Introduction to Information Security

12. Dynamic Analysis and Fuzzing

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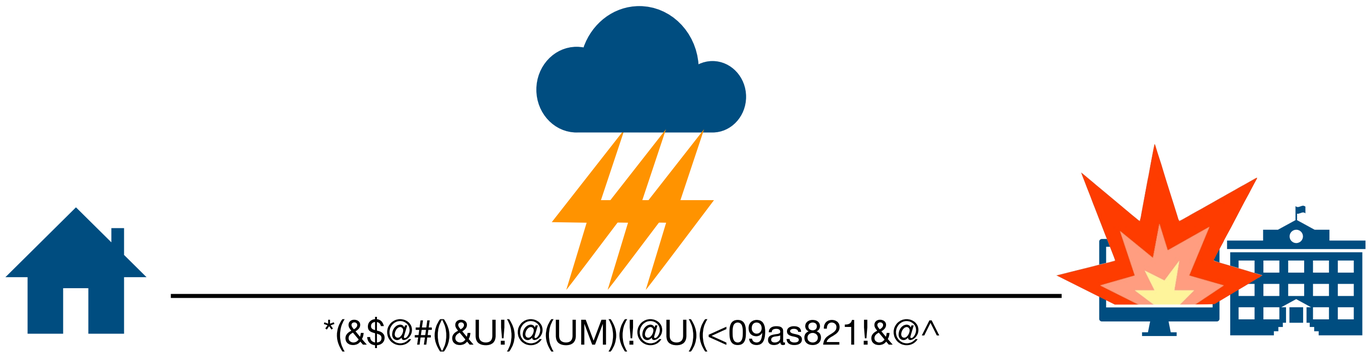
Testing

- Check a set of **finite executions**
  - e.g., random testing (a.k.a fuzzing)
- In general, **unsound yet complete**
  - Unsound: cannot prove the absence of errors
  - Complete: produce counterexamples (i.e., erroneous inputs)
- Example: Google's oss-fuzz (https://github.com/google/oss-fuzz)

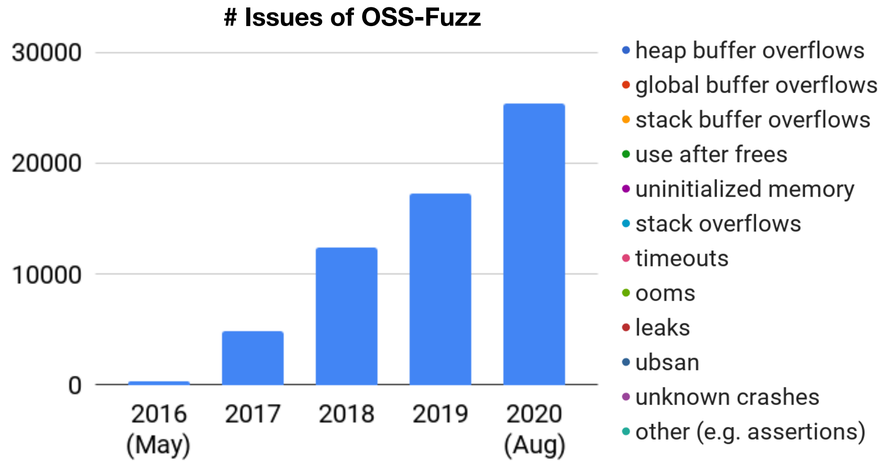
Fuzzing

- Initially, developed by Barton Miller in 1988
- Thunderstorm → noise on a network line → random characters → crash
- “Can we mimic the thunder-generated noise to check robustness?”

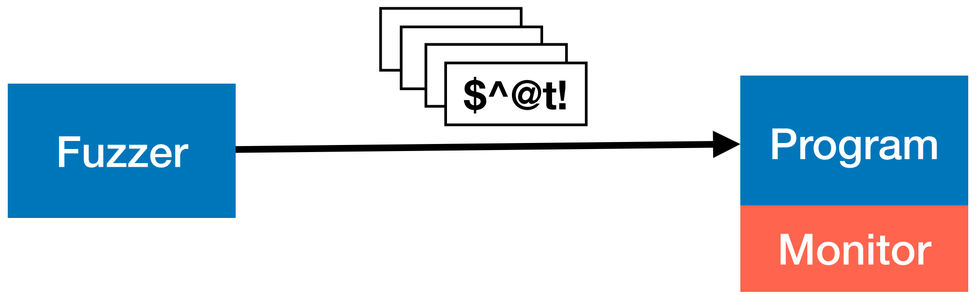


Success Stories

- Miller et al. found many crashes in UNIX utilities
- AFL (American Fuzzy Lop) has found a lot of security vulnerabilities
  - See https://lcamtuf.coredump.cx/afl/
- Google's OSS-Fuzz: continuous fuzzing platform for open source SW



Fuzzing Overview



What is going on inside the program?

