Lec 25: Fuzzing

CSED415: Computer Security

Spring 2024

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POSTECH

POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Administrivia

- All labs completed
  - Grace period for Lab 5 ends on May 26
- Final exam will be on June 4
  - Note: June 6 is a national holiday

Administrivia

- Project presentations next week
  - 15 min presentation + 5 min Q&A = 20 min per team
    - Three teams will present on Tue, May 28
    - The other three teams will present on Thu, May 30
  - Presentation order will be decided on Thu, May 23
  - Presentation should include a demonstration (live or recorded)
  - All teams MUST submit their slides, code, and report by **May 27**

Program Analysis for Bug Finding

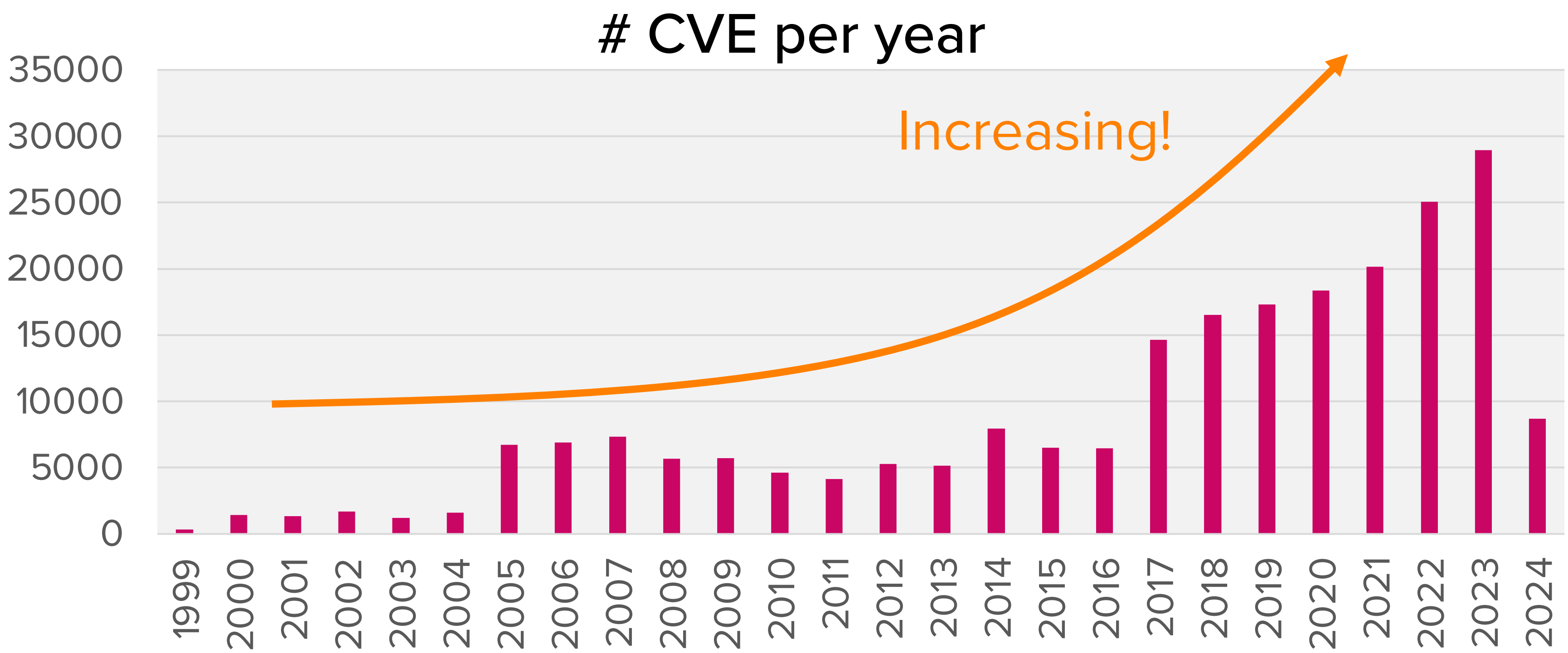
Motivation

- Many bugs exist
  - Some bugs are vulnerabilities that can be exploited by attackers to compromise the system

If we eliminate bugs, we can prevent attacks

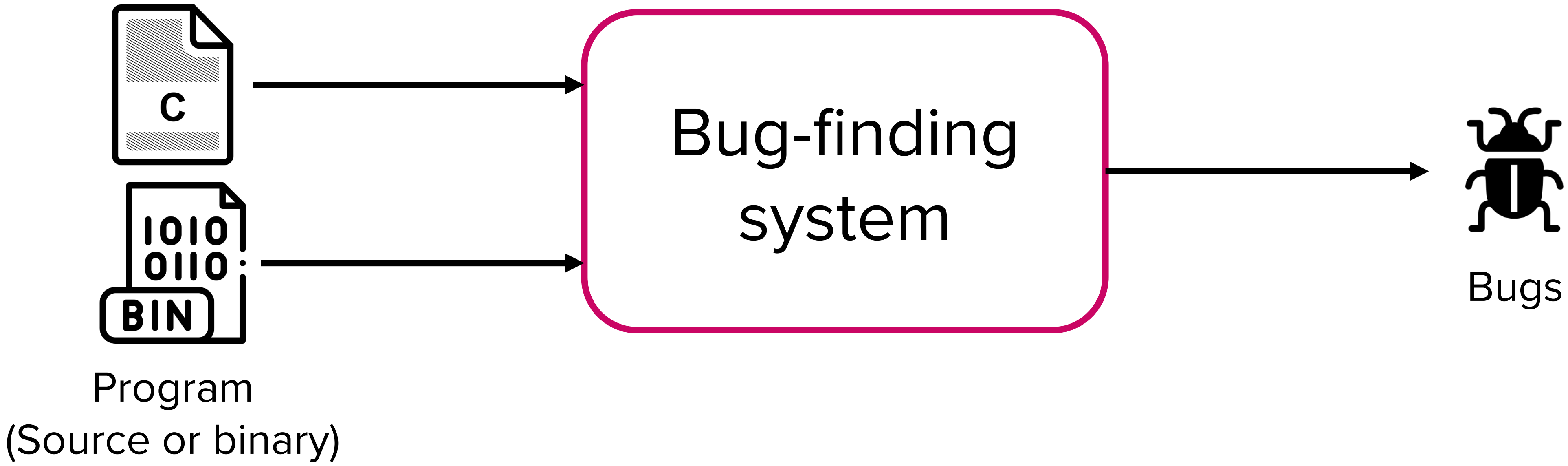
Motivation

- CVE (Common Vulnerability Enumeration)
  - List of publicly disclosed security flaws
  - Increasing every year



Question

- Can we build a system that automatically finds bugs?



Informal proof

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

```
def is_buggy(prog):
  # test the prog and return true or false
```

Informal proof

- Write a program buggy_prog

```
# buggy_prog.py
if __name__ == "__main__":
  if is_buggy("buggy_prog.py"):
    return
  else:
    corrupt_memory()
    launch_root_shell()
```

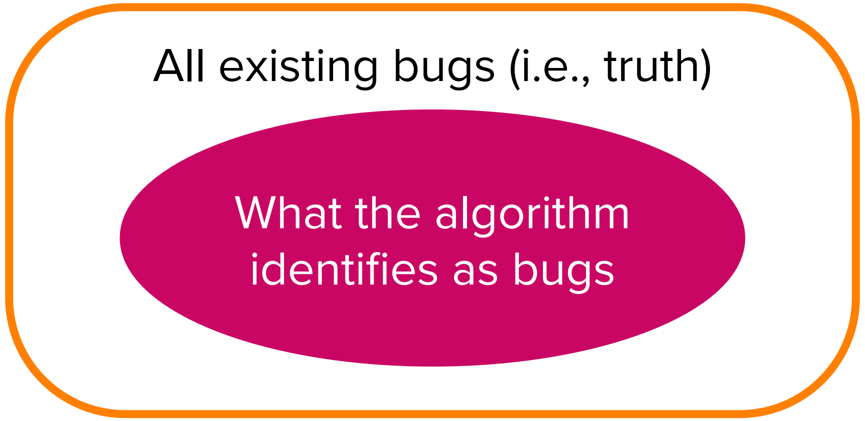
Self-contradictory! (similar to the case of anti-virus)

Back to the question..

