Fuzzing the PHP Interpreter via Dataflow Fusion

A novel fuzzing framework for detecting memory errors in the PHP interpreter

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>200 Verified Bugs

PHP Official Toolchain

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The PHP Security Challenge

PHP's Dominance in Web Development

- Cornerstone of the modern web, powering **over 70%** of websites globally
- Used for personal blogs to major e-commerce platforms
- Extensive **C codebase** (over a million lines) presents a significant attack surface

Overlooked Security Risks

- Existing PHP researches: application-level security (*e.g.*, SQL Injection)
- Memory corruption bugs in C most common cause of critical vulnerabilities

CVE-2023-3824

In PHP version 8.0.* when loading phar file, while reading PHAR directory entries, insufficient length checking may lead to a **stack buffer overflow**, leading potentially to memory corruption or RCE.

CVE-2024-8929

In PHP versions 8.1.* a hostile MySQL server can cause the client to **disclose the content of its heap** from other SQL requests and possible other data belonging to different users of the same server.

Research Question: how to improve the low-level security of PHP ecosystem?

Fuzzing

Fuzzing: well-known effective approach to discover bugs

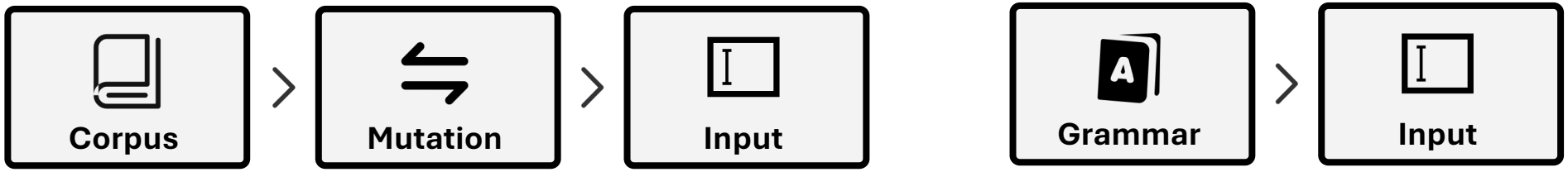
- Generating a diversity of inputs
- Driving software into unexpected states

Challenge: how to automatically generate diverse inputs?

- Mutation-based Input Generation
  - Starts from a corpus of existing inputs (seeds) and produces variants by applying random or heuristically guided mutations to those seeds.
- Grammar-based Input Generation
  - Uses a formal grammar (e.g., a BNF or ANTLR definition) of the input language to generate syntactically valid inputs from scratch.

Program Input Generation

Mutation- and Grammar-based Fuzzing



Mutation-based Fuzzing

Grammar-based Fuzzing

Common Weakness in Generation Programs

- Limited semantic diversity (although having high syntax correctness)
- Hard to reach deep logics when fuzzing compilers (*e.g.*, clang) or interpreters (*e.g.*, PHP)

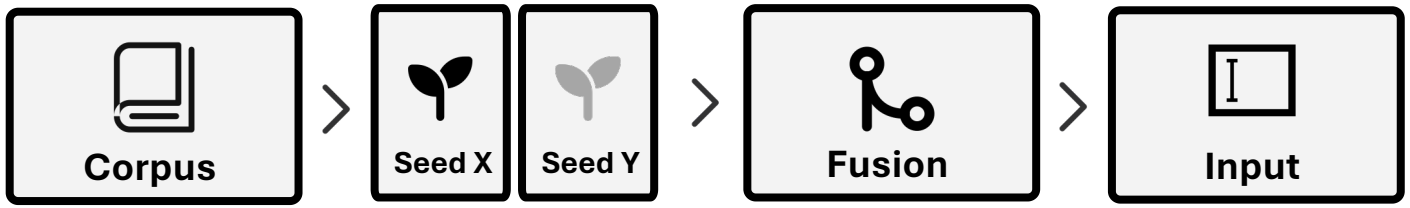
Research Question: how to generate inputs with diverse code semantics?

- Mutation-based fuzzing alters one input at one time

Can we take two or more inputs at one time and do further transformations?

Input Fusion

Fusion-based Fuzzing



What could be effective way to merge inputs with diverse semantics?