Runtime Monitoring

- Observe program executions
  - Explicitly trap the execution if an error happens
  - Give more detailed information (e.g., bug type, coverage, location)
- Important: achieving low overhead at runtime
- How?
  - If source code available: instrumentation via compilation(e.g., LLVM’s sanitizers)
  - If no source code available: binary rewriting (e.g., Pintool) or emulation (e.g., QEMU)

A Simple Fuzzing

- (Generate random inputs; run a given program w/ the inputs; see if it crashes)+
- Without considering the target program's detailed behavior
  - So called, **blackbox** fuzzing
- Initial success: a command-line fuzzer for UNIX utilities*
- The infinite monkey theorem actually works!

"A monkey randomly hitting keys for an infinite amount of time will produce any given text, such as Shakespeare's Hamlet"

*Barton Miller, et al., An Empirical Study of the Reliability of UNIX Utilities, *CACM*, 1990

Blackbox vs Whitebox

- Blackbox: generate inputs **regardless** of program's logic and structure
  - Easy to implement and low cost
  - Hard to explore deeper parts

```
x = input();
if (x == 482716115)
  bug();
```

- Whitebox: generate inputs by **observing** program's logic and structure
  - Can explore deeper parts
  - Require constraint solving (high overhead)

```
x = input();
y = input();
if (x < y)
  if (x^2 > 3)
    bug();
```

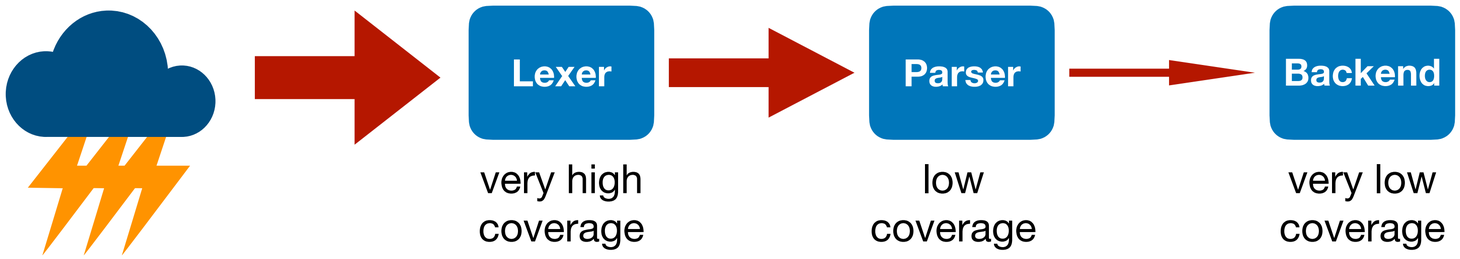
```
a = input();
b = input();
c = input();
n = input();

if (n > 2)
  if (a^n + b^n == c^n)
    bug();
```

Examples

- Monkey: a random testing tool for Android apps
  - Randomly generate streams of events such as clicks, touches, etc
  - A part of Android Studio
- Cuzz: a random testing tool for finding concurrency bugs
  - Randomly generate thread schedules
  - A part of Microsoft Application Verifier

Problems

- Very low test coverage!
- Random inputs are often filtered out in earlier stages of programs
  - E.g., “Invalid syntax”
- What are the chances of getting valid URL from random strings?
  - URL format: `scheme://netloc/path?query#fragment`



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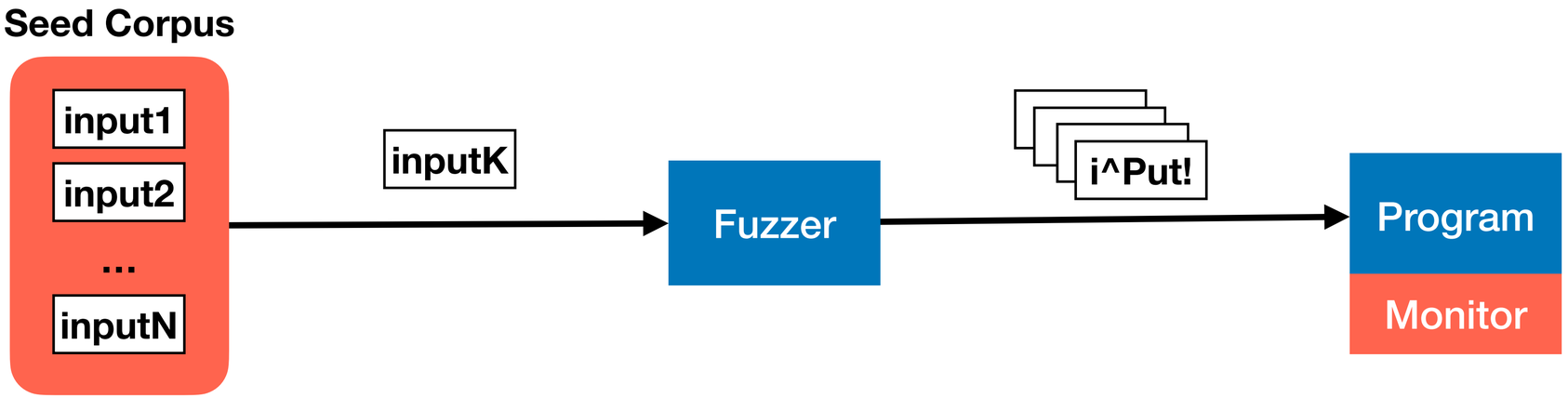


