IS893: Advanced Software Security

3. Fuzzing

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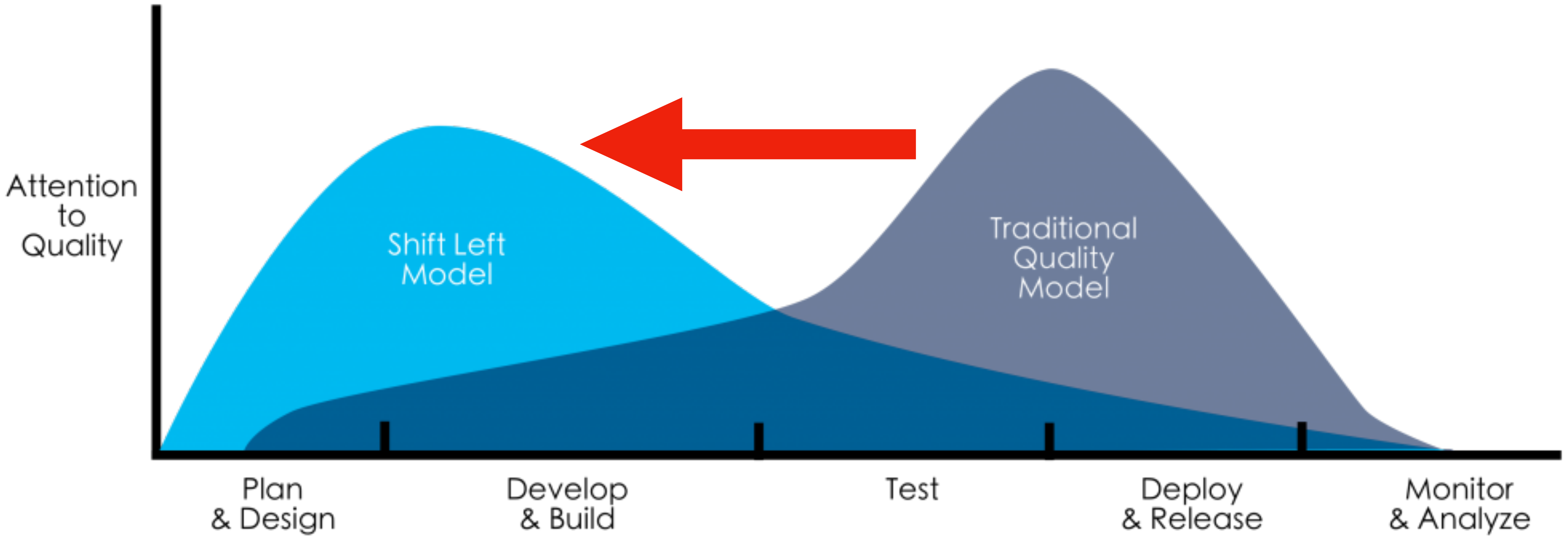
Discovering Software Errors

- The first step of SW security
- Key issue: how to detect SW errors as early as possible?

- IBM Systems Sciences Institute, 2015



A Hard Limit: Undecidability

Theorem (Rice's theorem). Any non-trivial semantic properties are undecidable.

- Non-trivial property: worth the effort of designing a program analyzer for
  - trivial: true or false for all programs
- Undecidable? If decidable, it can solves the Halting problem
  - An analyzer **A** for a property: "This program always prints 1 and finishes"
  - Given a program **P**, generate "**P**; print 1;"
  - **A** says "Yes": **P** halts, **A** says "No": **P** does not halt

Toward Computability

Undecidable

⇒ Automatic, terminating, and exact reasoning is impossible

⇒ If we give up one of them, it is computable!

- **Manual** rather than **automatic**: assisted proving
    - require expertise and manual effort
- **Possibly nonterminating** rather than **terminating**: model checking, testing
    - require stopping mechanisms such as timeout
- **Approximate** rather than **exact**: static analysis
    - report spurious results

Soundness and Completeness

- Given a semantic property $\mathscr{P}$, and an analysis tool **A**
- If **A** were perfectly accurate,

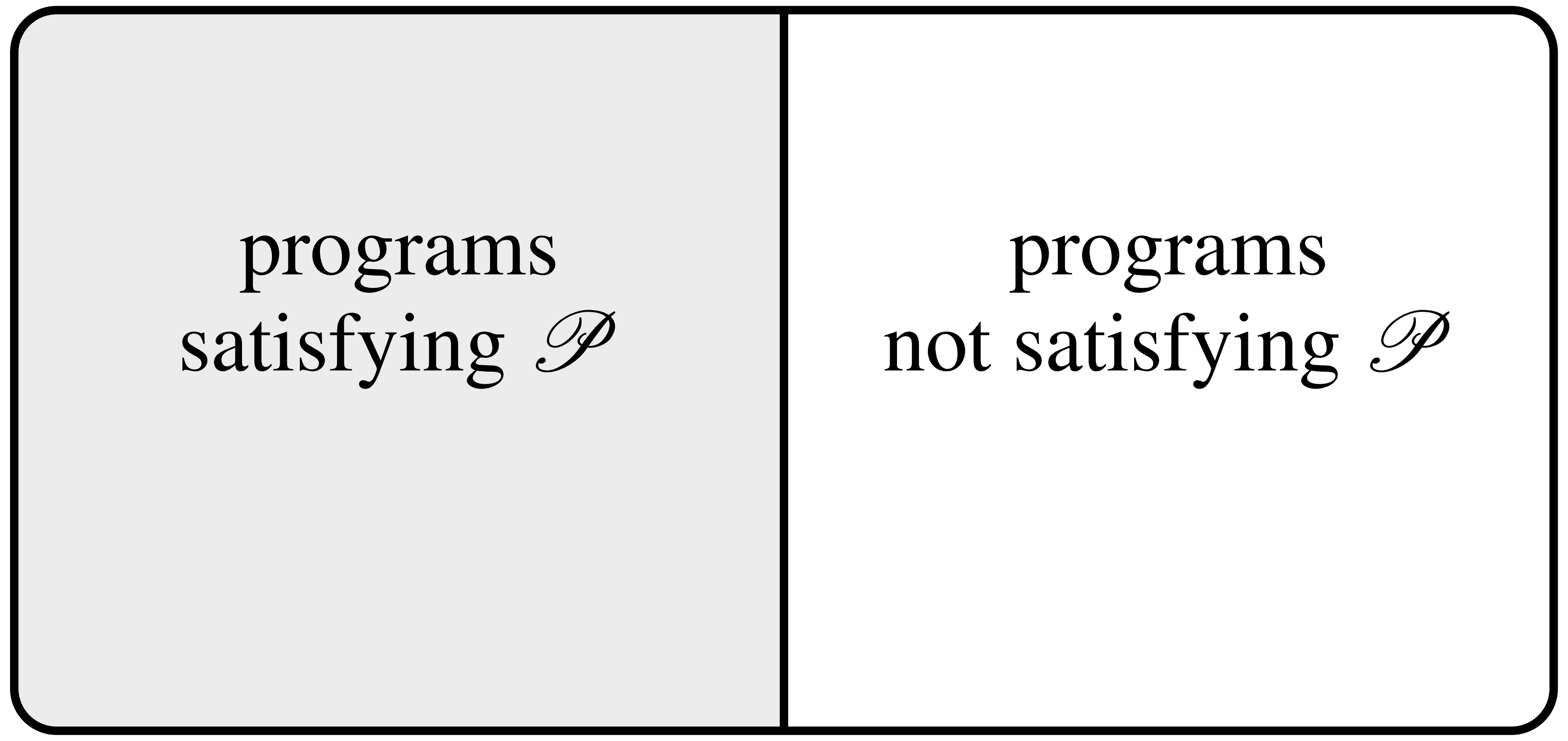
$$\text{For all program p, } \mathbf{A}(\text{p}) = \mathbf{true} \iff \text{p satisfies } \mathscr{P}$$