- Can we build a system that automatically finds bugs?
  - We have just proved that building a perfect bug-finding system is impossible!
- We take various best-effort approaches for partial bug identification
  - Bounded model checking
  - Static analysis
  - Dynamic analysis
  - …

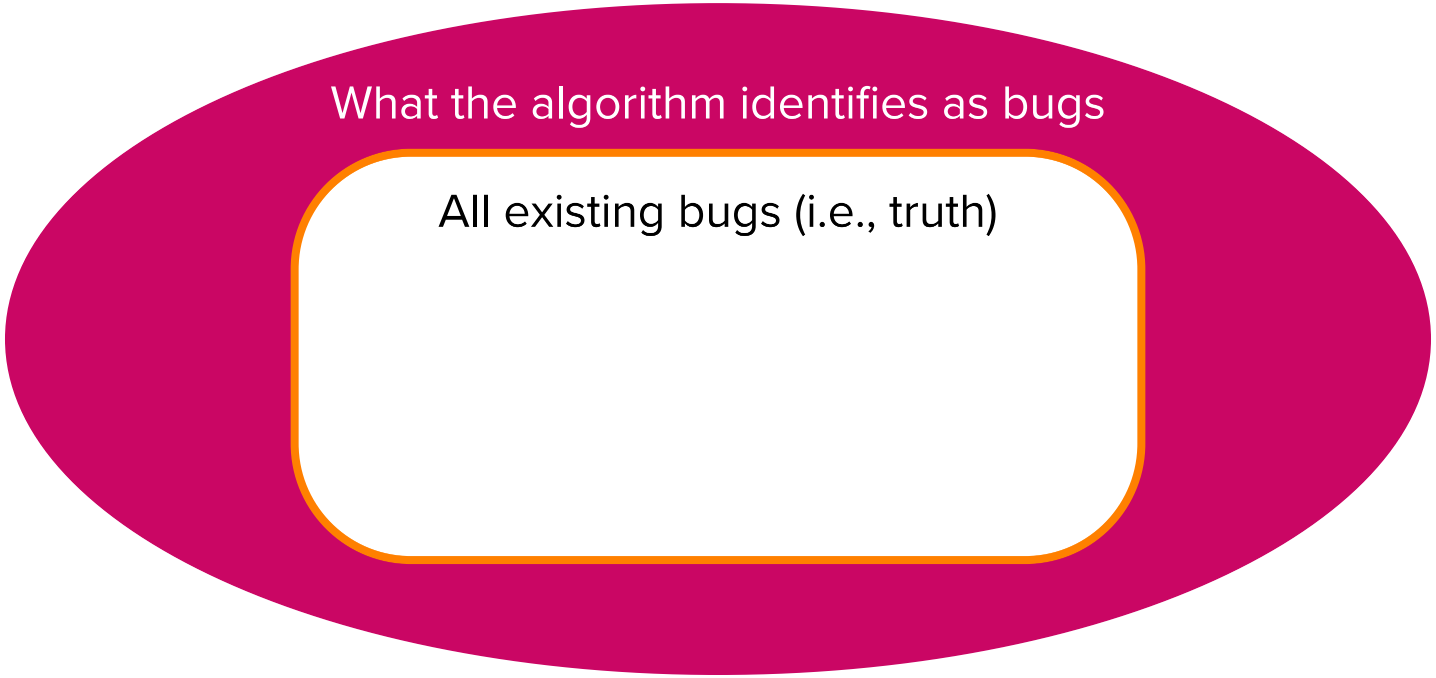
Definition of "partial"

- Soundness vs Completeness
  - An algorithm is sound if every result it produces is in fact true
    - If the algorithm says that X is a bug, then X is indeed a bug
    - Guarantees that there is no false positive (misclassifying a non-bug as bug)



Definition of “partial”

- Soundness vs Completeness
  - An algorithm is complete if it can derive all truths
    - If X is a bug, then the algorithm says X is a bug
    - Guarantees that there is no false negative (missing a bug)



Perfect analysis

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

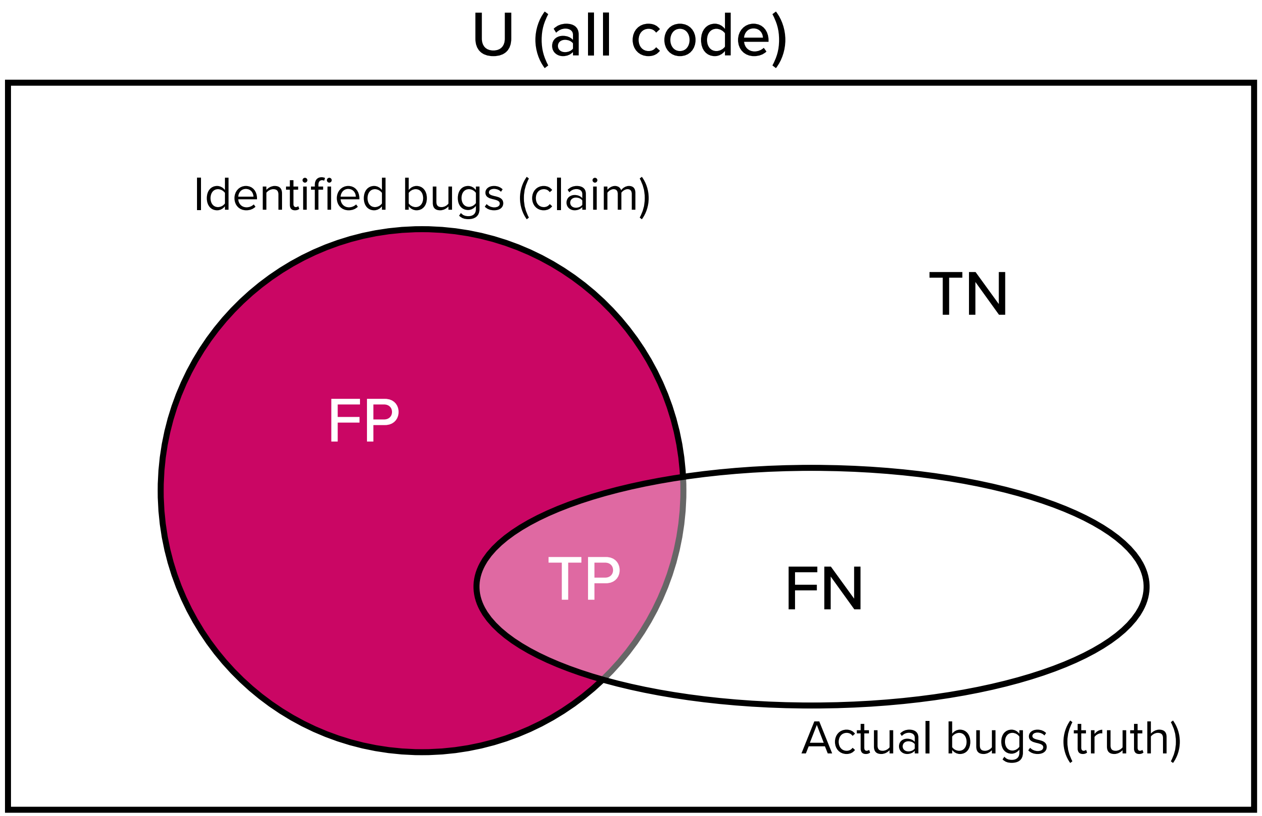
All existing bugs (i.e., truth)

