# NEZHA: Efficient Domain-Independent Differential Testing

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Columbia University

# Differential Testing

# Differential Testing

- Fuzzing: memory corruption bugs

- Differential testing: logic bugs

# Differential Testing

- Multiple apps of the same functionality
- Applications usually follow some specification/standard

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- All usually to follow some specification/standard
- Deviations from the specifications/standards likely to be bugs
- Applicable in different domains (e.g., compiler testing)

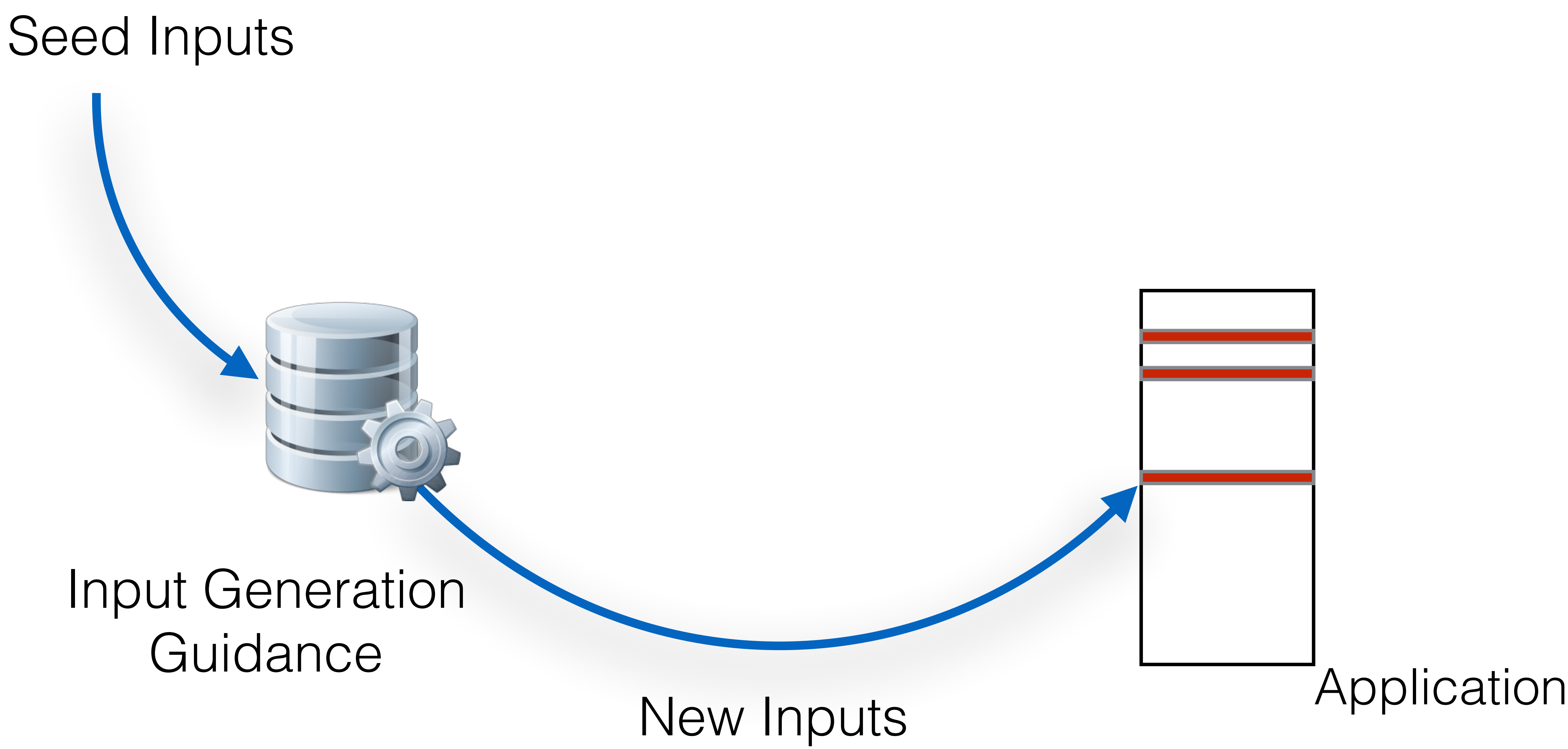
# Key challenges

- Existing tools are domain-specific