which consists of

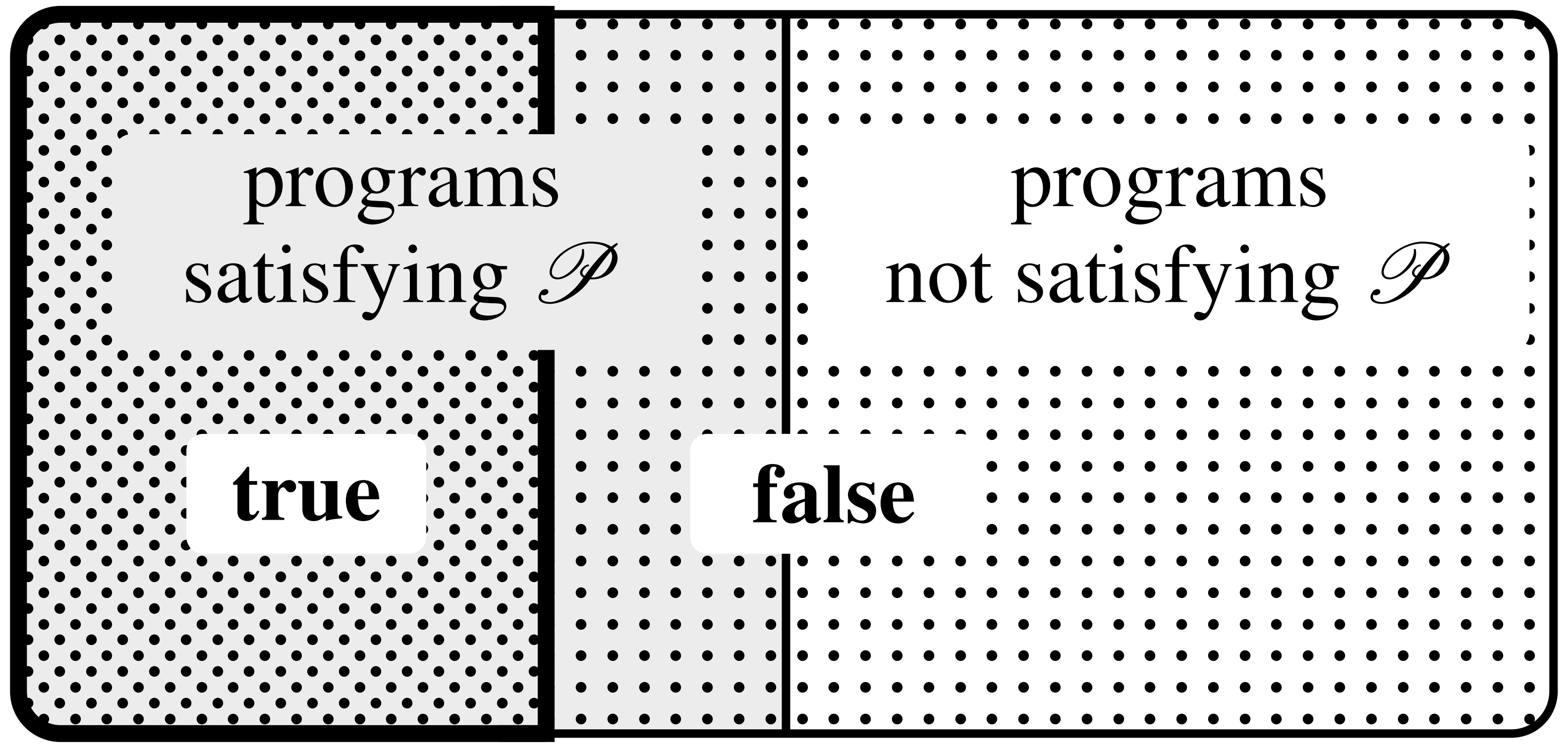
$$\text{For all program p, } \mathbf{A}(\text{p}) = \mathbf{true} \Rightarrow \text{p satisfies } \mathscr{P} \qquad \textbf{(soundness)}$$

$$\text{For all program p, } \mathbf{A}(\text{p}) = \mathbf{true} \Leftarrow \text{p satisfies } \mathscr{P} \qquad \textbf{(completeness)}$$