=

What the 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:
  - Analysis that is performed without executing a program
  - Examples:
    - Decompilation
    - Pointer analysis
    - Symbolic execution (Next topic)
- Dynamic analysis:
  - Analysis that is performed during program execution
  - Examples:
    - Fuzzing (Today's topic)
    - Concolic execution

Fuzzing

Fuzzing

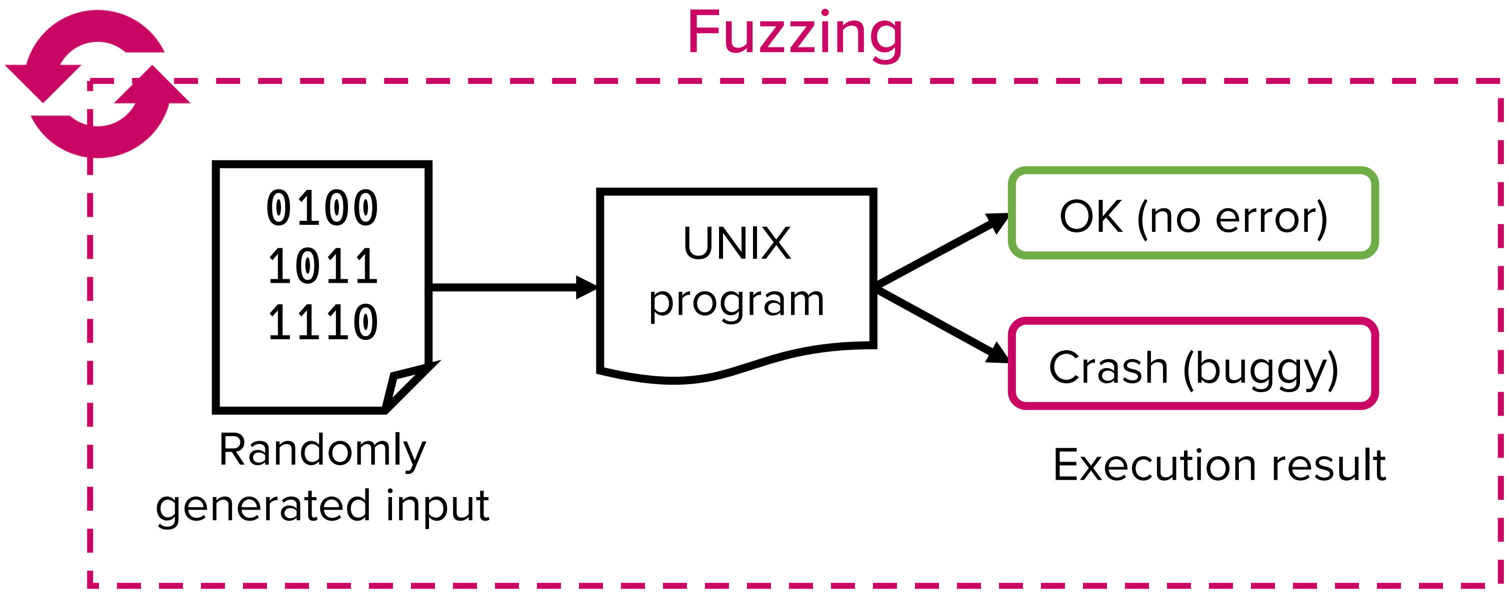
- Fuzzing (or fuzz-testing)
  - An automated software testing technique that involves providing invalid, unexpected, or random data as inputs to a program
  - During this process, the program is monitored for any anomalous behavior (crashes, hangs, memory leaks, …)
  - Goal is to find as many bugs (and vulnerabilities) as possible

History 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
  - The noise kept generating spurious characters on the line
  - Programs on the workstation kept crashing due to the junk characters
  - He coined the term “fuzz” from the experience

Early days of fuzzing

- 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
  - Will check the result at the end of today's lecture

target.c

```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);
```

```c
  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;
}
```

Experiment

- Let's put Miller's fuzzer to the test with a simple program
  - Will check the result at the end of today's lecture

fuzz.py

```
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
```

Interpretation of Miller's success

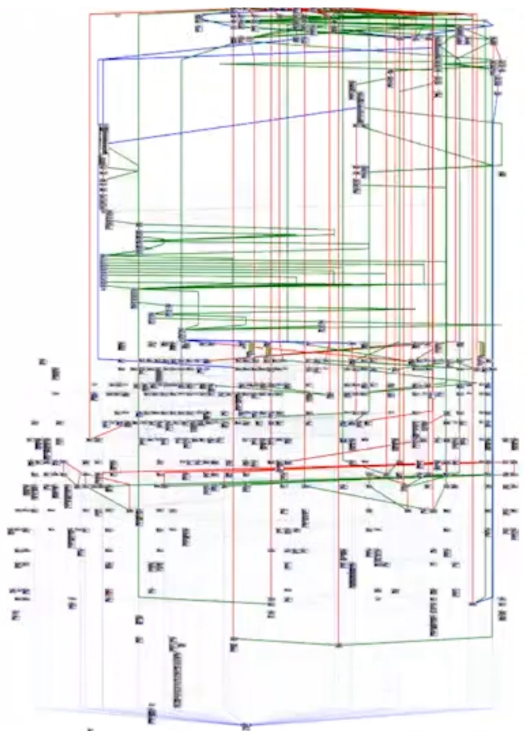
- Fuzzing is simple, yet effective
- Insight from the software bugs we covered
  - Buffer overflow, control flow hijacking, authentication bypass, malware, DoS, SQL injection, …

  → Attacks are initiated from (unsanitized) user inputs
  - Fuzzing is a way to "simulate" these user inputs

Used by many security practitioners

Fuzzing in modern times

- 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
- It is infeasible and inefficient to manually analyze such large projects
  - Imagine manually checking 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 and generation-based fuzzing

Blackbox to Greybox Fuzzing

Overview of Black, grey, and whitebox fuzzing

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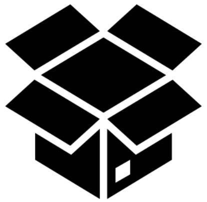
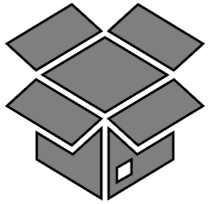
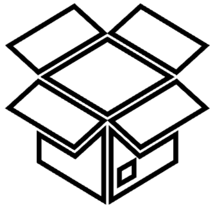


- Generates random inputs
- Fuzzer has no knowledge of the program internals
- The approach of Miller et al.
- Pros:
  - Extremely fast
  - Easy to use
  - Scalable
- Cons:
  - Poor effectiveness
  - Poor code coverage



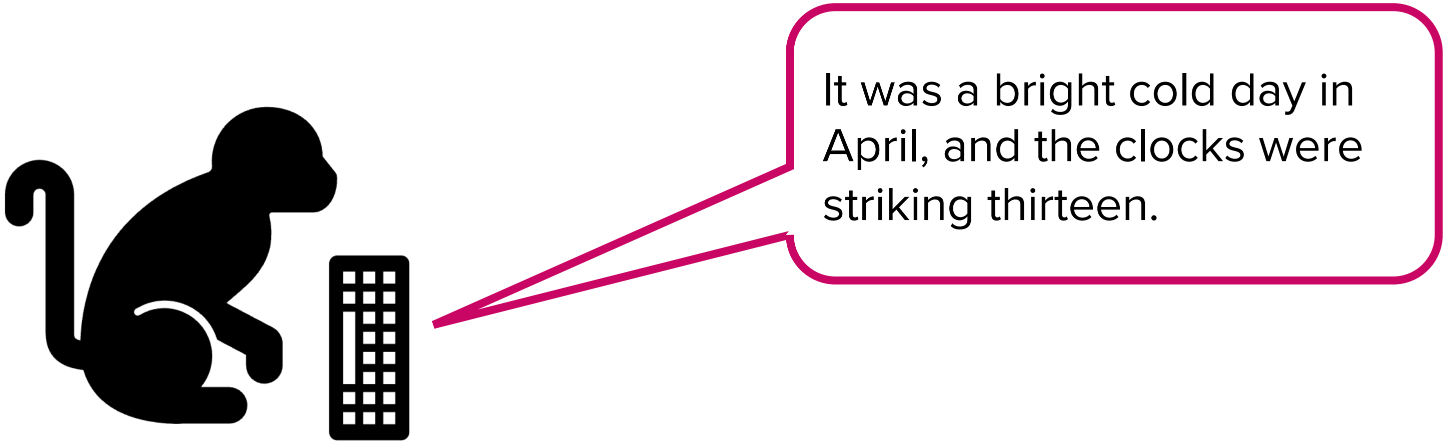
- Relies on “lightweight” instrumentation of the program under test
- Fuzzer has some knowledge of the program internals during fuzzing
  - Generates semi-random inputs based on the knowledge
- Pros: Best of both worlds
  - Scalable
  - Relatively fast
  - Decent code coverage