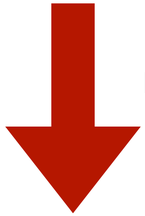
Mutation-based Fuzzing

- Idea: generate new inputs by **mutating** existing valid inputs (seeds)
  - valid inputs usually reach deeper parts
- Mutation operators: random flips or heuristics
- Success story: AFL (2013)
  - See this blog post by the author of AFL*

*https://lcamtuf.blogspot.com/2014/08/binary-fuzzing-strategies-what-works.html

Example: Mutating URLs

Seed input: http://www.google.com/search?q=fuzzing



randomly insert/delete/flip characters

0 mutations: http://www.google.com/search?q=fuzzing
5 mutations: http:/L/www.googlej.com/seaRchq=fuz:ing
10 mutations: http:/L/www.ggoWglej.com/seaRchqfu:in
15 mutations: http:/L/wwggoWglej.com/seaR3hqf,u:in
20 mutations: htt://wwggoVgle"j.som/seaR3hqf,u:in
25 mutations: htt://fwggoVgle"j.som/eaRd3hqf,u^:in
30 mutations: htv://>fwggoVgle"j.qom/ea0Rd3hqf,u^:i
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*https://www.fuzzingbook.org/html/MutationFuzzer.html

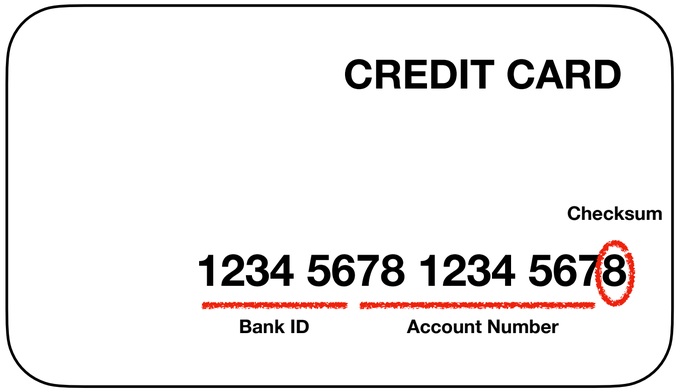
Example Mutation Operators

- **Random bit-flipping**: randomly flip bits with a certain probability
- **Arithmetic mutation**: perform simple arithmetic on a value (e.g., x + r)
- **Block-based mutation**: insert/delete/replace/permute/resize a subpart of an input
- **Dictionary-based mutation**: use a set of pre-defined values for mutation such as {0, -1, 1} or {“%s”, “%x”}

*Manes et al., The Art, Science, and Engineering of Fuzzing: A Survey, TSE, 2019

Problems

- Limited by seed inputs
- Random mutations often violate complicated syntactic or semantics rules
  - E.g., XML, Javascript, magic number, checksum