- Inefficient input generation

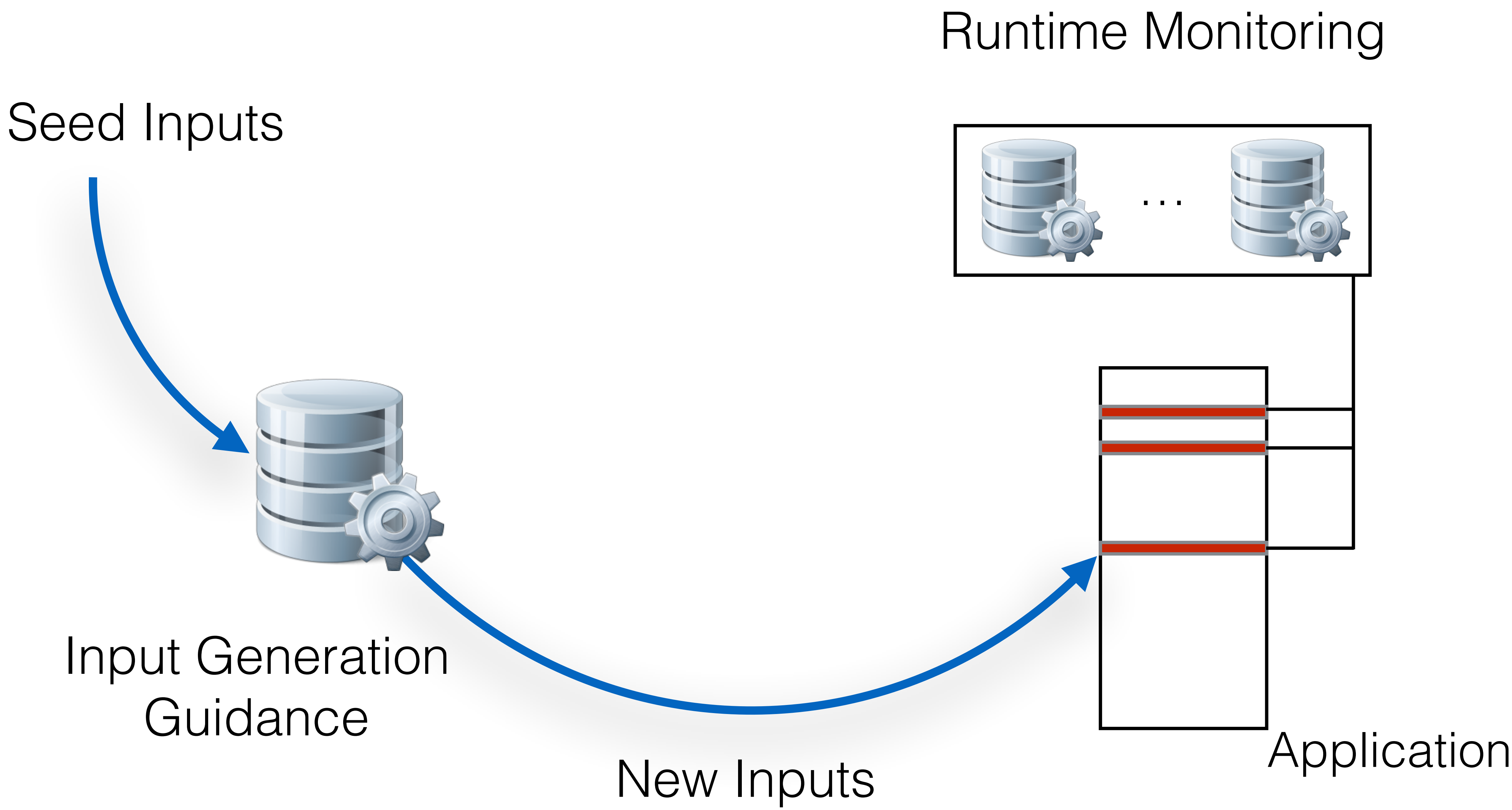
# Goal of NEZHA

Efficient domain-independent differential testing

# Domain-Independent Evolutionary Testing



# Domain-Independent Evolutionary Testing



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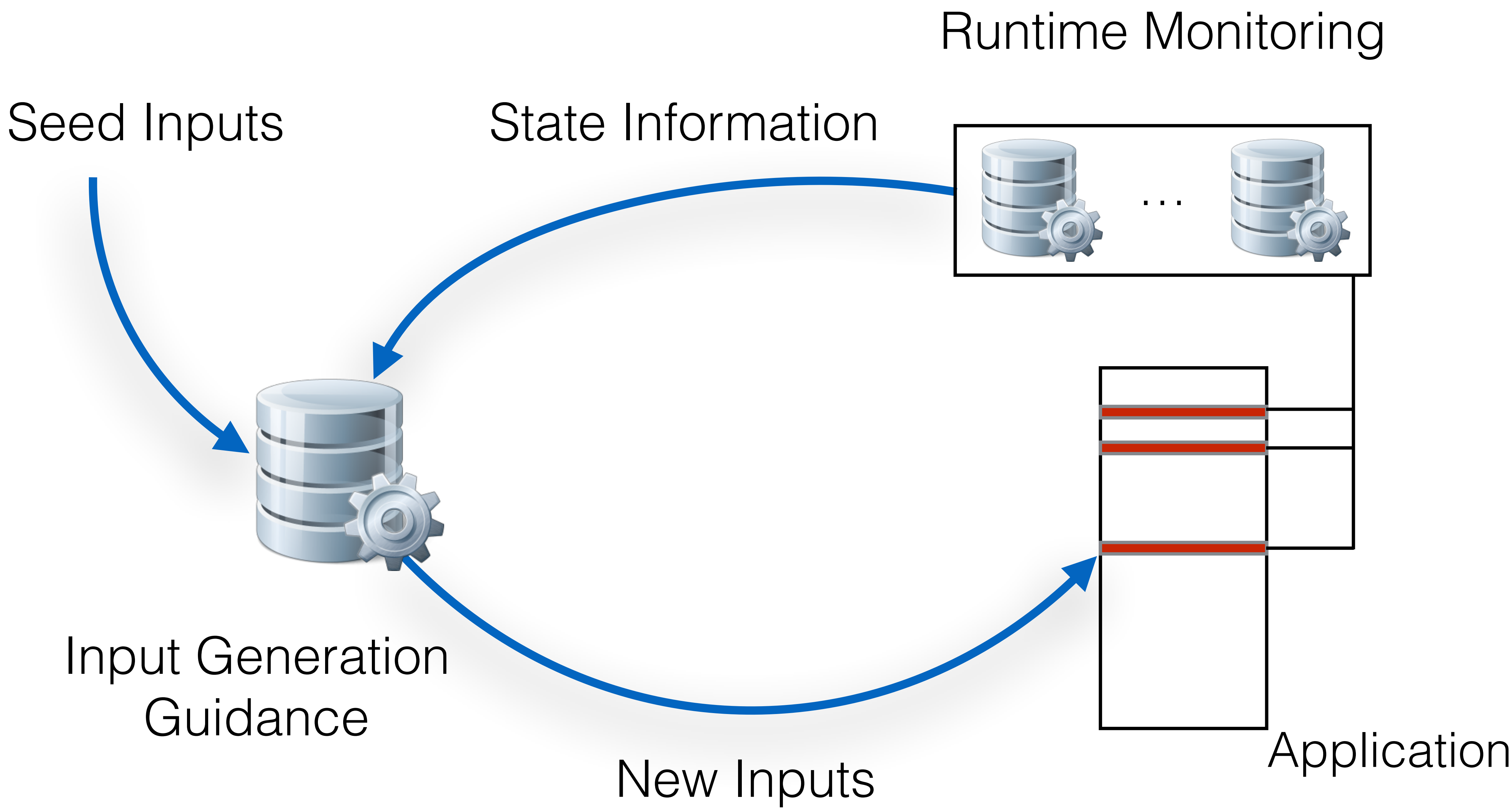