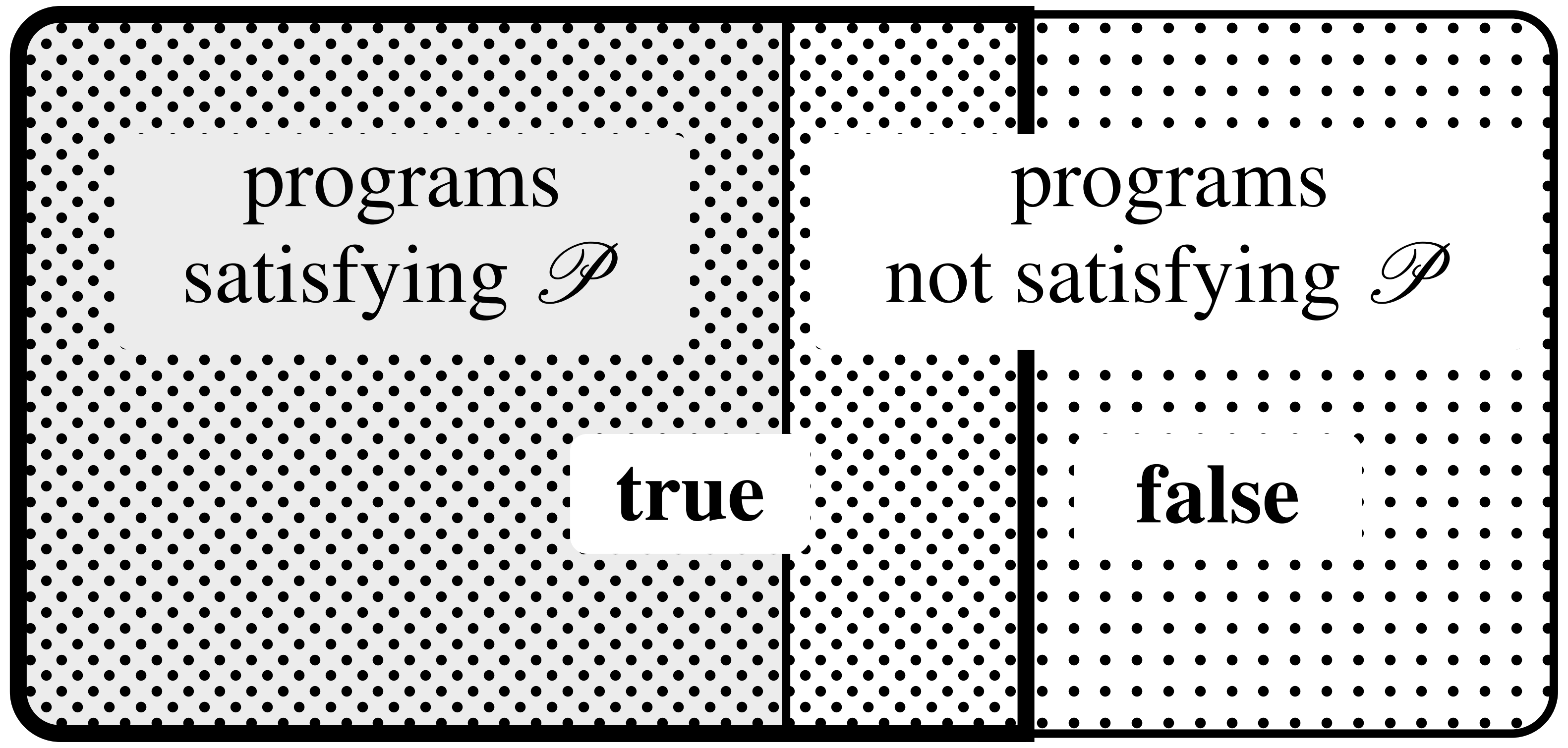
Soundness and Completeness



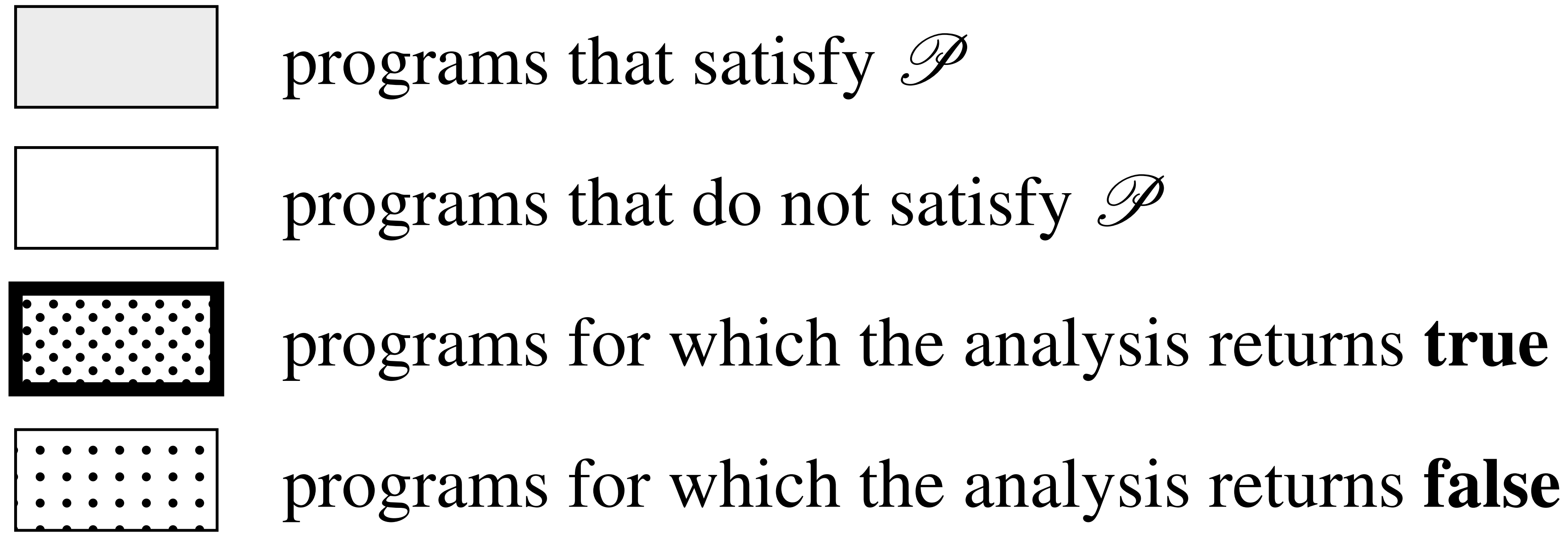
(a) Programs



(b) Sound, incomplete analysis



(c) Unsound, complete analysis



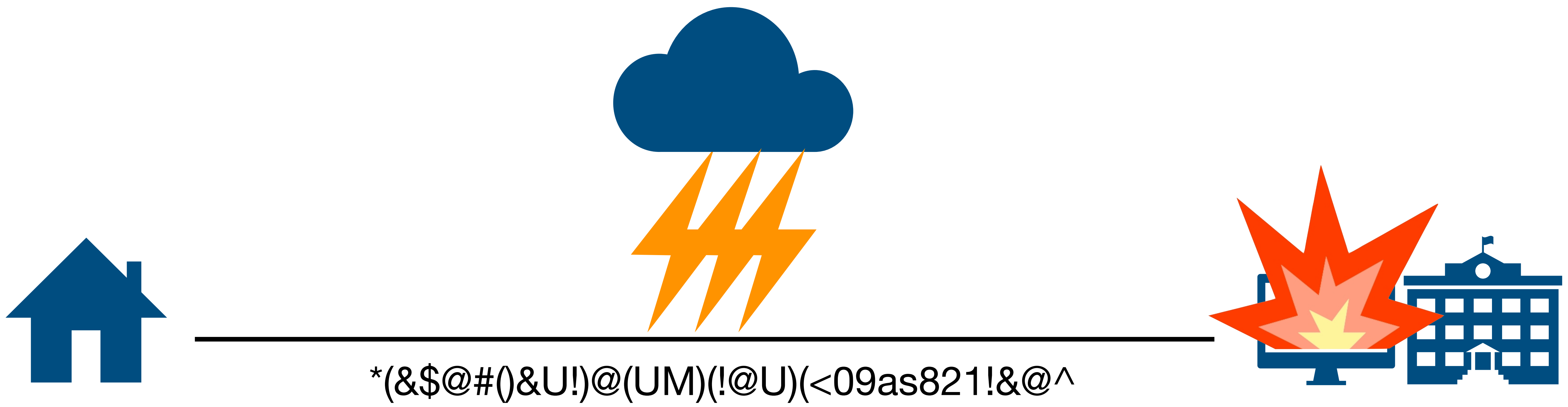
(d) Legend

Two Approaches

- Dynamic approaches: with running programs
  - **Completeness**: give a concrete buggy input
  - **Under-approximation**: may not cover all possible behavior
- Static approaches: without running programs
  - **Soundness**: give a correctness proof
  - **Over-approximation**: may have spurious error reports