- Seed concatenation? It makes no big difference from executing them separately

Recall Seed Selection

- Known **Proof** of Concepts from bug reports, **unit** tests, *etc*.
- **Minimized** code snippet to test one single feature or bug reproduction

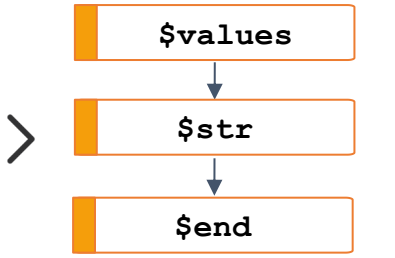
Seeds are typically unit-level program snippets designed to test a single functionality or regression in the codebase. They generally (*e.g.*, 96.1% in PHP) execute sequentially (*i.e.*, without branches). This implies that control flow has minimal impact on their code semantics.

Data Flow as a Representation

Data Flow

- Definition: how values move from their points of definition to their points of use

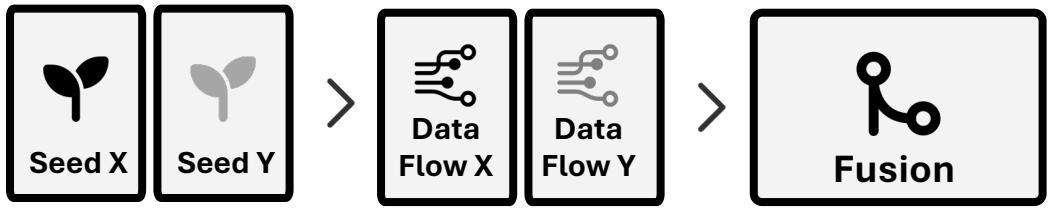
```php
<?php
  /* Test Case A */
  $values = array("Hello World", "\n\t1\r\n");
  foreach($values as $str) {
    $enc = base64_encode($str);
  }
```



data flow of PHP program

Seed Fusion to Data Flow Fusion

- Data flow can well represent code semantics of seeds due to the simple control flow
- Seed fusion becomes data flow fusion



Data Flow Fusion

Data Flow Fusion

- Randomly interleaving data flows among two or more seed programs

```php
<?php
  /* Test Case A */
  $values = array("Hello World", "\n\t1\r\n");
  foreach($values as $str) {
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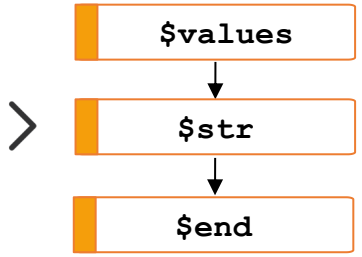
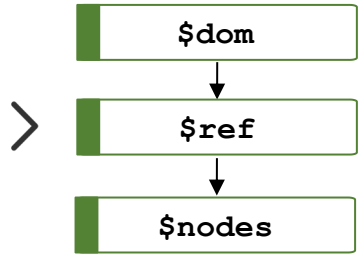


Test Case A: base64 encoding

```php
<?php
  /* Test Case B */
  $dom = new DOMDocument;
  $dom->loadXML('<tag>value</tag>');
  $ref = $dom->documentElement->firstChild;
  $nodes = $ref->childNodes;
```



Test Case B: DOM operations

Data Flow Fusion

Data Flow Fusion

- Randomly interleaving data flows among two or more seed programs

```php
<?php
  /* Test Case A */
  $values = array("Hello World", "\n\t1\r\n");
  foreach($values as $str) {
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  }
```
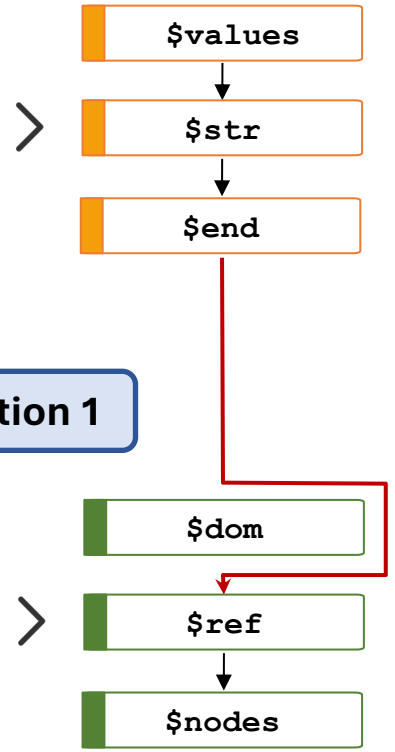

Test Case A: base64 encoding

```php
<?php
  /* Test Case B */
  $dom = new DOMDocument;
  $dom->loadXML('<tag>value</tag>');
  $ref = $dom->documentElement->firstChild;
  $nodes = $ref->childNodes;
```

Test Case B: DOM operations



Dataflow fusion option 1