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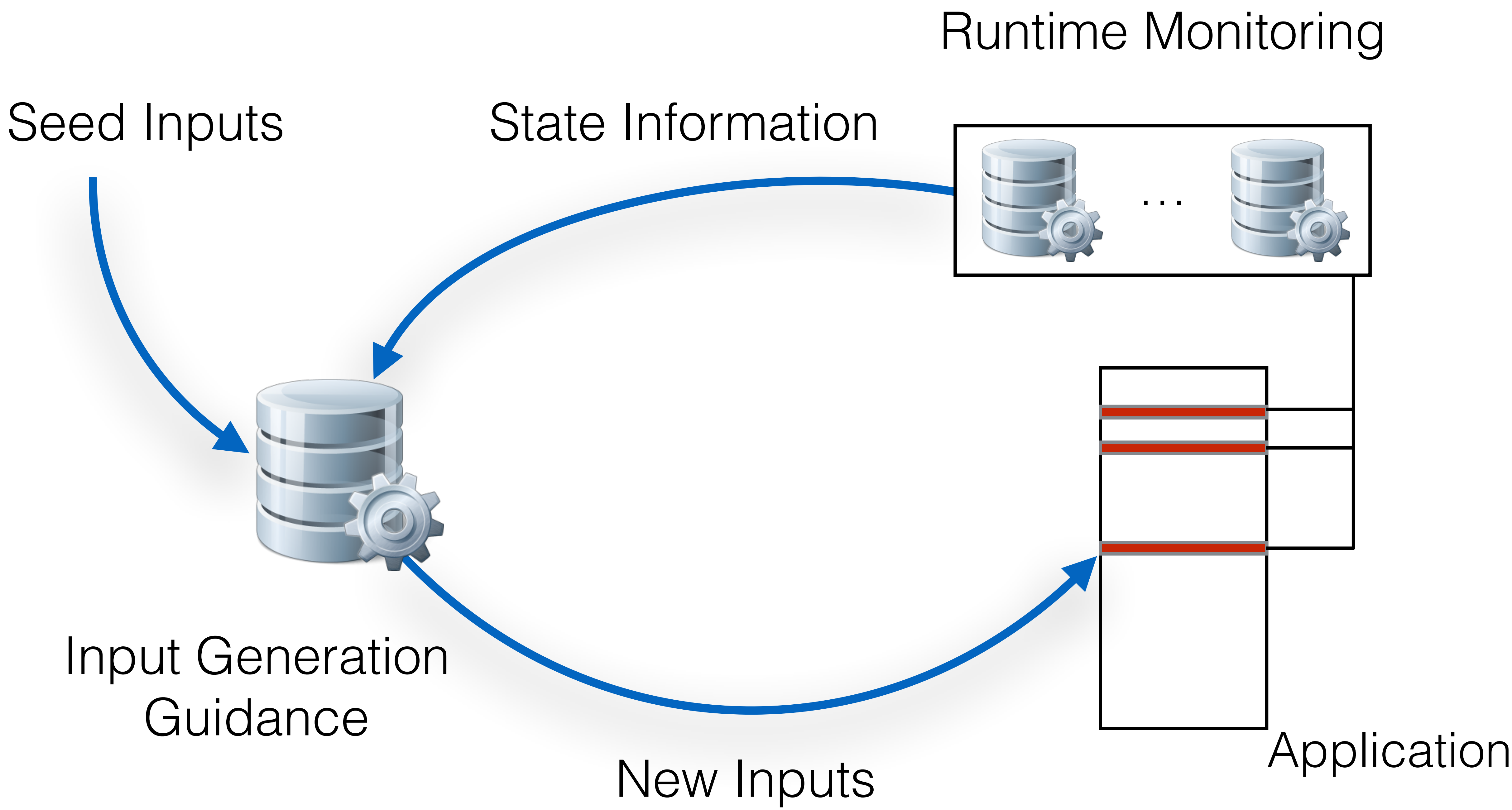