- Fuzzer has perfect knowledge of the program internals
- 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, finish a full sentence?

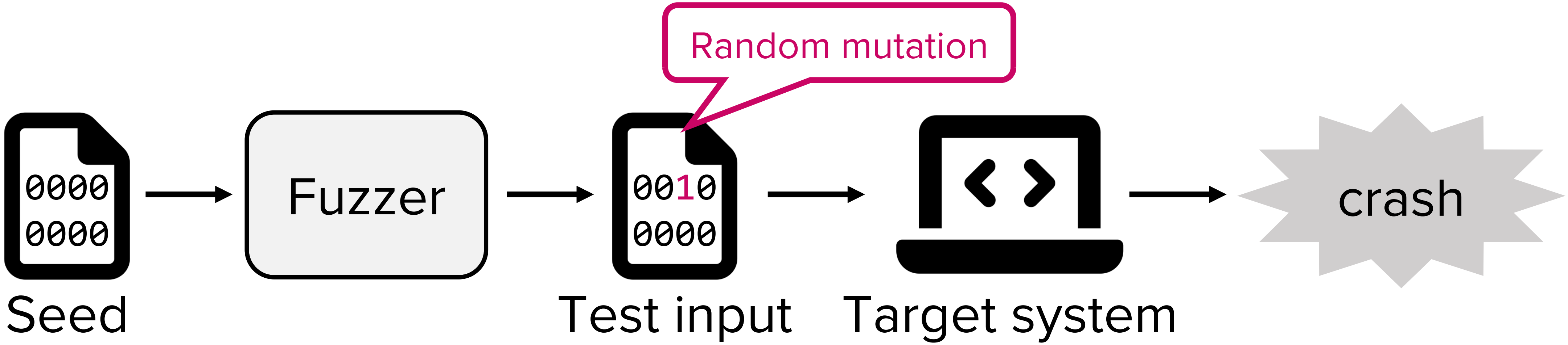


The possibility is non-zero; the monkey will “almost surely” type any given sentence