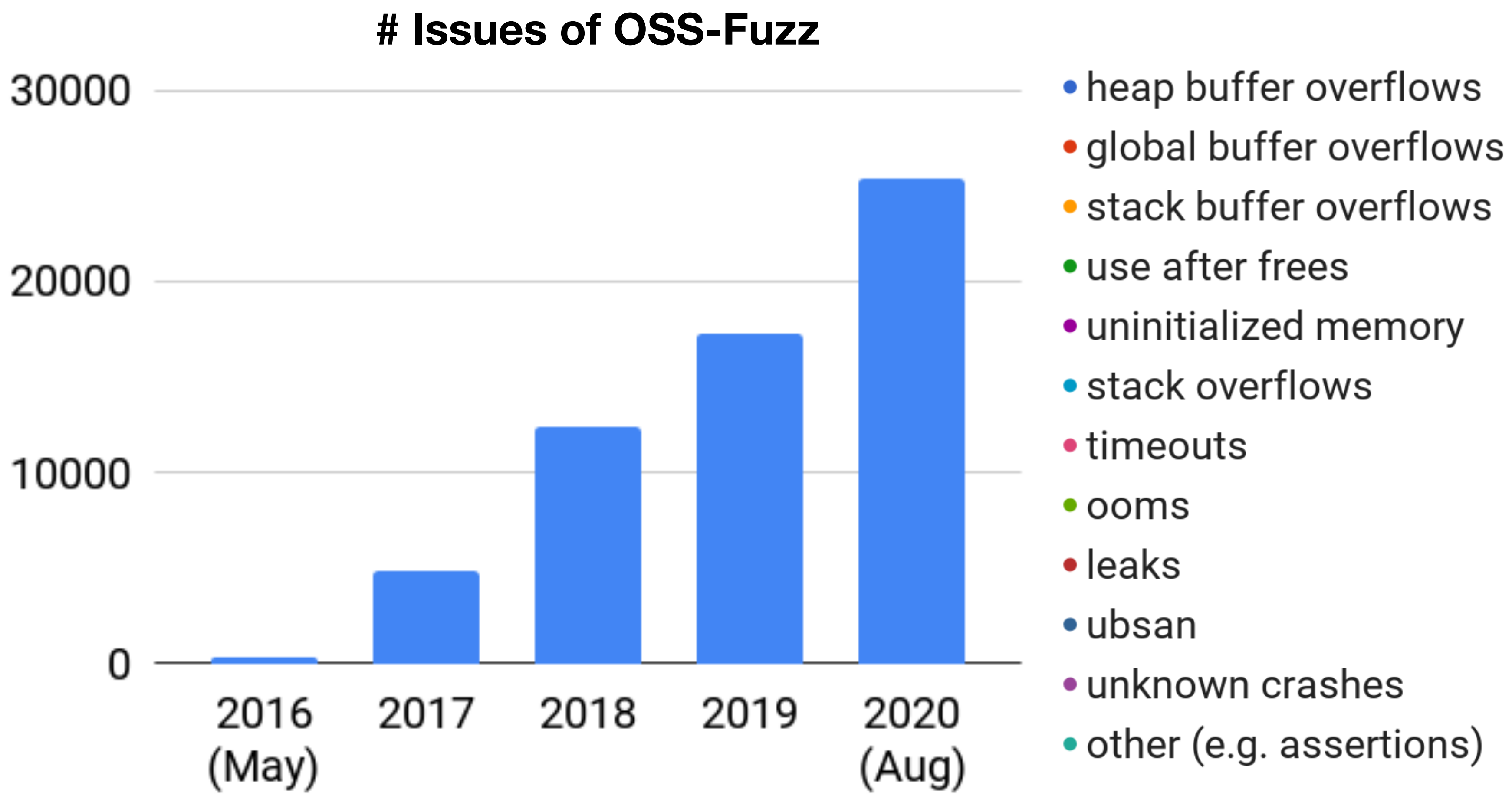
Fuzzing

- 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?”