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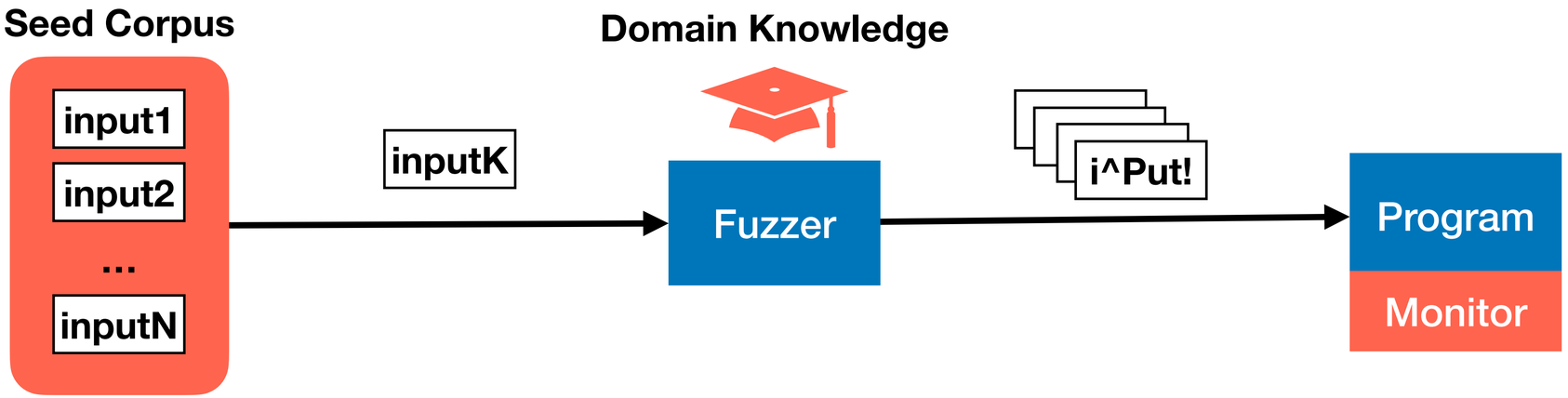