However, it will take a huge 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"
```

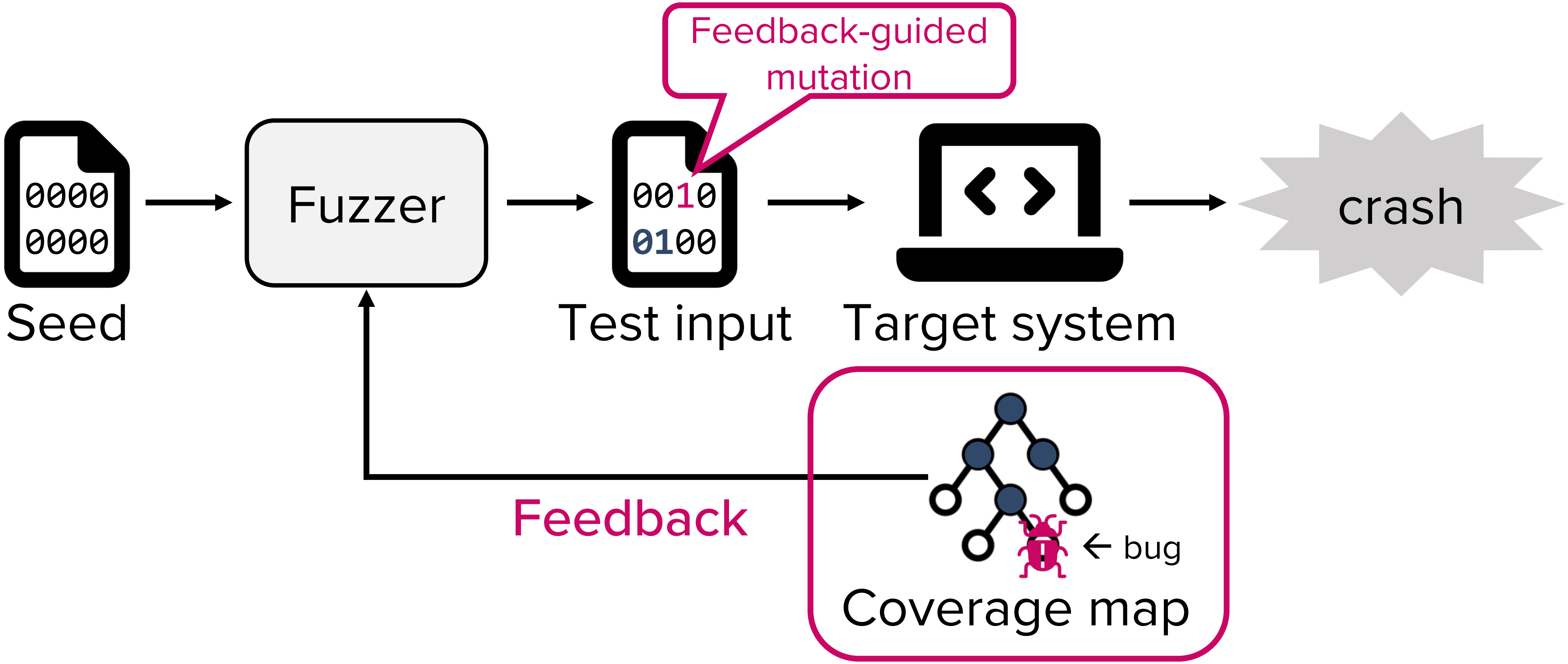
Test input

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

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

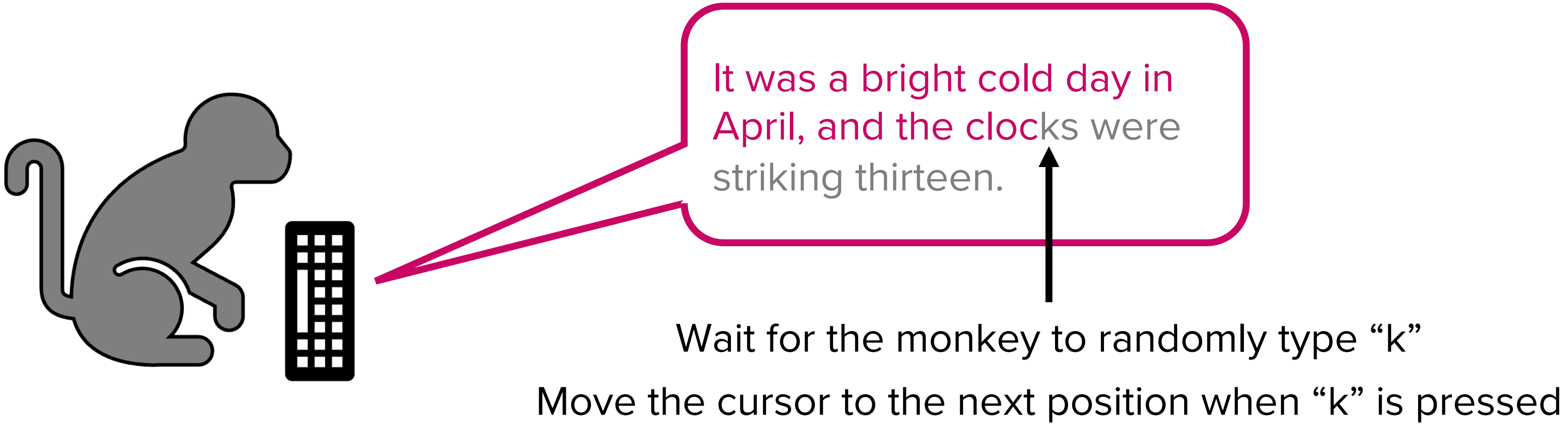
Recent breakthrough

- Greybox fuzzing with code coverage feedback



Breakdown of fuzzing efficiency

- A typing monkey problem (Greybox edition)
  - Keep the character that is correct
  - Restart typing from the next position



Breakdown of fuzzing efficiency

- A typing monkey problem (Greybox edition)
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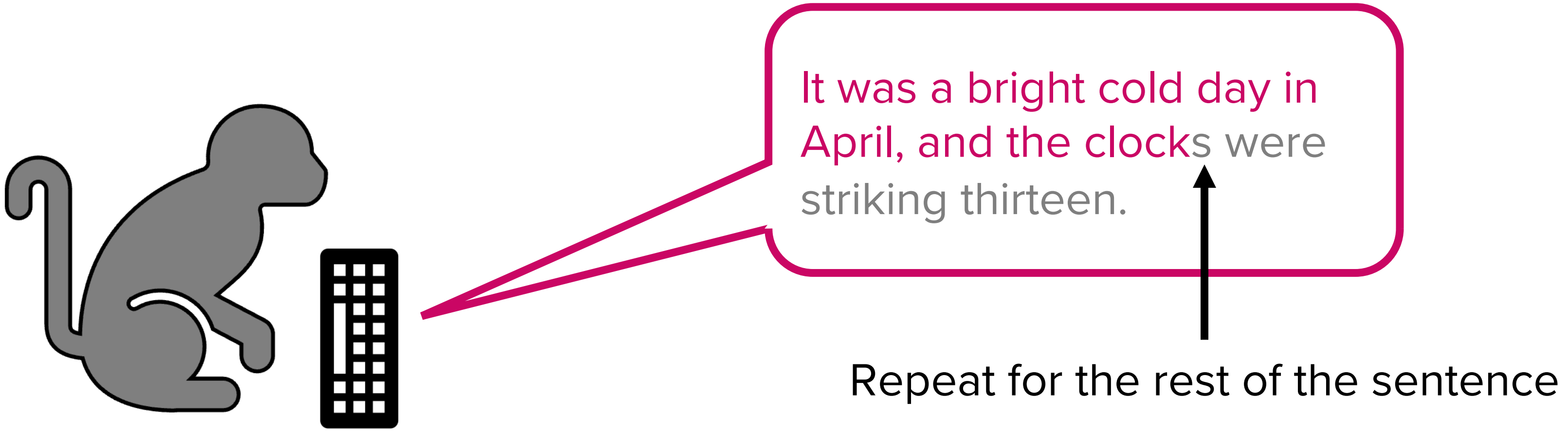

The possibility is dramatically increased

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

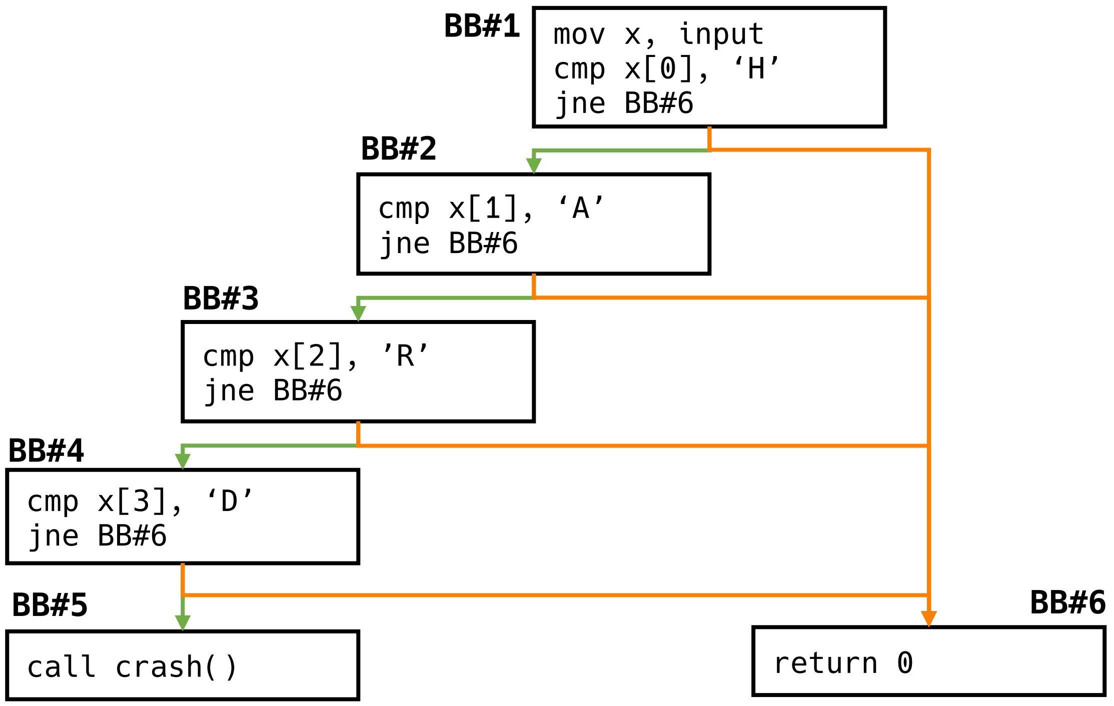
Select right position

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

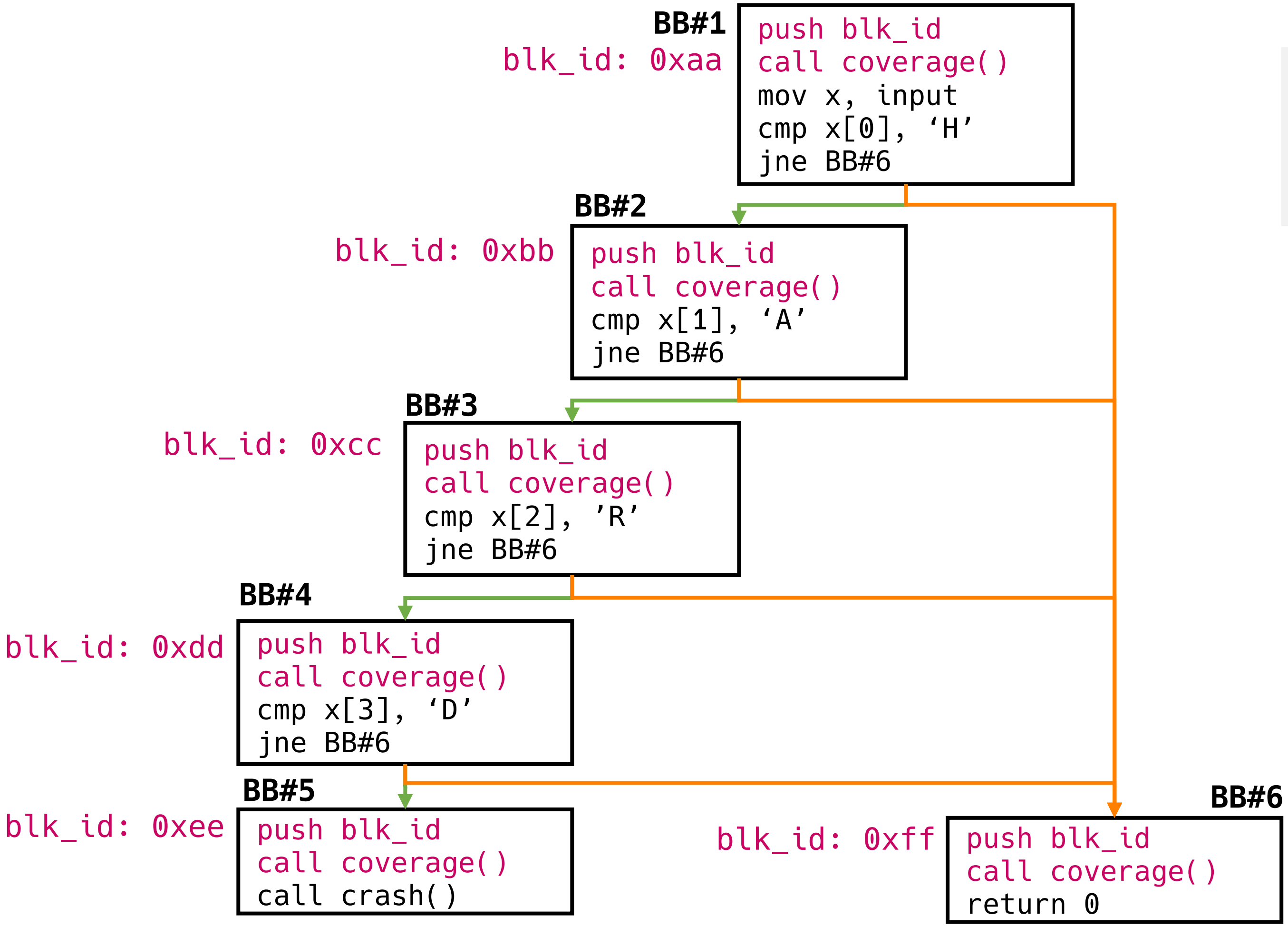
How to track code coverage?

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



How to track code coverage?

- Instrumentation for code coverage tracking




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