```php
<?php
  /* Fused Test 01 */
  $values = array(..);
  foreach($values as $str) {
    $enc = base64_encode($str);
  }

  $fusion = $enc;

  $dom = new DOMDocument;
  $dom ->loadXML ('<tag>value</tag>');
  $ref = $fusion-> documentElement->..;
  $nodes = $ref->childNodes;
```

Observation:
See? Now we have a new test case to fuzz the DOM operation on base64 object!

Data Flow Fusion

Data Flow Fusion

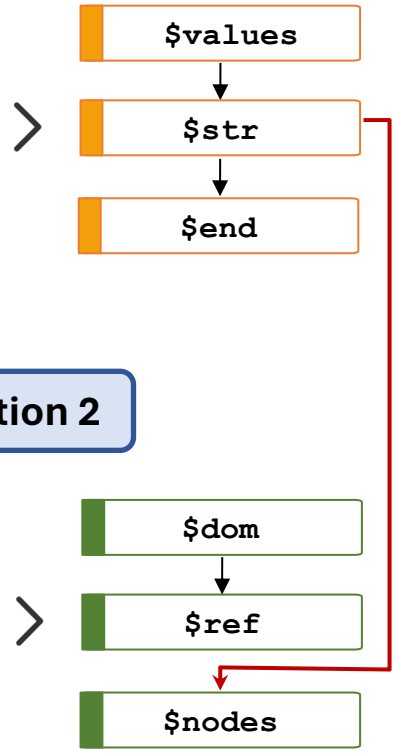
- Randomly interleaving data flows among two or more seed programs

```php
<?php
  /* Test Case A */
  $values = array("Hello World", "\n\t1\r\n");
  foreach($values as $str) {
    $enc = base64_encode($str);
  }
```

Test Case A: base64 encoding

```php
<?php
  /* Test Case B */
  $dom = new DOMDocument;
  $dom->loadXML('<tag>value</tag>');
  $ref = $dom->documentElement->firstChild;
  $nodes = $ref->childNodes;
```

Test Case B: DOM operations



Dataflow fusion option 2

```php
<?php
  /* Fused Test 02 */
  $values = array(..);
  foreach($values as $str) {
    $enc = base64_encode($str);
  }

  $fusion = $str;

  $dom = new DOMDocument;
  $dom ->loadXML ('<tag>value</tag>');
  $ref = $dom-> documentElement->..;
  $nodes = $fusion->childNodes;
```

Observation:
Random data flow combinations can create variant code semantics.

Data Flow Fusion

Data Flow Fusion

- Randomly interleaving data flows among two or more seed programs

```php
<?php
  /* Test Case A */
  $values = array("Hello World", "\n\t1\r\n");
  foreach($values as $str) {
    $enc = base64_encode($str);
  }
```

Test Case A: base64 encoding

```php
<?php
  /* Test Case B */
  $dom = new DOMDocument;
  $dom->loadXML('<tag>value</tag>');
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```
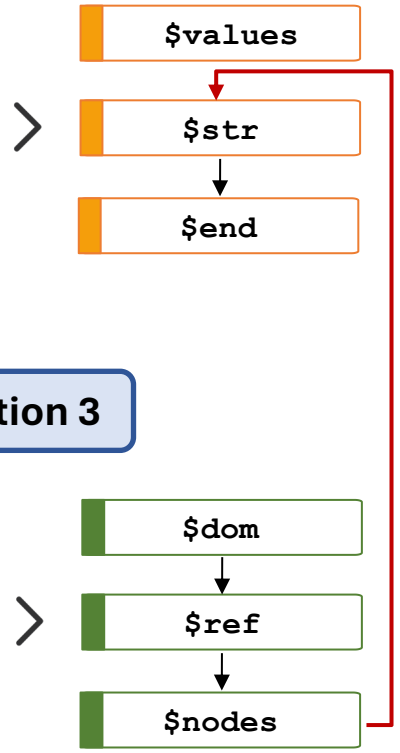