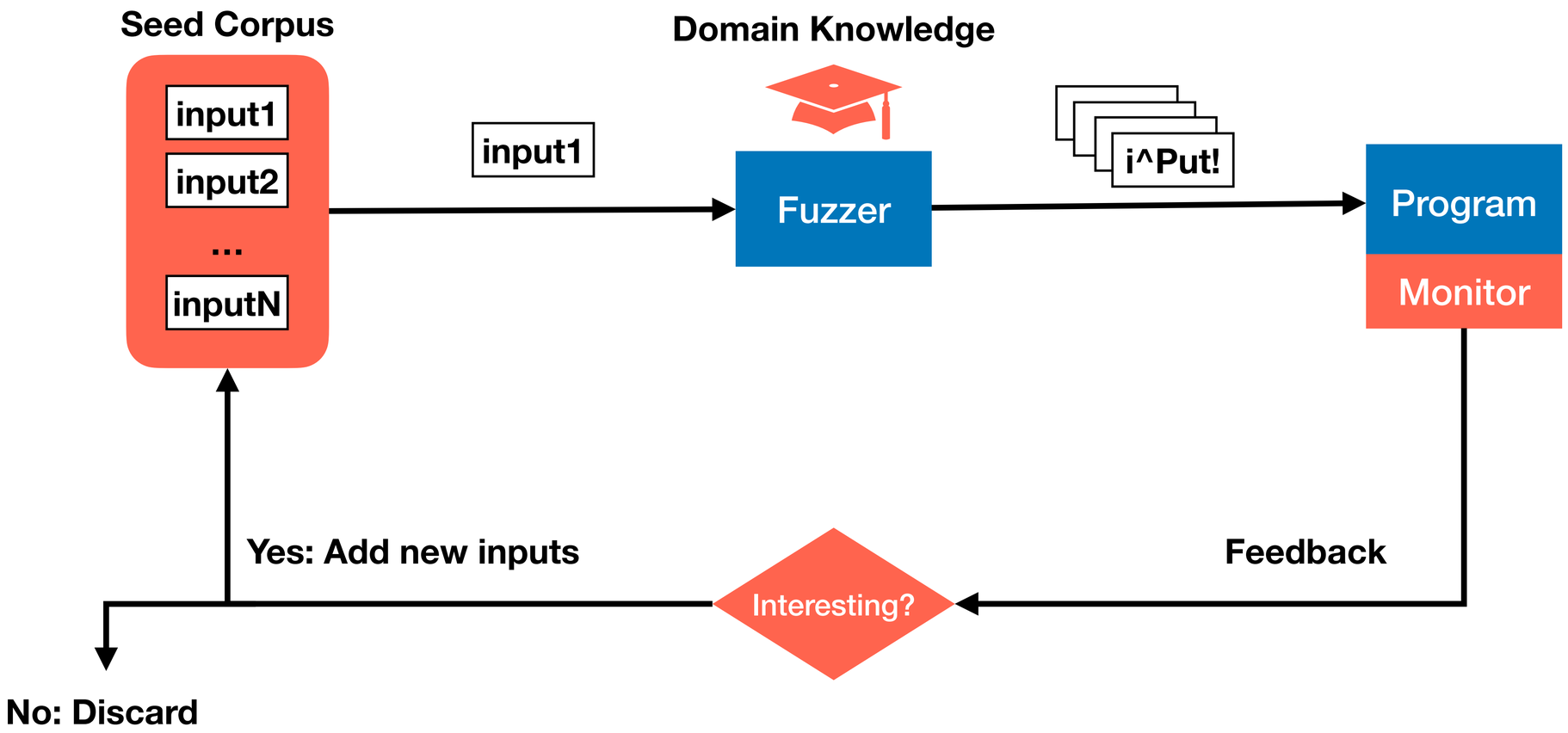
Generation-based Fuzzing

- Generate inputs based on a **given model**
  - manually defined or automatically inferred
- Examples:
  - Kernel APIs: system call templates (i.e., function signatures)
  - Formatted data: DOM objects, PNG, MP3, etc
  - Programs: Javascript, PHP, C, etc
  - Network protocols: TLS, NFC, etc

Still in the Dark

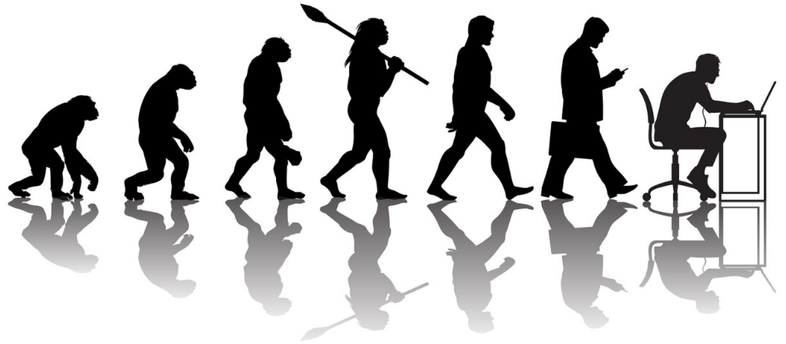
- How much fuzzing is enough?
- How to evaluate fuzzer's performance?
  - Are we going in the right direction?
  - Or stuck at some point?
- Which mutant is better than others?
  - Does it explore new execution paths?
  - Or revisit redundant paths?

Fuzzing Overview



Coverage-guided Fuzzing

- Fuzzing as a **genetic algorithm**
  - Chromosome population: seed corpus
  - Genetic mutation: mutation
  - Fitness function: coverage
- Key idea: keep mutants that increase **code coverage** for future mutations
  - So-called **grey-box** fuzzing
  - E.g., AFL, LLVM's libFuzzer



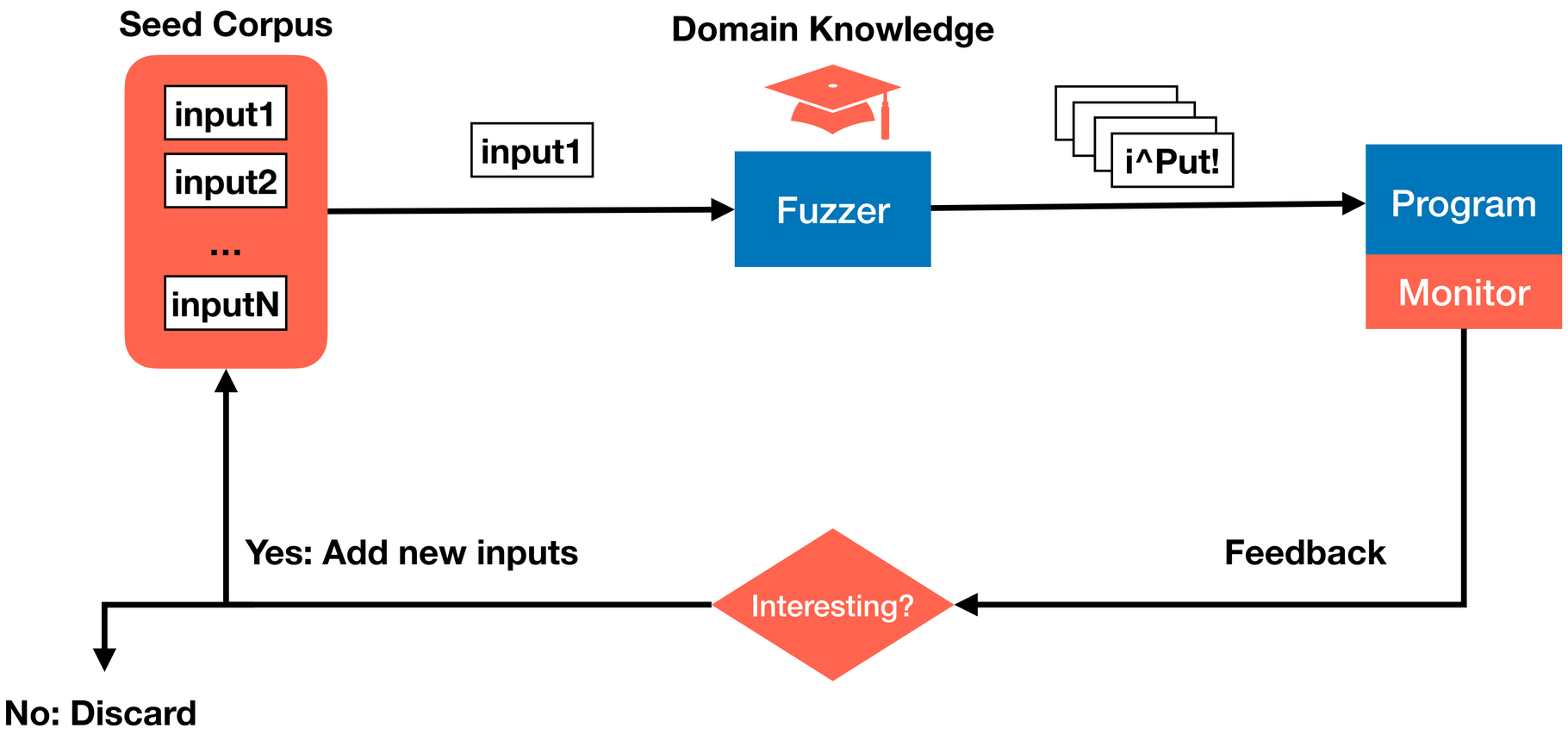
```
arr = input();
if (arr[0] > 0) {
  if (arr[1] > 10) {
    if (arr[2] > 100) {
      bug();
    }
  }
}
```

