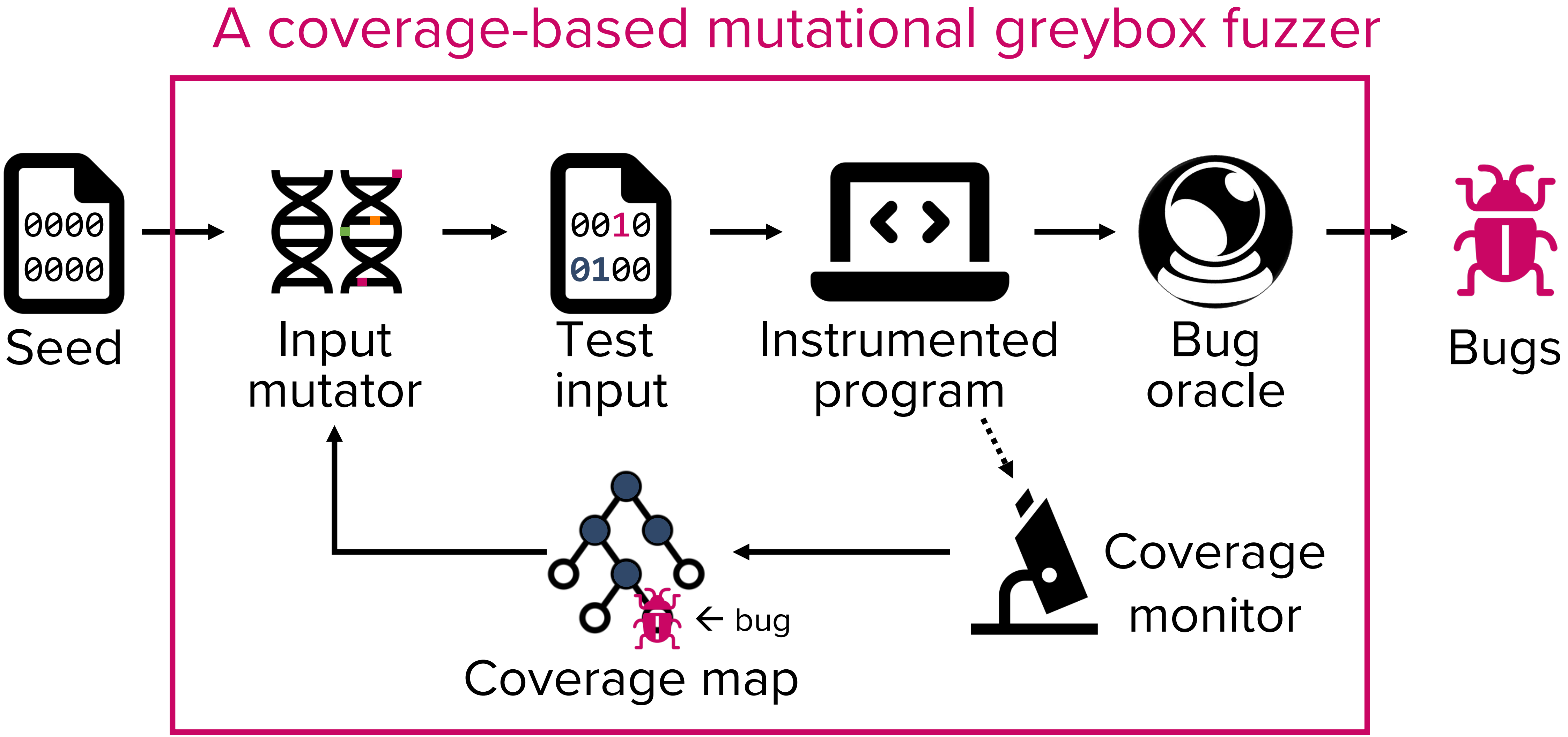
```
// oob.c
#include <stdio.h>
int numbers[] = { 1, 2, 3 };
int main() { /* classic out of bounds read error. */
  printf("The 4th number in my array is: %i\n", numbers[4]);
}
```

```
$ gcc oob.c -fsanitize=address -o oob_asan
```

```
$ ./oob_asan
=================================================================
==365994==ERROR: AddressSanitizer: global-buffer-overflow on address 0x55aceaed5030 at pc 0x55aceaed2223 bp
0x7ffe8cfc2c20 sp 0x7ffe8cfc2c10
READ of size 4 at 0x55aceaed5030 thread T0
    #0 0x55aceaed2222 in main (/home/seulbae/test/asan/oob_asan+0x1222)
    #1 0x7fa6faf1ed8f in __libc_start_call_main ../sysdeps/nptl/libc_start_call_main.h:58
    #2 0x7fa6faf1ee3f in __libc_start_main_impl ../csu/libc-start.c:392
    #3 0x55aceaed2124 in _start (/home/seulbae/test/asan/oob_asan+0x1124)

0x55aceaed5030 is located 4 bytes to the right of global variable 'numbers' defined in ‘oob.c:8:5' (0x55aceaed5020)
of size 12
SUMMARY: AddressSanitizer: global-buffer-overflow (/home/seulbae/test/asan/oob_asan+0x1222) in main
Shadow bytes around the buggy address:
  0x0ab61d5d29f0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
=>0x0ab61d5d2a00: 00 00 00 00 00 04[f9]f9 f9 f9 f9 f9 00 00 00 00
  0x0ab61d5d2a10: f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9 f9
```