Test Case B: DOM operations



Dataflow fusion option 3

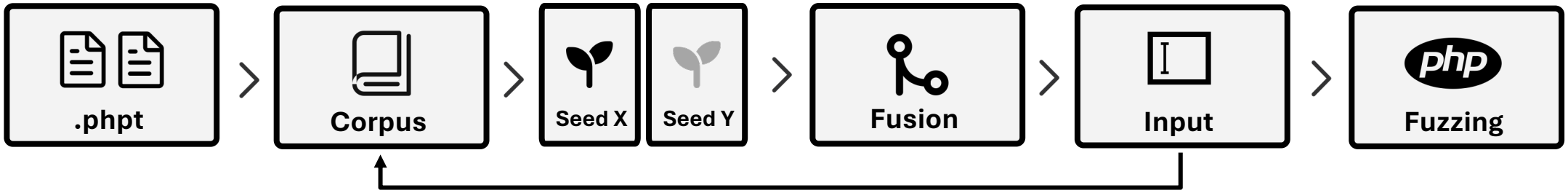
```php
<?php
  /* Fused Input 03 */
  $dom = new DOMDocument;
  $dom->loadXML('<tag>value</tag>');
  $ref = $dom->documentElement->firstChild;
  $nodes = $ref->childNodes;

  $fusion = $nodes;

  $values = array(..);
  foreach($fusion as $str) {
    $enc = base64_encode($str);
  }
// AddressSanitizer: heap-use-after-free
```

This data flow fusion triggers a **20-year-old** memory error existed in PHP interpreter!

FlowFusion Overview

Workflow

- FlowFusion collects phpt files as corpus, and execute inputs in PHP engines for fuzzing



Recursive Fusion

- Fused inputs can be added back to corpus if they have new coverage or find new bugs
- Recursive fusion enables more complex semantic fusion among >2 seed programs

Fuzzing Setup

- Continuously fuzzing the nightly build of PHP interpreters for six months
- Oracles: address sanitizer and undefined behavior sanitizers; crashes; assertion failures

Complementary Strategies

Test Mutation

- Before fusion, FlowFusion applies mutations to original test cases
- Introduces semantic variations while maintaining syntactic validity
- Examples: operators exchange (‘+’ to ‘%’), special values (‘1’ to ‘int_max’)

Interface Fuzzing

- After generating fused test cases, FlowFusion injects random calls to internal functions
- Uses variables from the fused context as arguments for these functions
- Effectively tests the robustness of PHP's API under novel and unexpected conditions

Environment Crossover

- Merges configurations (required modules, .ini settings) of seeds
- Randomly introduces other valid configurations collected from the entire test suite
- Examples of altered settings: memory limits, JIT settings, Opcache modes

Bug Results

Key Findings (from paper)

- FlowFusion detected **158** unique and unknown bugs
- Our bug reports led to security improvements across **80+** source files
- Developers introduce patches that modified **5,000+** lines of code

Bug Status Breakdown

- Among 158 bugs, 125 are fixed, 11 confirmed, 18 pending, 4 expected

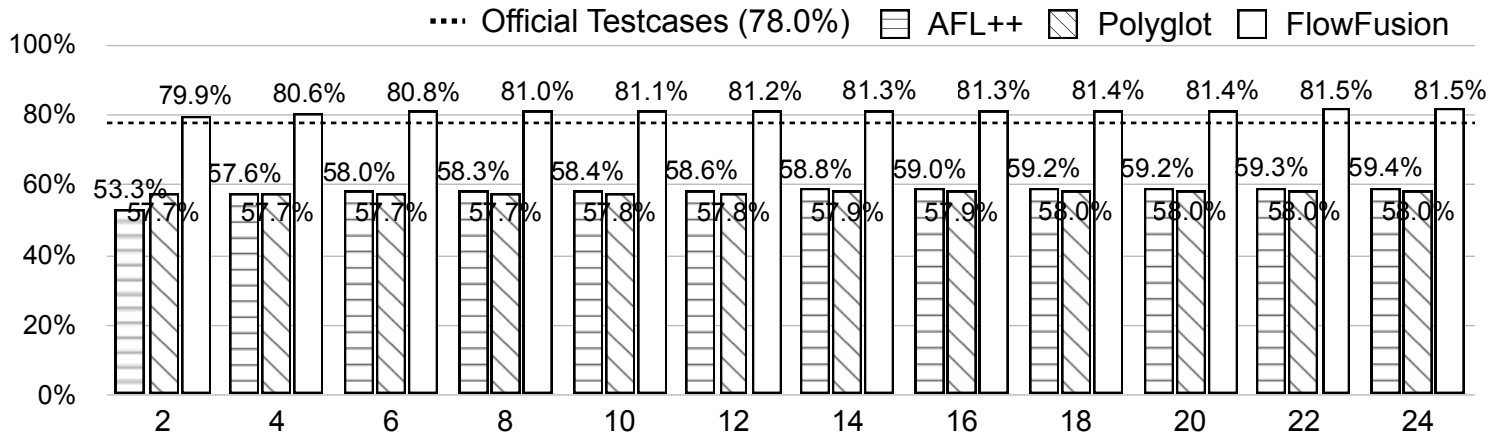
Discovered CWE Types

- FlowFusion covers bugs spanned 10 different CWE categories
- Examples: CWE-121 Stack-based Buffer Overflow, CWE-122 Heap-based Buffer Overflow, CWE124 Buffer Underwrite,, CWE-416 Use After Free, *etc.*