Code Coverage

- A metric that determines how much code has been executed
- Obtained from the runtime monitor
  - E.g., LLVM's SanitizerCoverage, gcov, etc
- Many criteria: line/stmt coverage, branch coverage, path coverage, etc
- Caveat: 100% coverage does not mean exhausted exploration

```
// x : -1, 1
x = inputs();
if (x < 0) {
  skip;
} else {
  skip;
}
assert(x != 0);
```

More Research Questions



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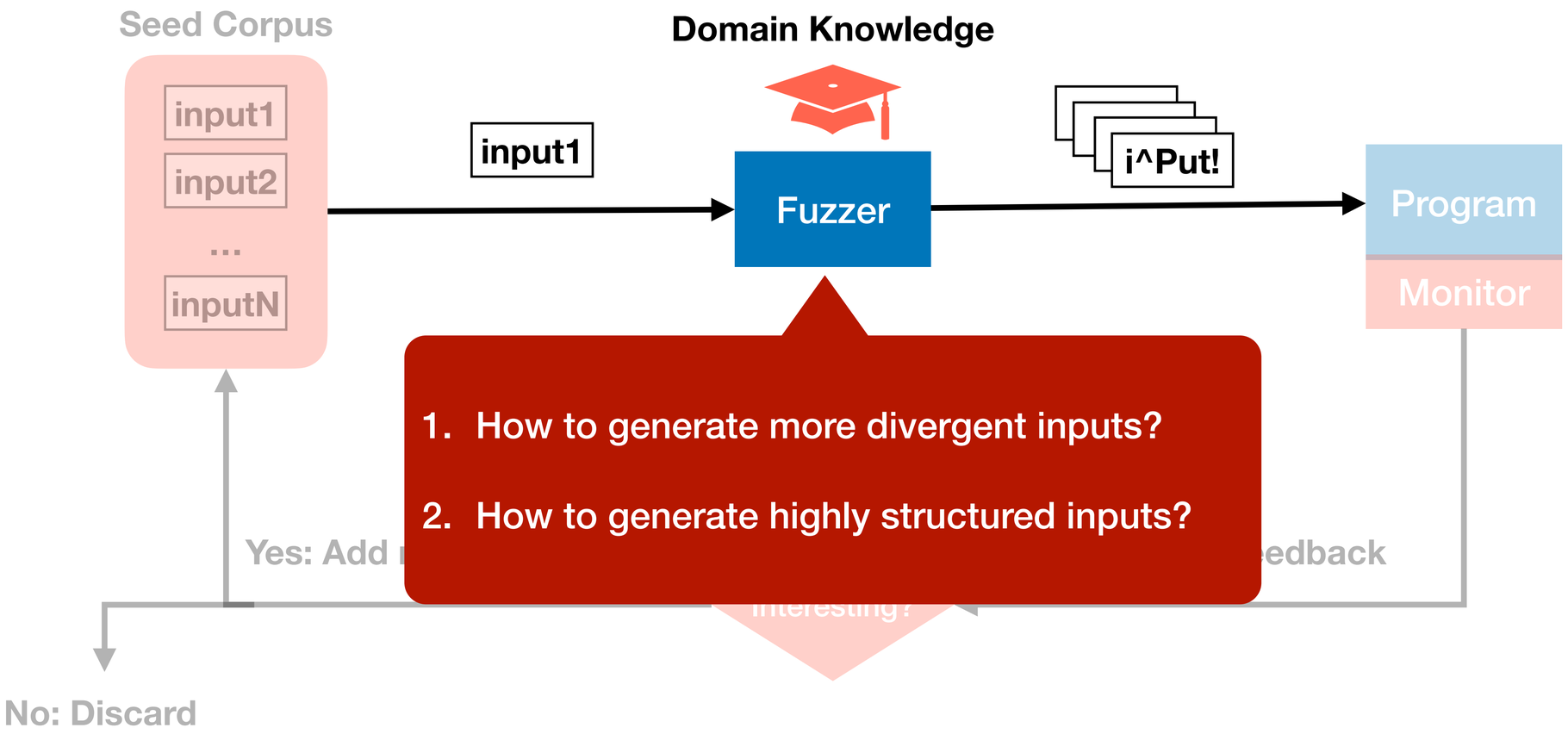