Final picture



Let's check the fuzzing results (from page 23)

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- How many trials were required to find the bug through blackbox fuzzing?
  - Random mutation, no coverage feedback
  - Crash: Random 4 bytes being identical to `"\xde\xad\xbe\xef"`
    - Theoretically requires $2^{32} \approx 4.2$ billion trials
    - Experimentally: (see terminal)

vs AFL

- AFL: The most widely used coverage-guided mutation-based fuzzer
  - Instrumentation for code coverage using AFL’s custom complier

```
$ afl-cc target.c -O0 -o target_afl
```

  - Prepare a seed input

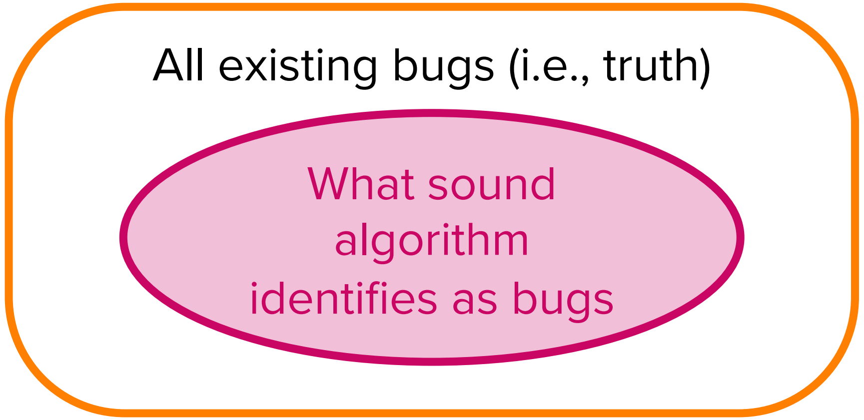
```
$ rm -rf in out
$ mkdir in out
$ echo -ne "\xff\xff\xff\xff" > in/seed
```

  - Run fuzzer

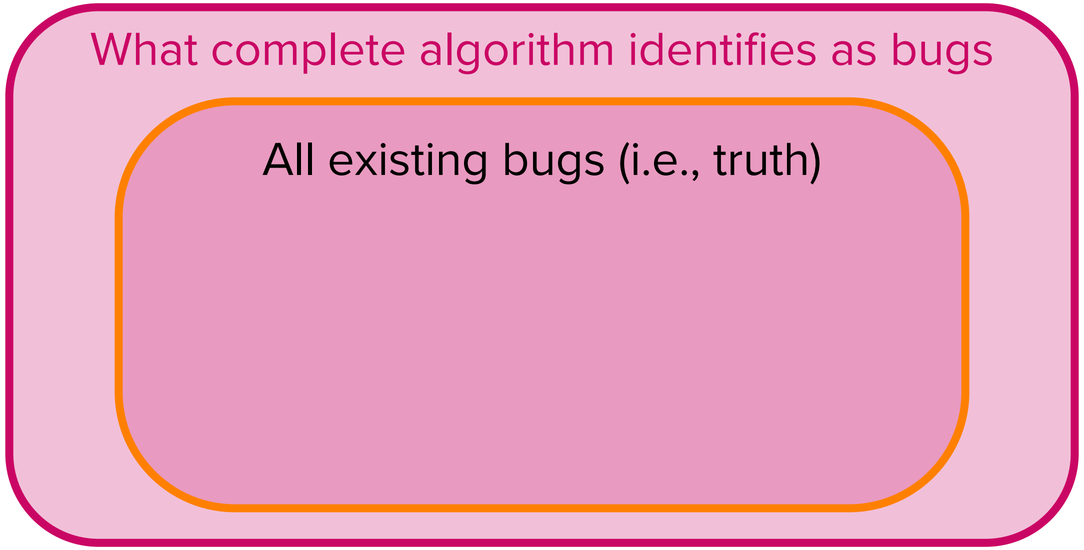
```
$ afl-fuzz -i in -o out -- ./target_afl
```

Questions

- Is fuzzing sound? (no false positives?)
- Is fuzzing complete? (no missed bugs?)



→ Fuzzer can have FP if its oracles are unsound



→ Fuzzer can miss bugs as it partially explores target program

Conclusion: Fuzzing is neither sound nor complete, but it is practical and scalable

Questions?