More Effectiveness

Comparison to existing works

- Baselines:
  - PHP test suite: maintained by PHP developers for CI/CD testing
  - AFL++: a well-known fuzzer that adds advanced instrumentation, persistent fuzzing, and customizable feedback for faster vulnerability discovery
  - PolyGlot (S&P'21): a multi-language fuzzer that translates inputs into a uniform IR, applies constrained, semantics-preserving mutations with semantic validation
- Settings: code coverage (collected via *gcovr*) after 24 hours fuzzing



Continued Impacts

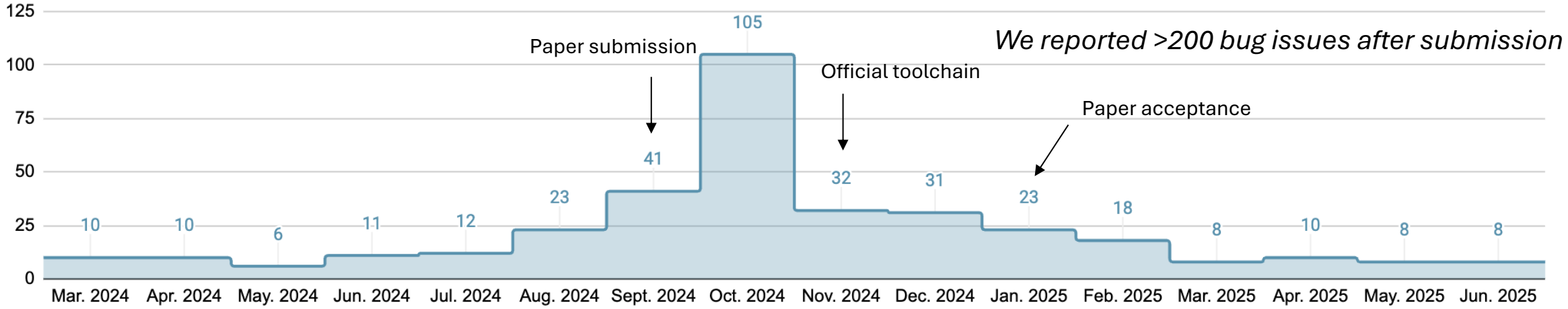
Living Project

FlowFusion seamlessly incorporates nightly builds in PHP source code to testing new features and patches. FlowFusion gets auto-updates when new test cases are added to official test suite.

Community Integration

FlowFusion becomes an official toolchain (i.e., available at https://github.com/php/flowfusion) for its outstanding bug discover effectiveness to help developers improve PHP interpreter security.

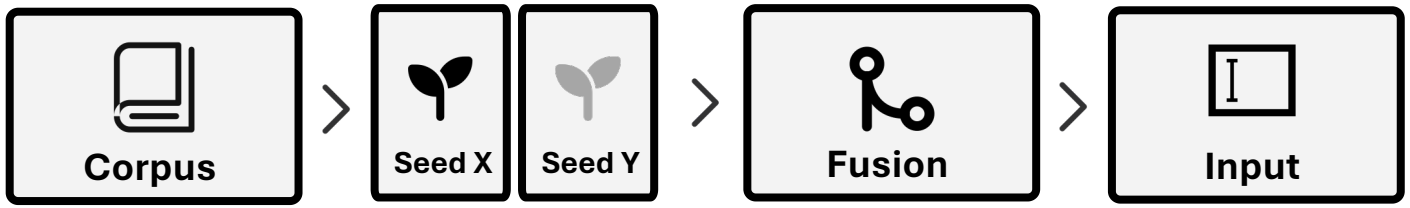
FlowFusion's Monthly Bug Report Count



FlowFusion's impact is not bound by paper submission or acceptance; it focuses on sustained community support. FlowFusion continuously detects new PHP memory errors nearly every week.

Summary

Fusion-based Fuzzing



(Data Flow As a Representation)

Availability

- Source code: https://github.com/php/flowfusion
- Bug reports: https://github.com/php/php-src/issues?q=author%3AYuanchengJiang

Future work

- More oracles to detect other bug categories (*e.g.*, logic bugs) that FlowFusion missed
- Adaptation to other programming language implementations (*e.g.*, cPython, v8)
- Combination with large language models