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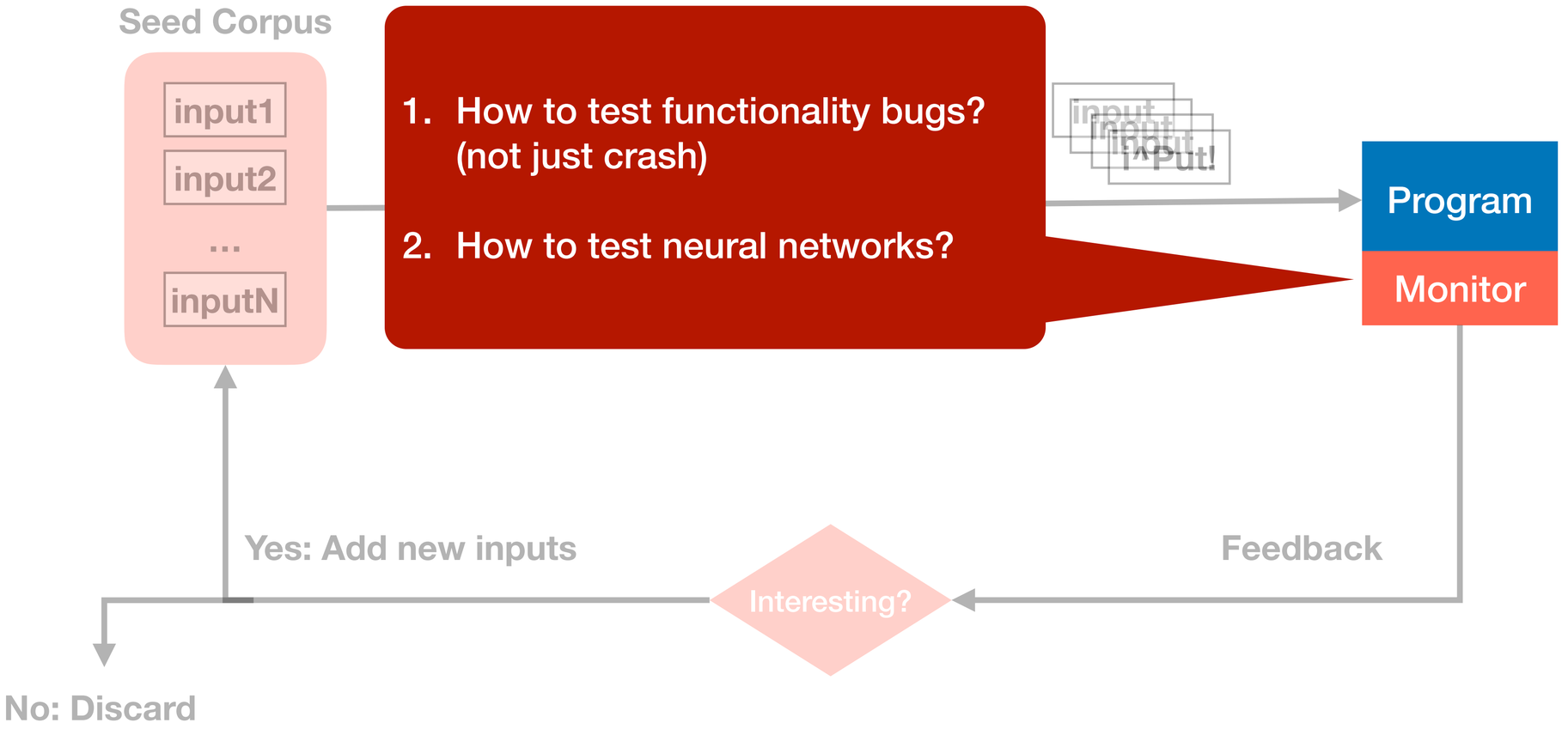