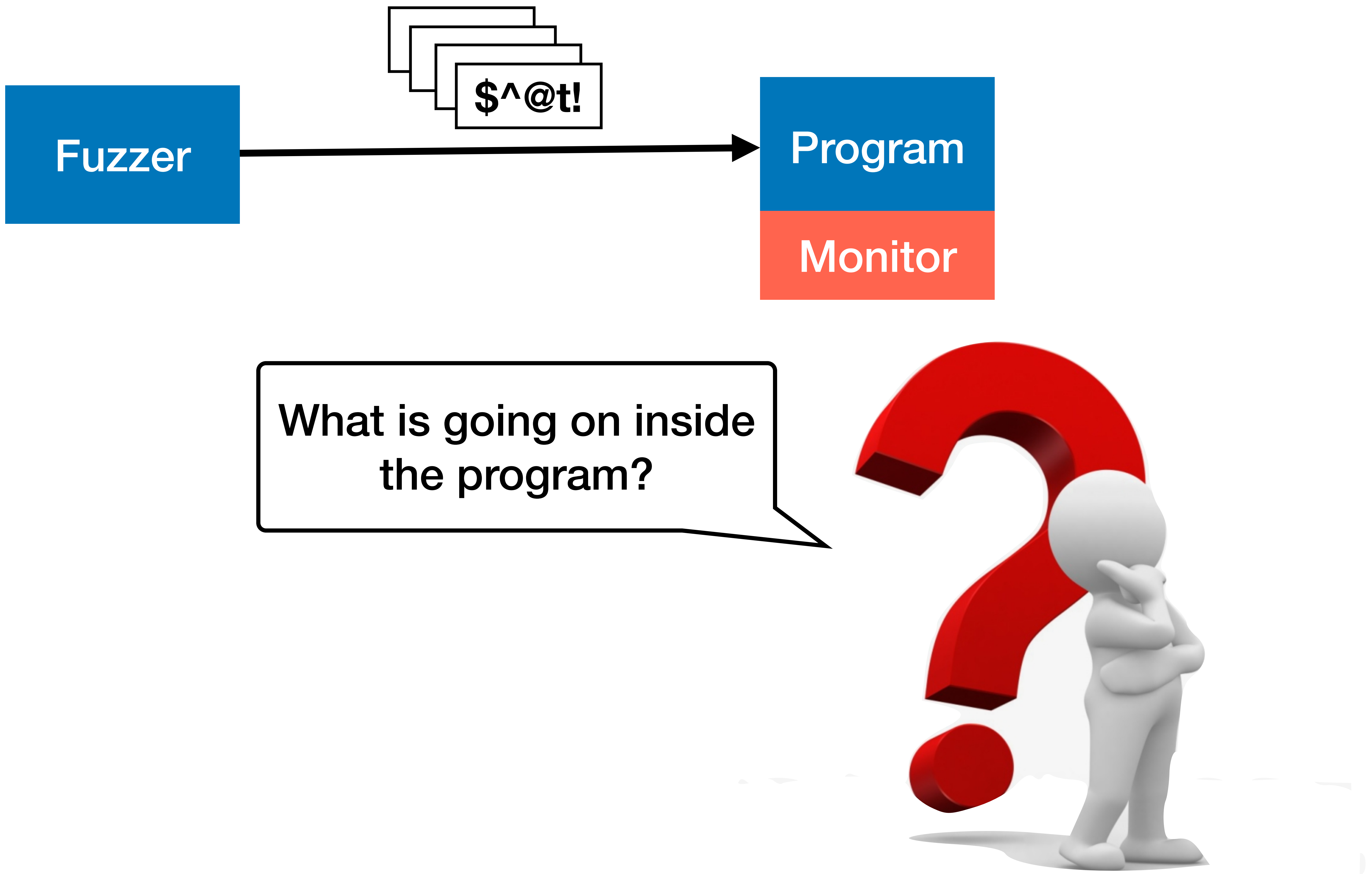


Success Stories

- 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



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 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();
```

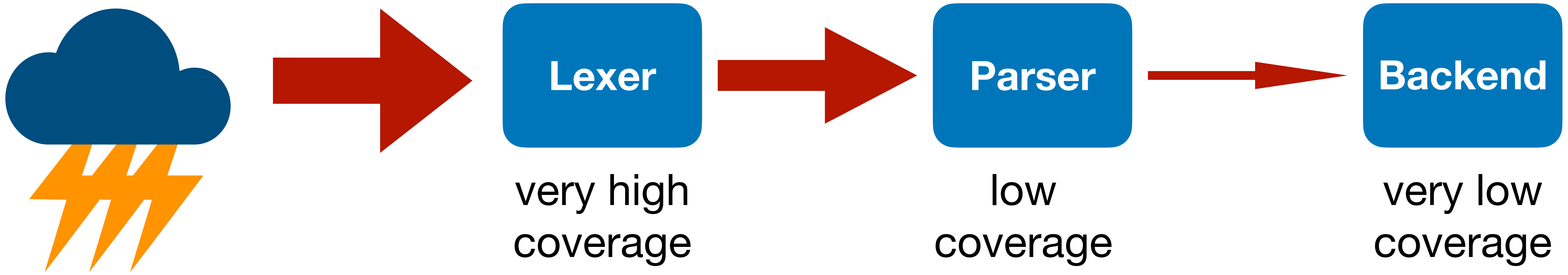
- Whitebox: generate inputs by **observing** program’s logic and structure
  - Can explore deeper parts
  - Require constraint solving (high overhead)

Examples

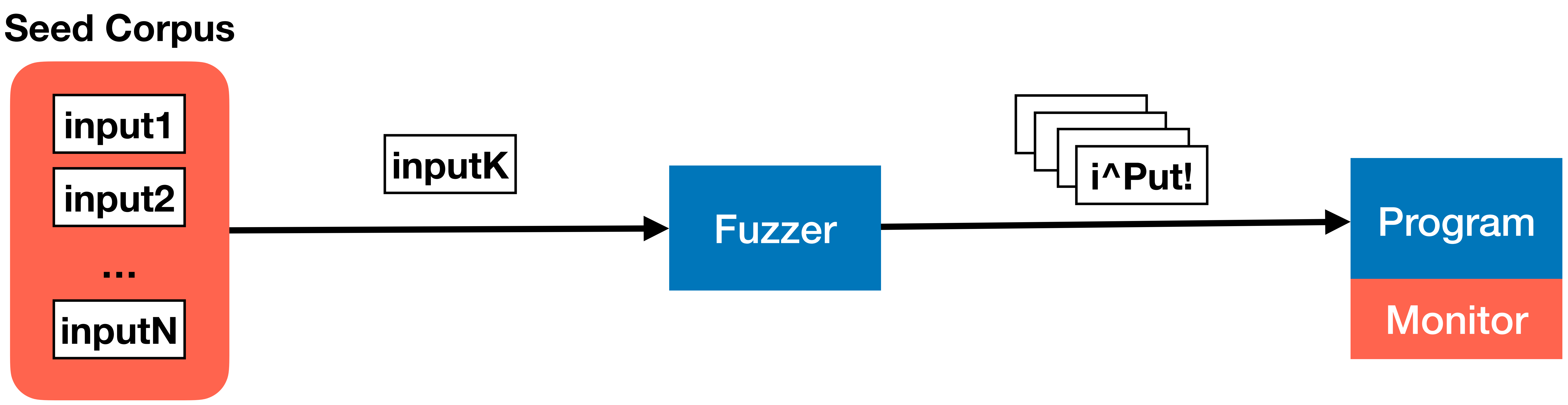
- Monkey: a random testing tool for Android apps
    - Randomly generate streams of events such as clicks, touches, etc
    - A part of Android Studio