Evolve an input corpus that is guided based on an analysis engine

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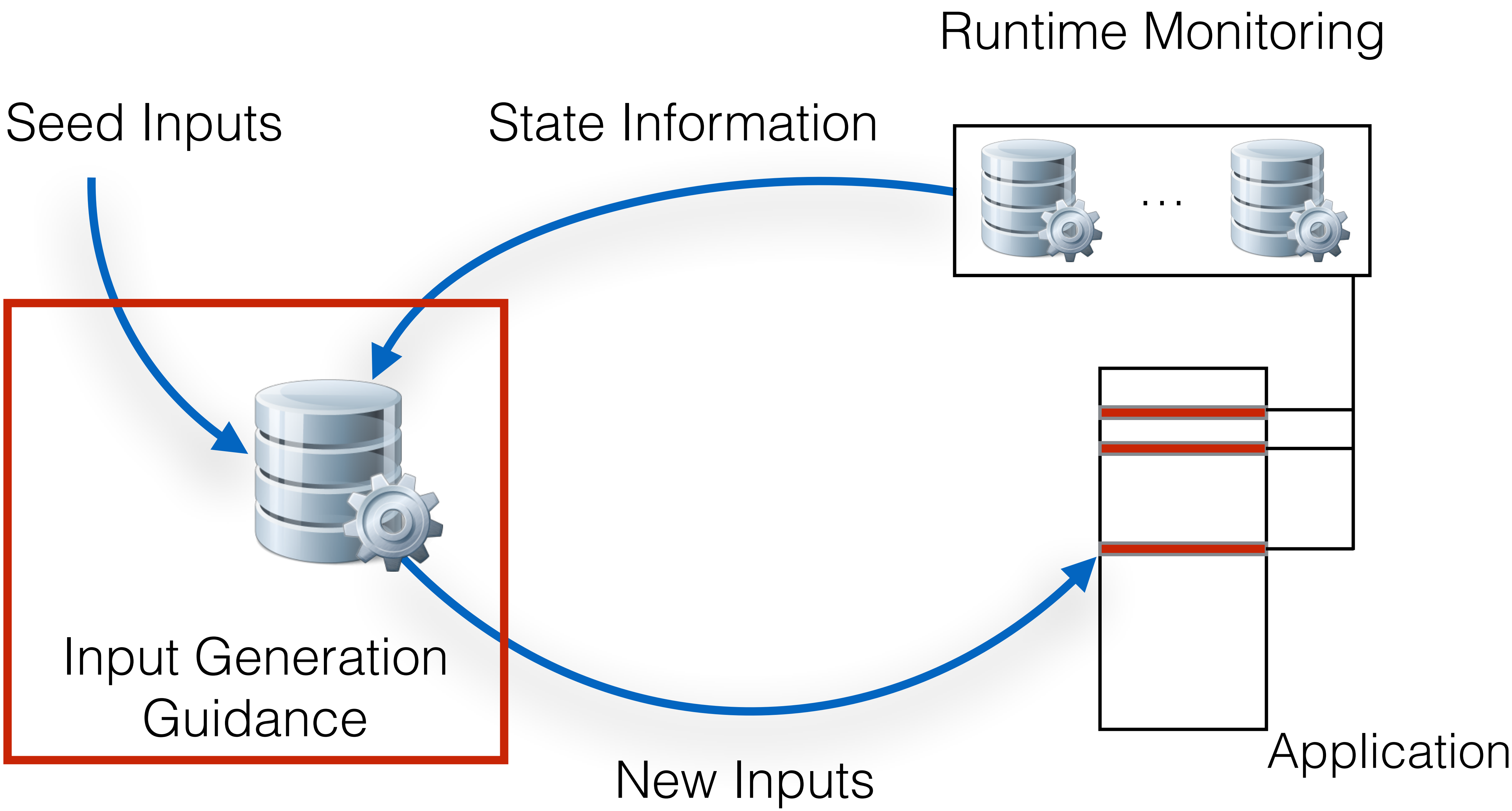
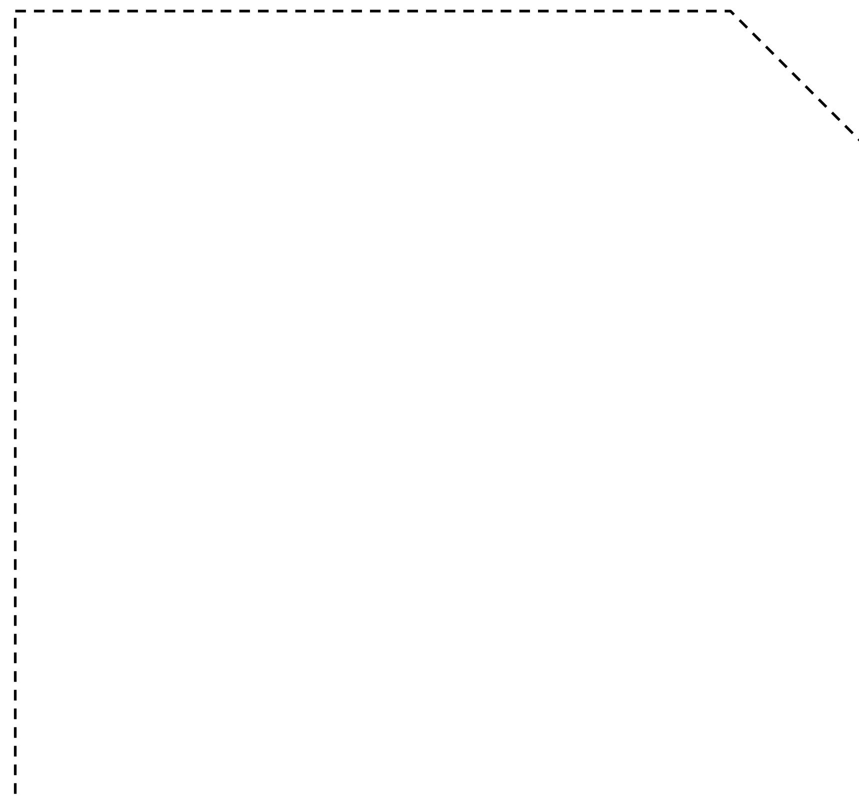