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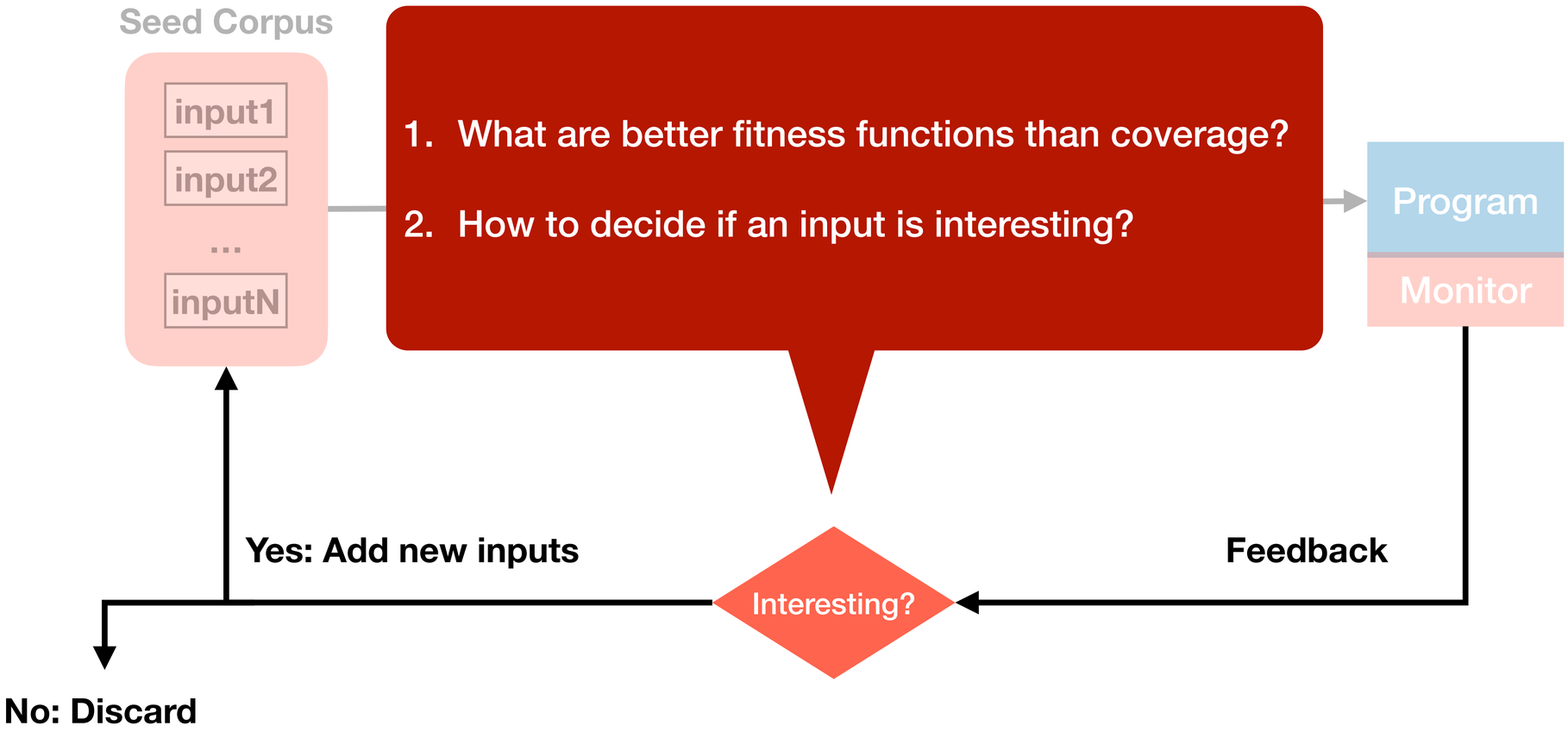

Summary

- Fuzzing: efficient and effective testing technique
  - Input generation: mutation-based, generation-based
  - Feedback: blackbox, greybox, whitebox
- Complete but unsound with respect to program correctness
- Challenges
  - Efficiency (e.g., higher coverage)
  - Expressiveness (e.g., functionality errors)
  - Etc