How to track code coverage?

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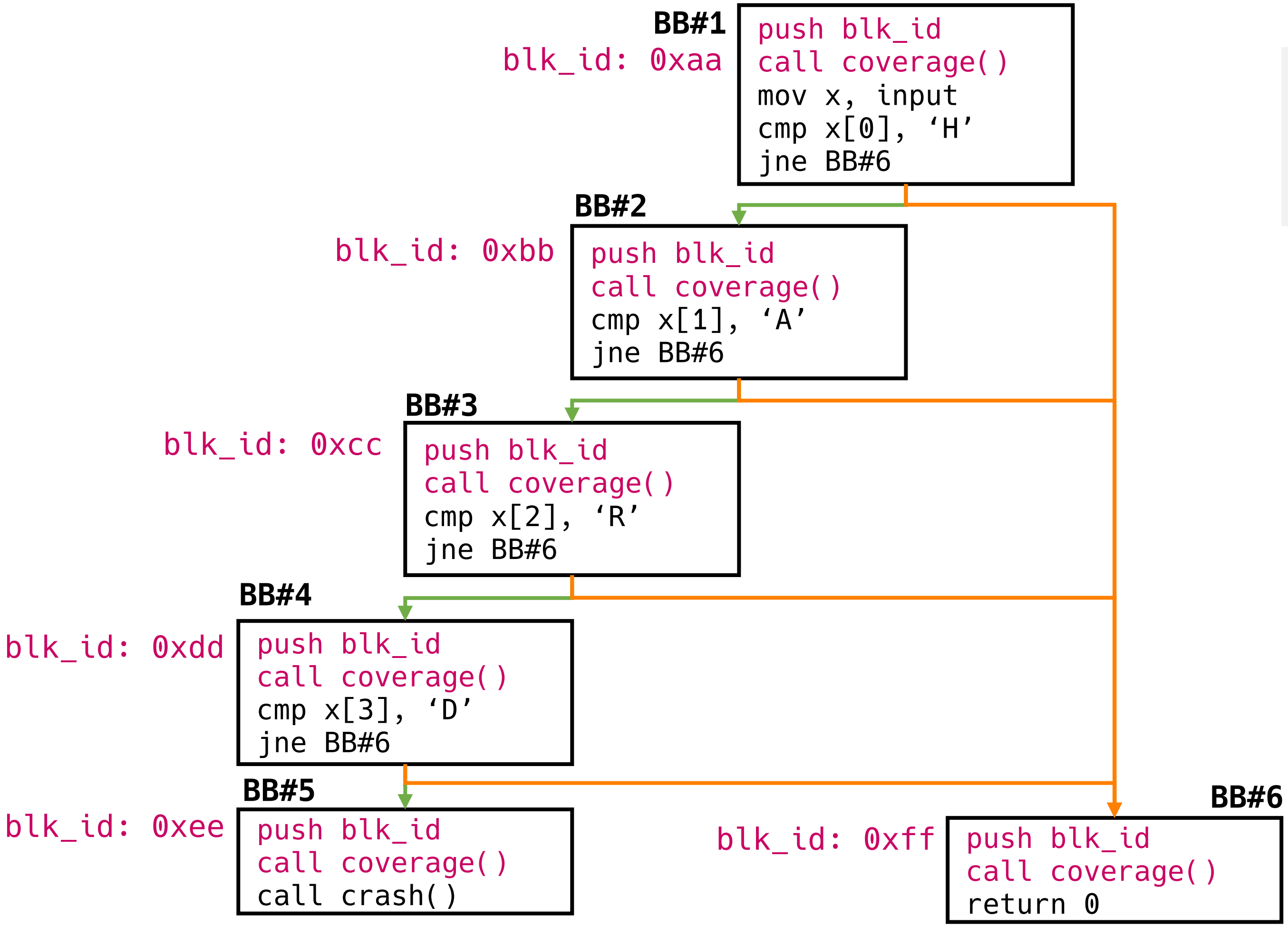
- Instrumentation for code coverage tracking




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

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

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

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

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

New coverage found!

Feedback-driven greybox fuzzing is effective

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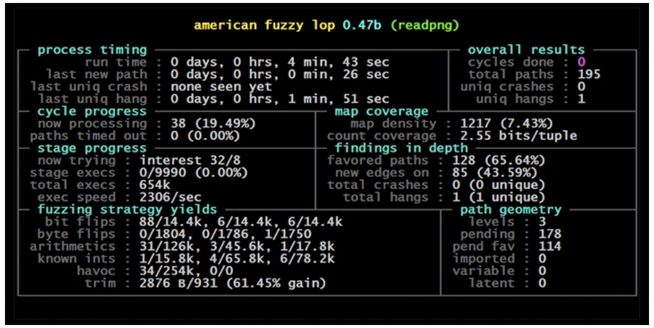
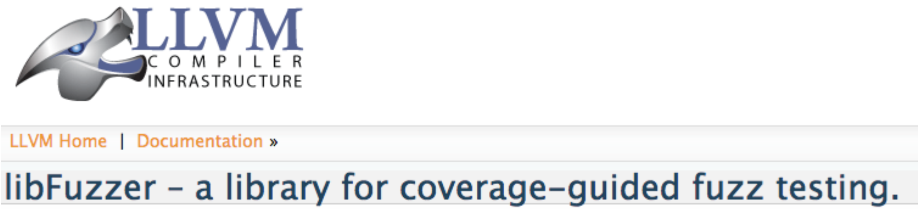


AFL



libFuzzer

OSS-Fuzz

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

Test Input Generation

Mutation- vs Generation-based fuzzing

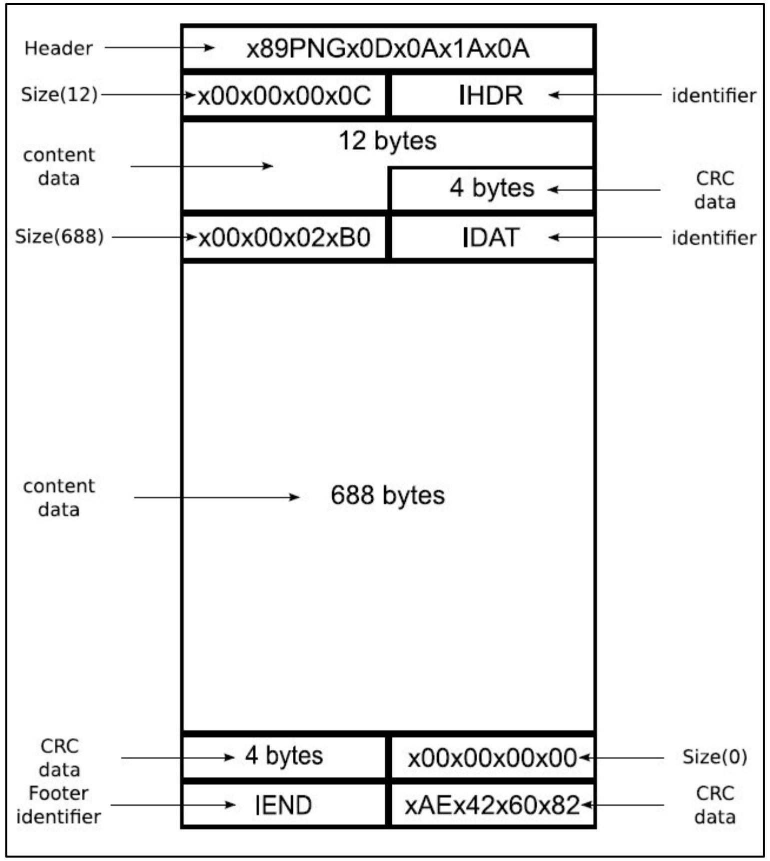
- Motivation: Randomly generated inputs are likely rejected by the program under test
  - e.g., When fuzzing a video player application, it is very unlikely that one generates a vaild mp4 file at random
- Two methods for better input generation
  - Mutation: Mutate a given seed to generate test inputs
    - Seed: A valid mp4 file