- Cuzz: a random testing tool for finding concurrency bugs
    - Randomly generate thread schedules
    - A part of Microsoft Application Verifier

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`



Fuzzing Overview



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

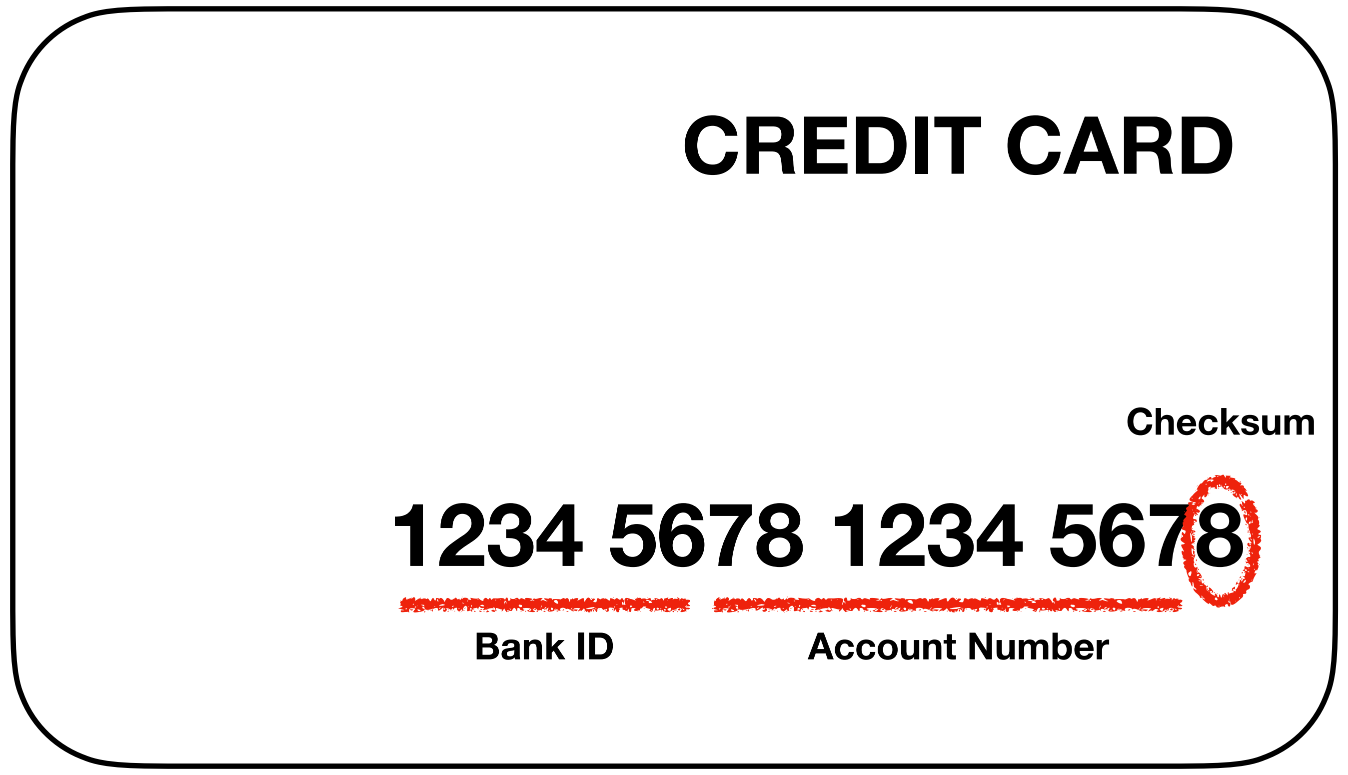
Example Mutation Operators

- **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”}

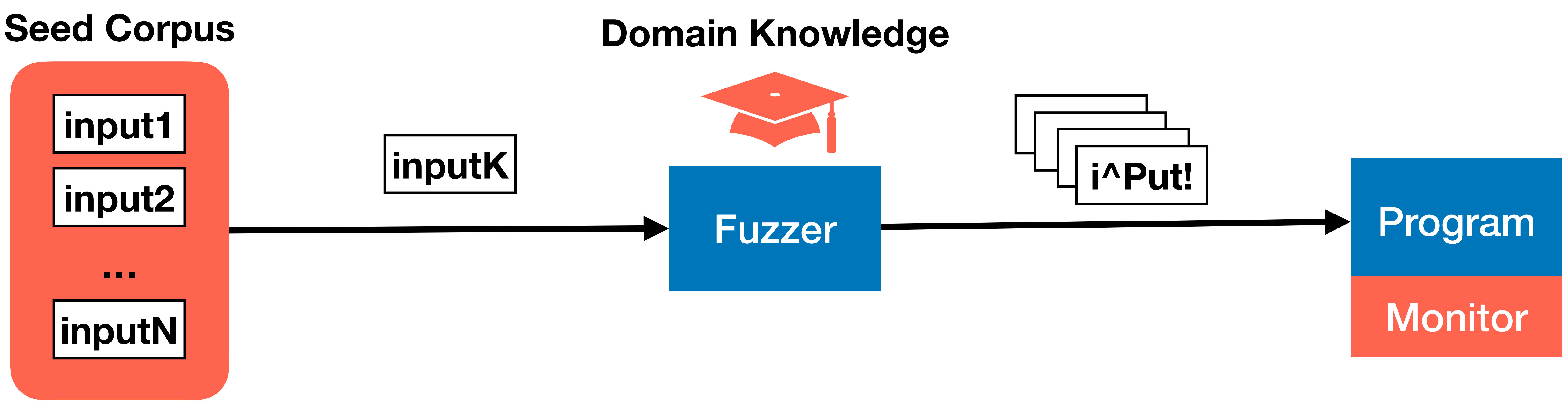
*Manes et al., The Art, Science, and Engineering of Fuzzing: A Survey, TSE, 2019

Problems

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



Fuzzing Overview



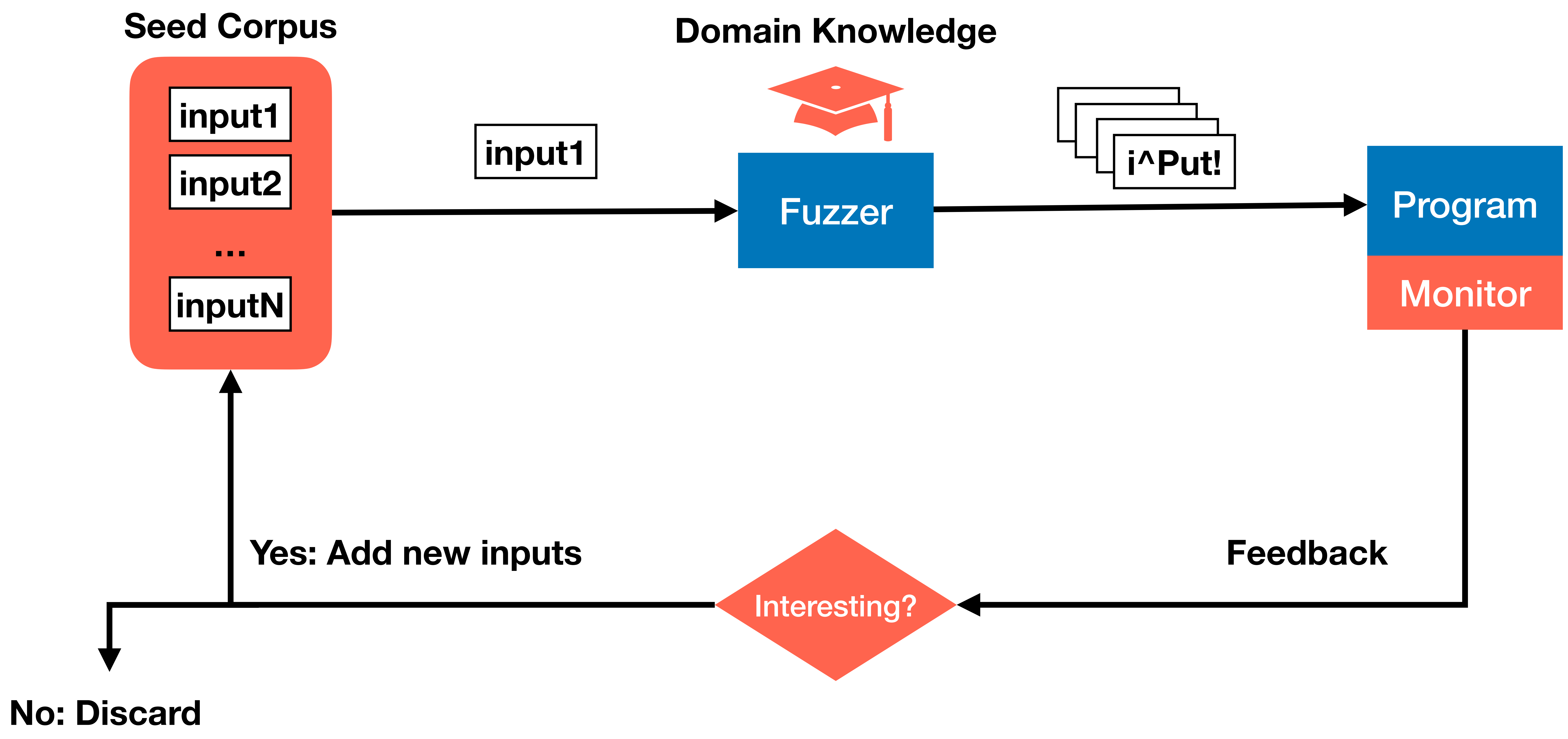
Generation-based Fuzzing

- 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

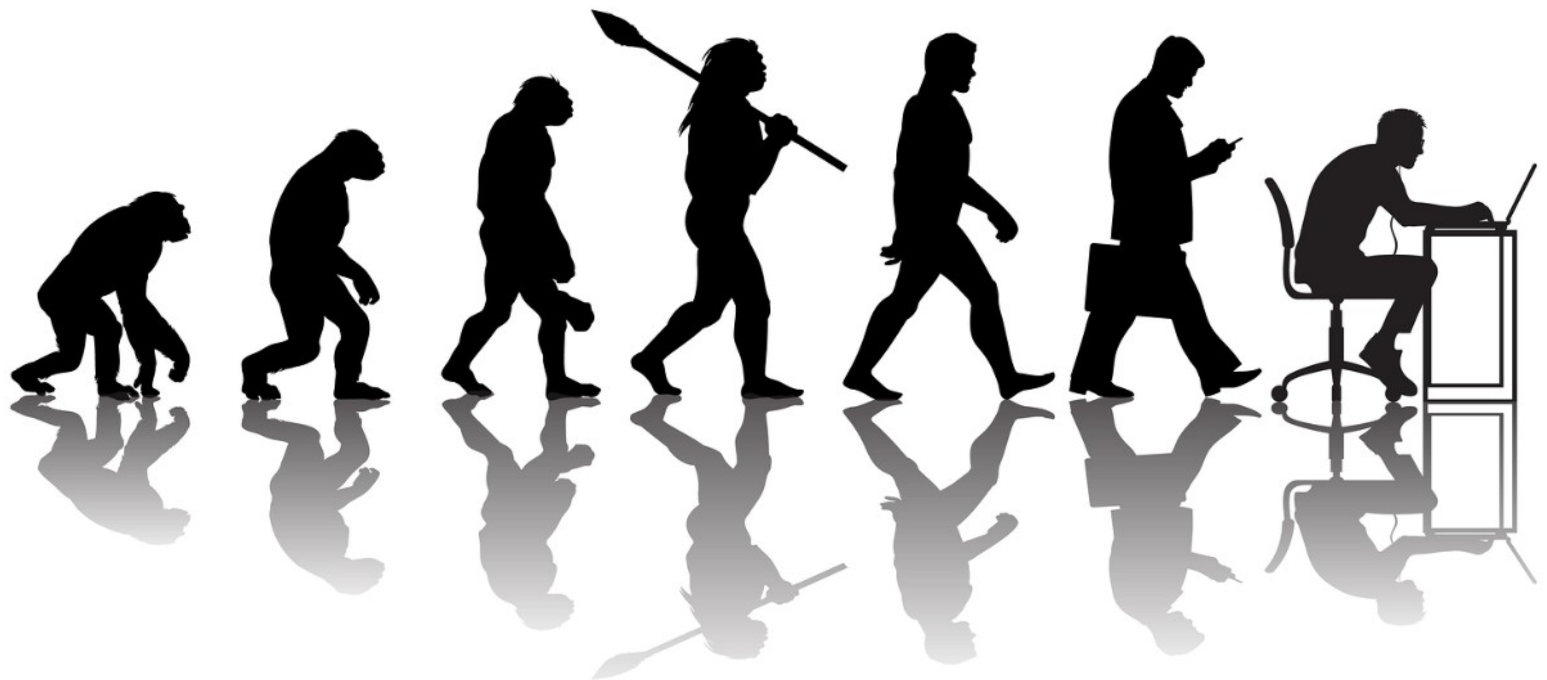
Still in the Dark

- How much fuzzing is enough?
- How to evaluate fuzzer's performance?
- Which mutant is better than others?

Fuzzing Overview



Coverage-guided Fuzzing



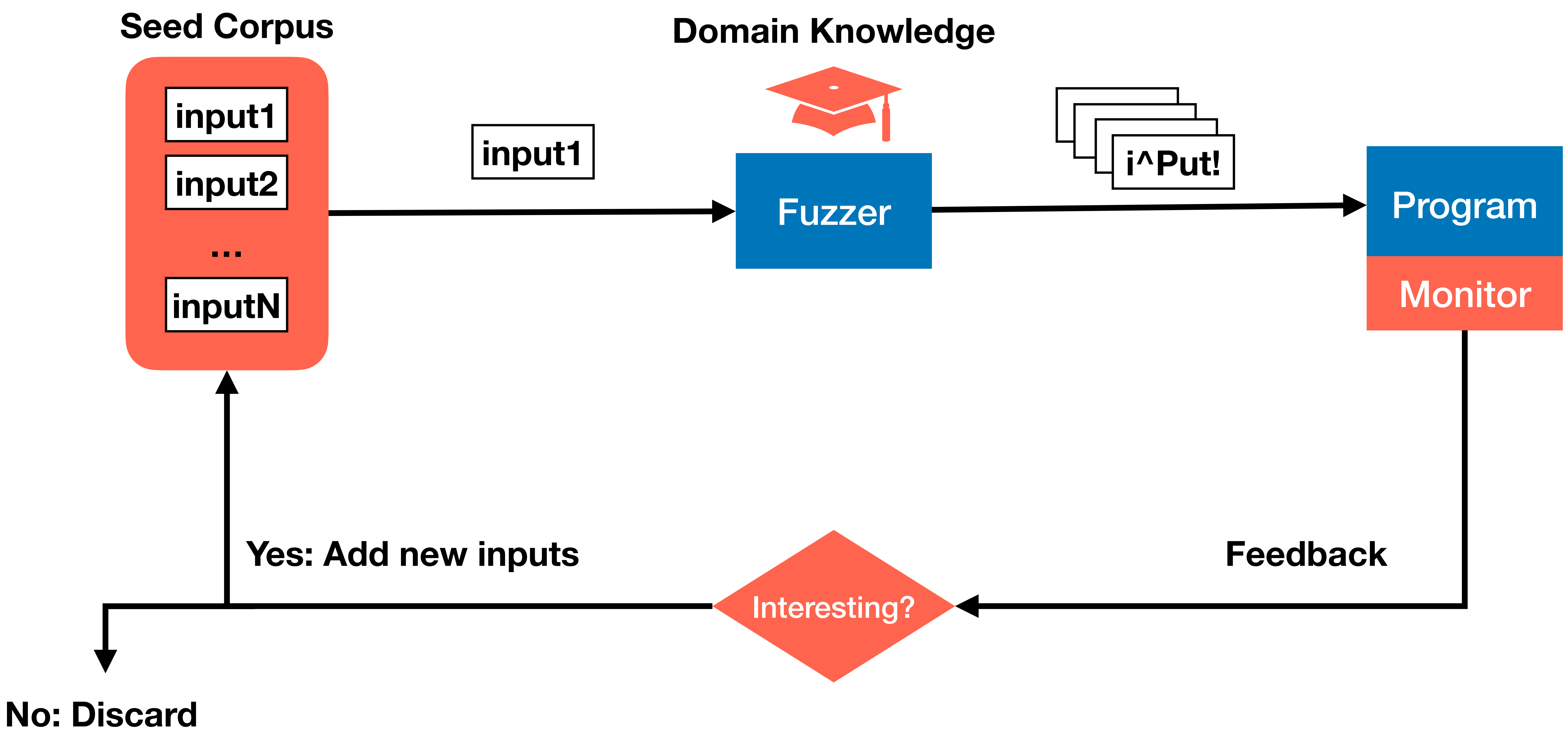
- Fuzzing as a **genetic algorithm**
  - Chromosome population: seed corpus
  - Genetic mutation: mutation
  - Fitness function: coverage
- Key idea: keep mutants that increases **code coverage** for future mutations
  - So called **grey-box** fuzzing
  - E.g., AFL, LLVM's libFuzzer

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