  - Generation: Generate test inputs from a 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

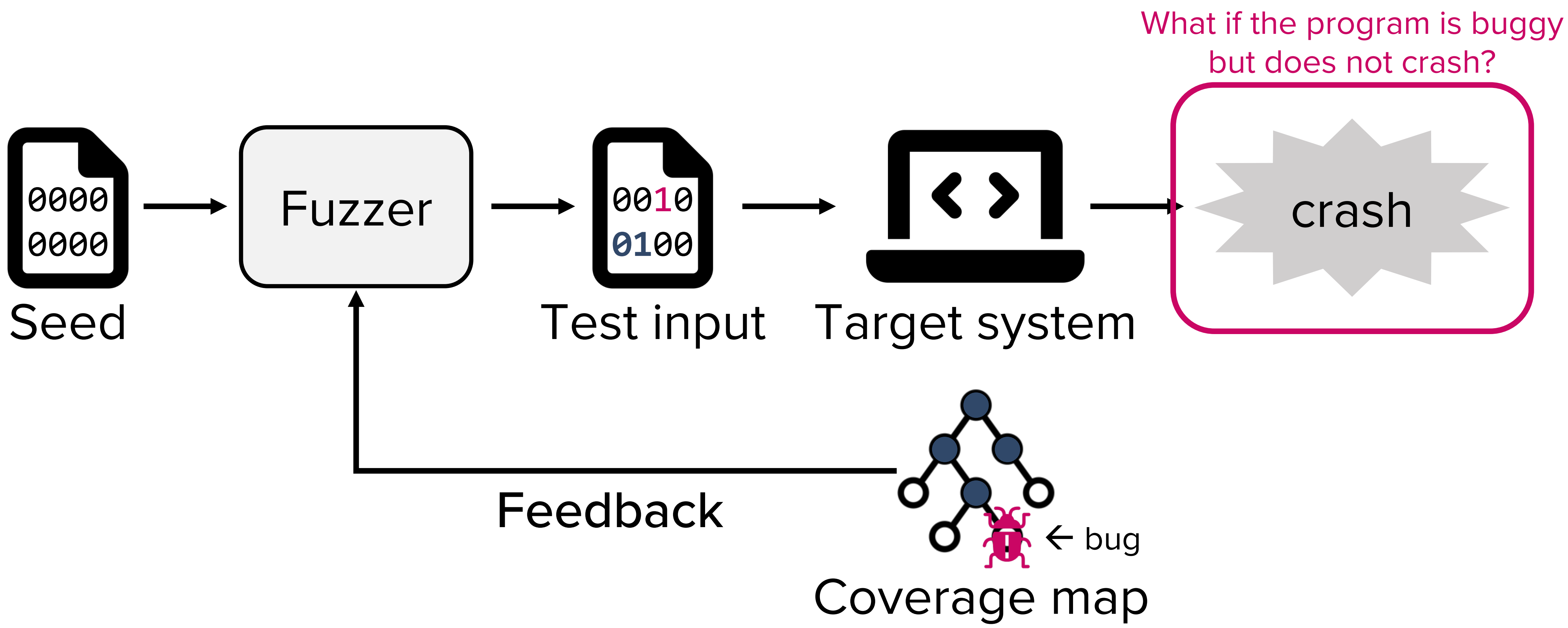
- Generate inputs that the program under test accepts
- A model describes the correct format
  - e.g., a grammar spcifying the input format
    - PNG input has header and size fields
    - The header field must have the “magic number” of PNG in order for the input to be accepted by the parser



PNG format

Bug Oracles

Mutation-based greybox fuzzing overview



A need for bug oracles

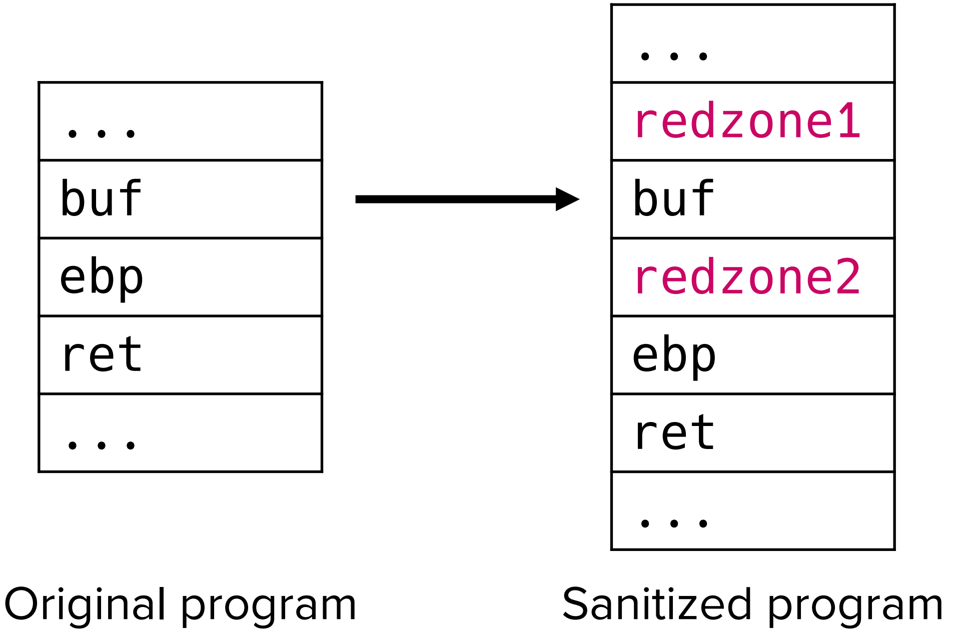
- What types of anomalous behavior do we want to find?
  - Crashes, but not all vulnerabilities lead to crashes (e.g., Lab 01)
  - Memory corruption: e.g., Use-After-Free (UAF) vulnerabilities
  - Hang: Program does not finish within a timeout period
  - Memory leaks, race conditions, specification violation, …
- 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

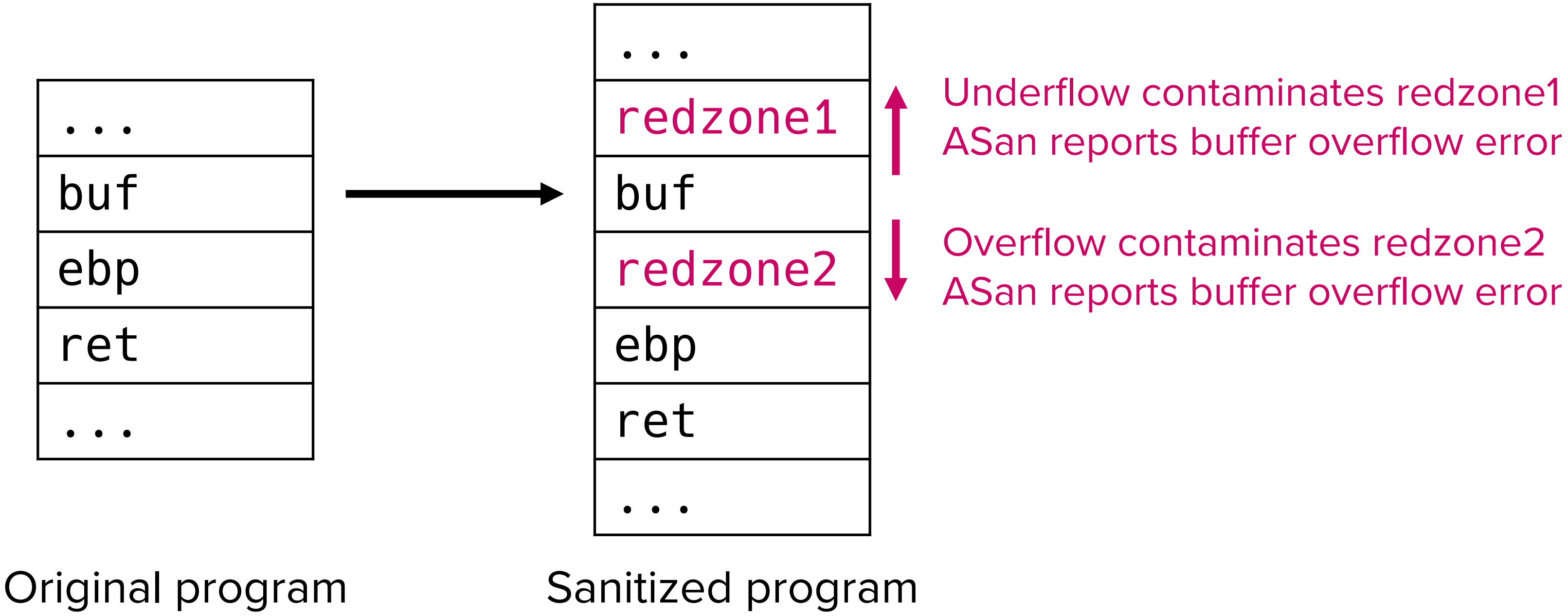
Address sanitizer

- Implemented as compiler module (clang, gcc)
  - Instruments all load and store instructions
  - Inserts redzones around stack and global variables



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

```
$ gcc obo.c -o obo
```

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

The bug is missed

Address sanitizer in action

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- With ASan

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

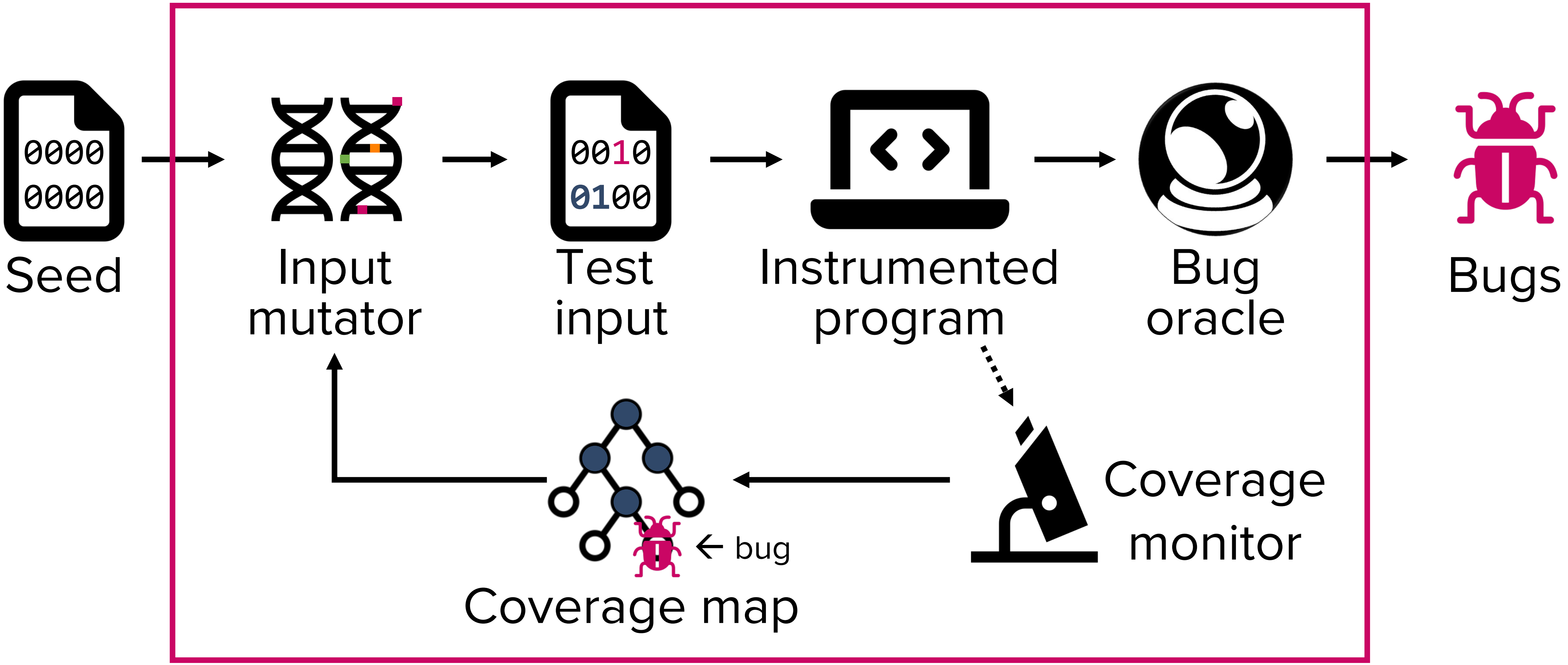
```
$ gcc obo.c -fsanitize=address -o obo_asan
```

```
$ ./obo_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/obo_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/obo_asan+0x1124)

0x55aceaed5030 is located 4 bytes to the right of global variable 'numbers' defined in 'obo.c:8:5' (0x55aceaed5020)
of size 12
SUMMARY: AddressSanitizer: global-buffer-overflow (/home/seulbae/test/asan/obo_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

A coverage-based mutational greybox fuzzer



Fuzzing results?

- How many trials were required to find the bug with dumb fuzzing?
  - Dumb: Random mutation, no coverage feedback
  - Theoretically: Random 4 bytes being identical to “\xde\xad\xbe\xef”
    → $2^{32} \approx 4.2$ billion trials
  - Experimentally:

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
$ echo -ne “\xff\xff\xff\xff” > in/seed
```

  - Run fuzzer

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

Questions

- Is fuzzing sound?
- Is fuzzing complete?

Questions?