```
a, b, c = inputs();
if (a > 0)
  a = 1;
if (b > 0)
  b = 1;
if (c > 0)
  c = 1;
assert(a + b + c != -5);
```

More Research Questions



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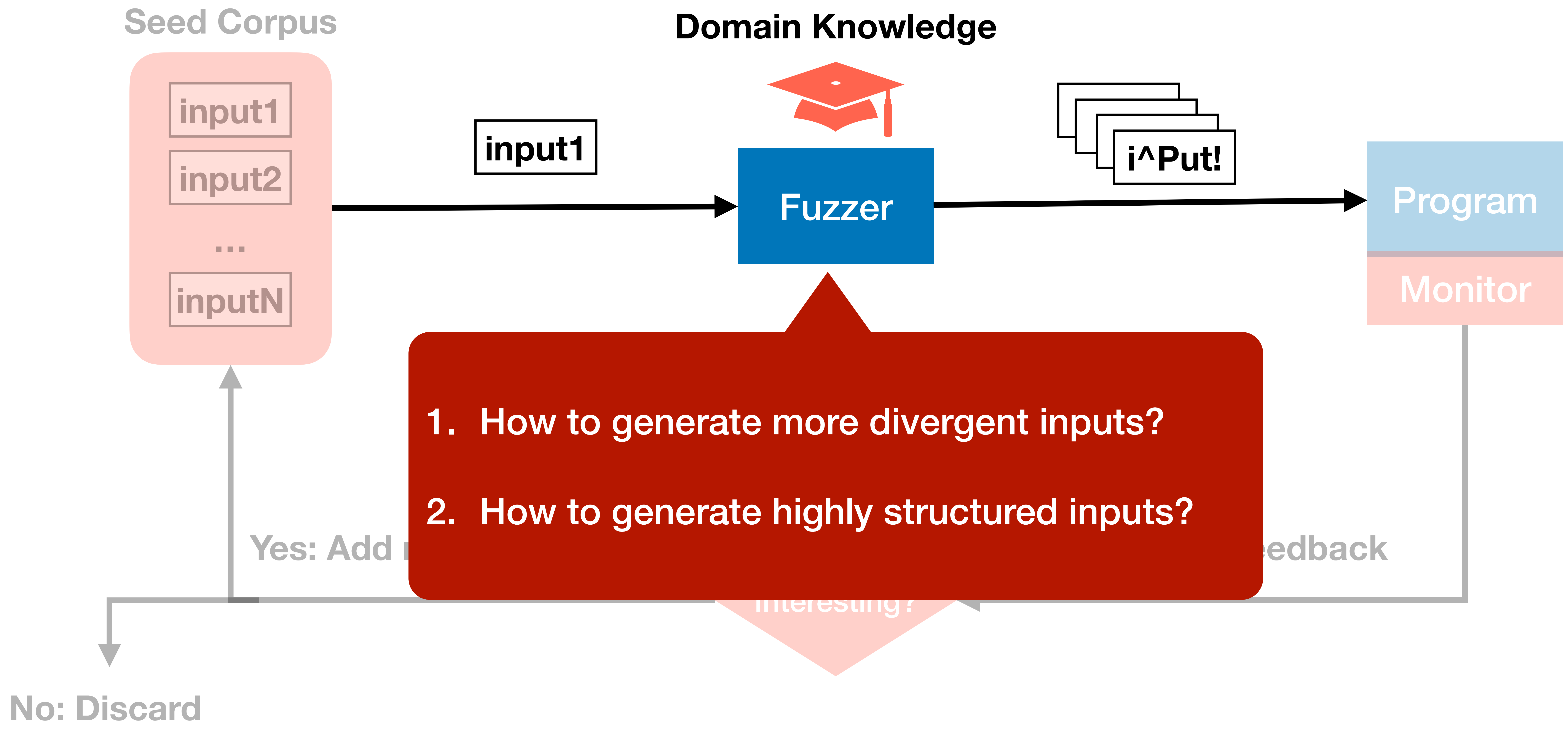
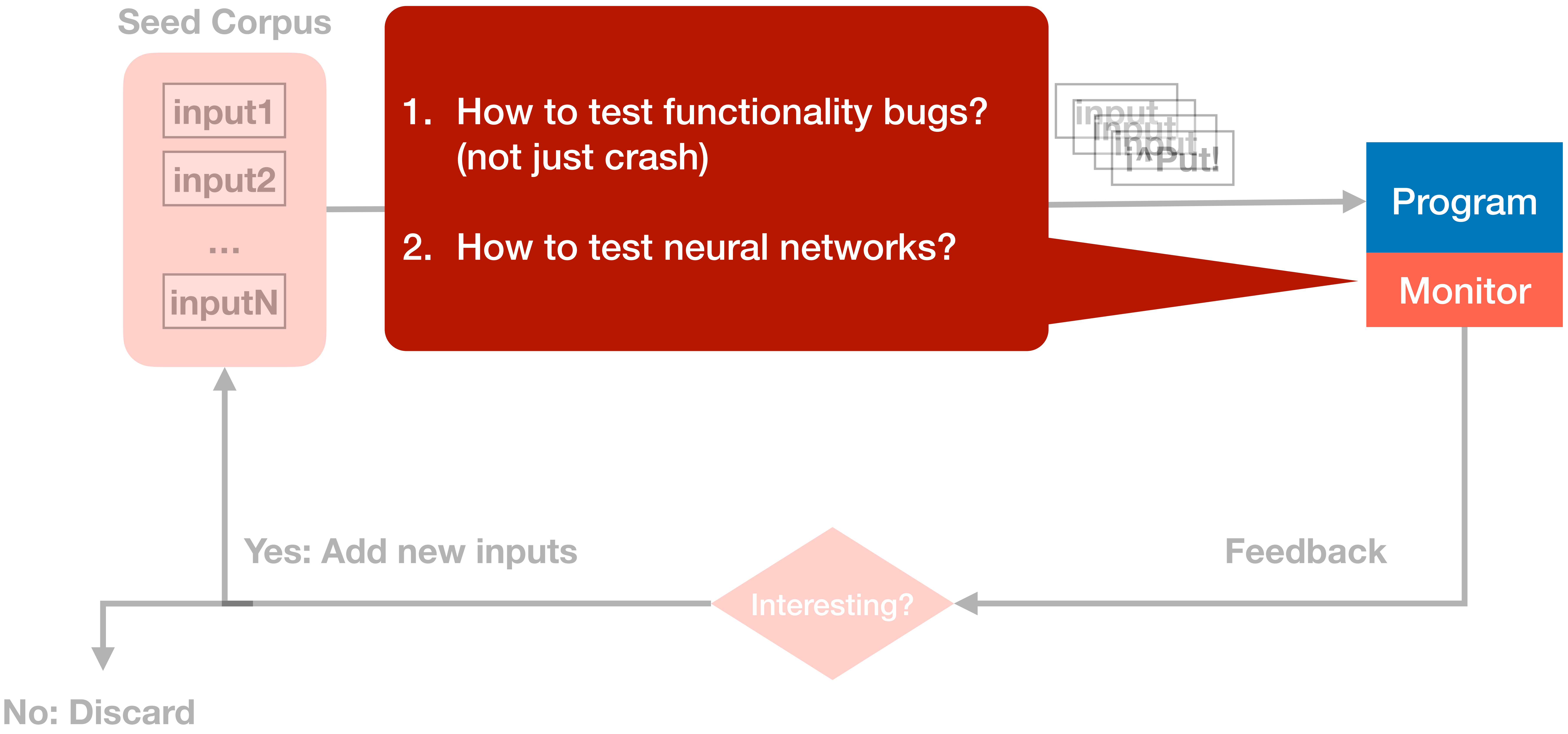


1. How to generate more divergent inputs?
2. How to generate highly structured inputs?

More Research Questions



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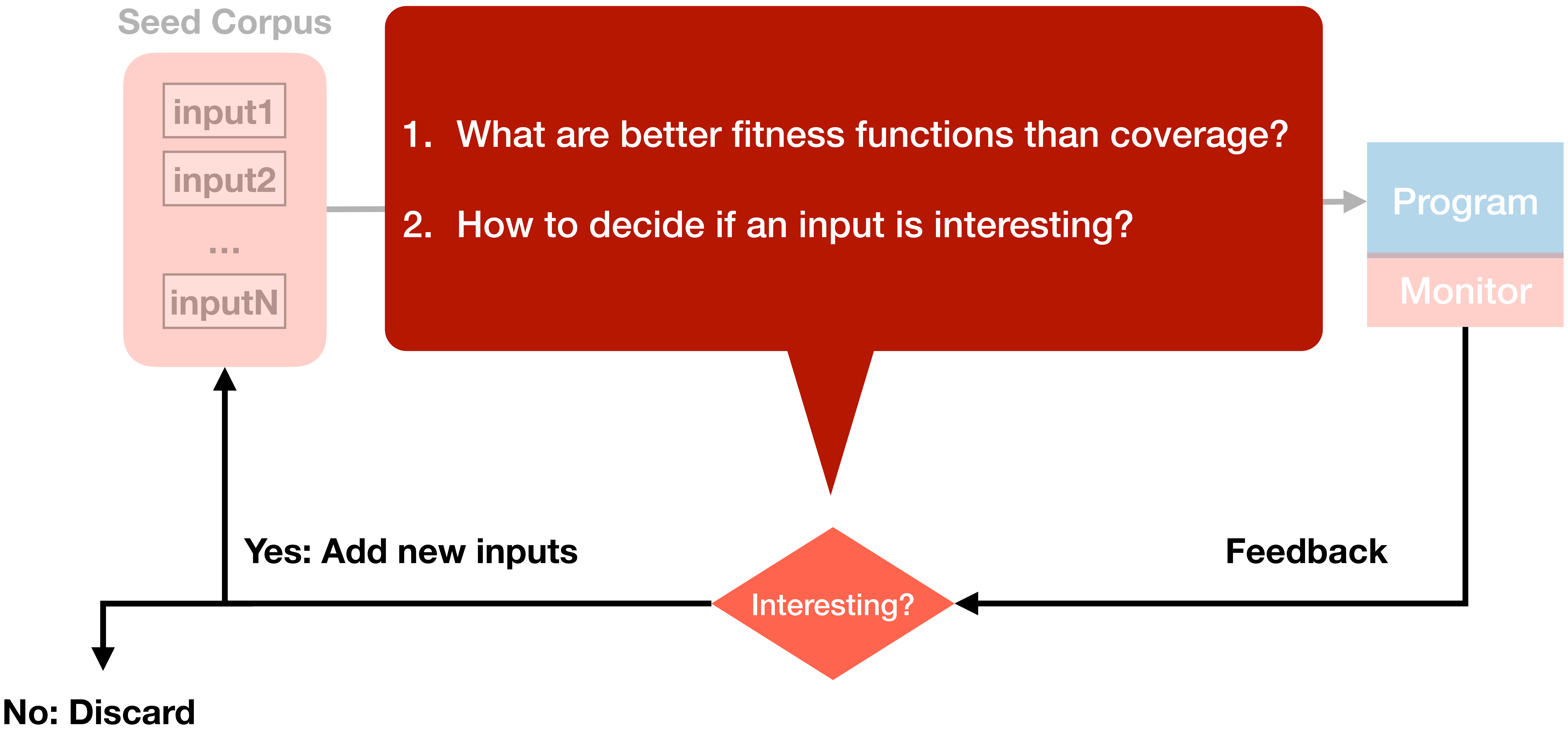

Conclusion

- Fuzzing: efficient and effective testing technique
  - Input generation: mutation-based, generation-based
  - Feedback: blackbox, greybox, whitebox
- Challenges
  - Efficiency (e.g., higher coverage), expressiveness (e.g., functionality errors), etc