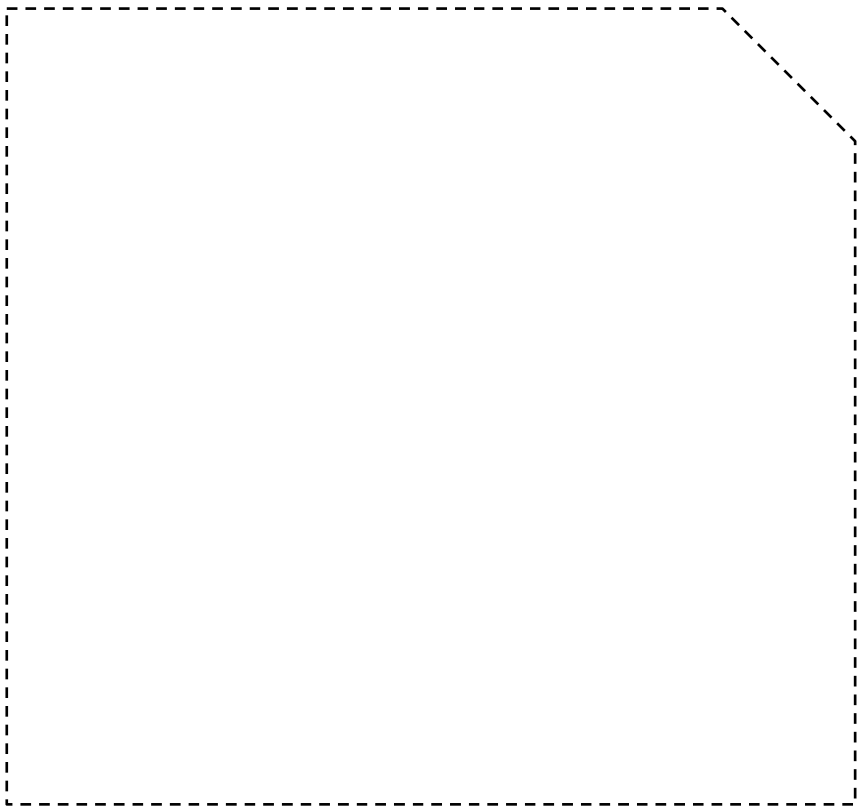

Evolve an input corpus that is guided based on an analysis engine

# Code Coverage - Single-App



All possible code paths

# Code Coverage - Single-App



Input Corpus

Per-Input Coverage

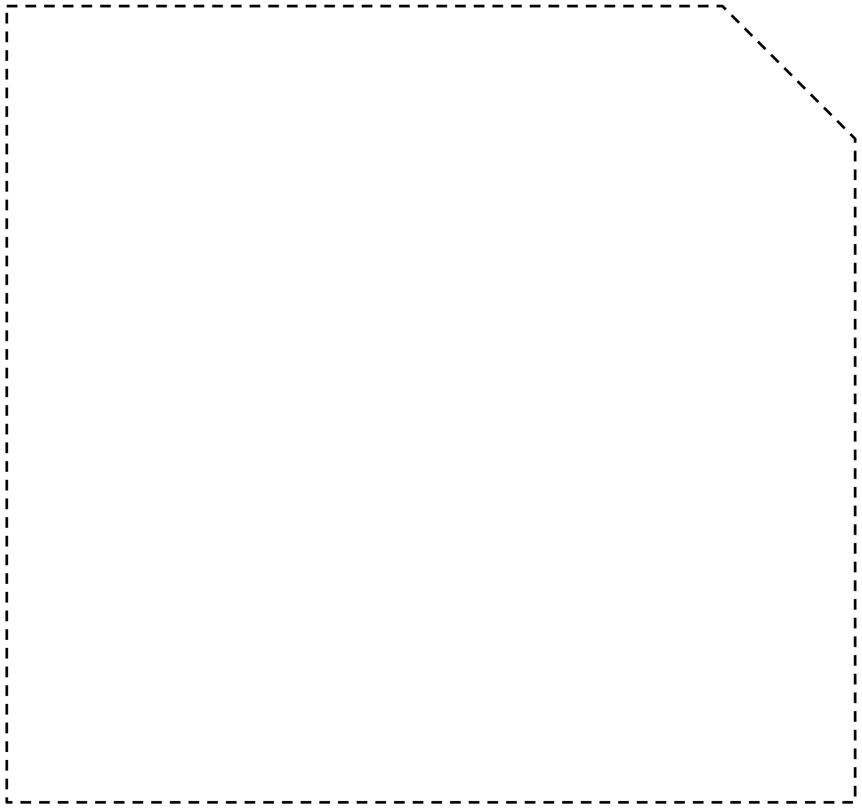
All possible code paths

Code coverage - Global

Code coverage - Input

# Code Coverage - Single-App

**Input 1**



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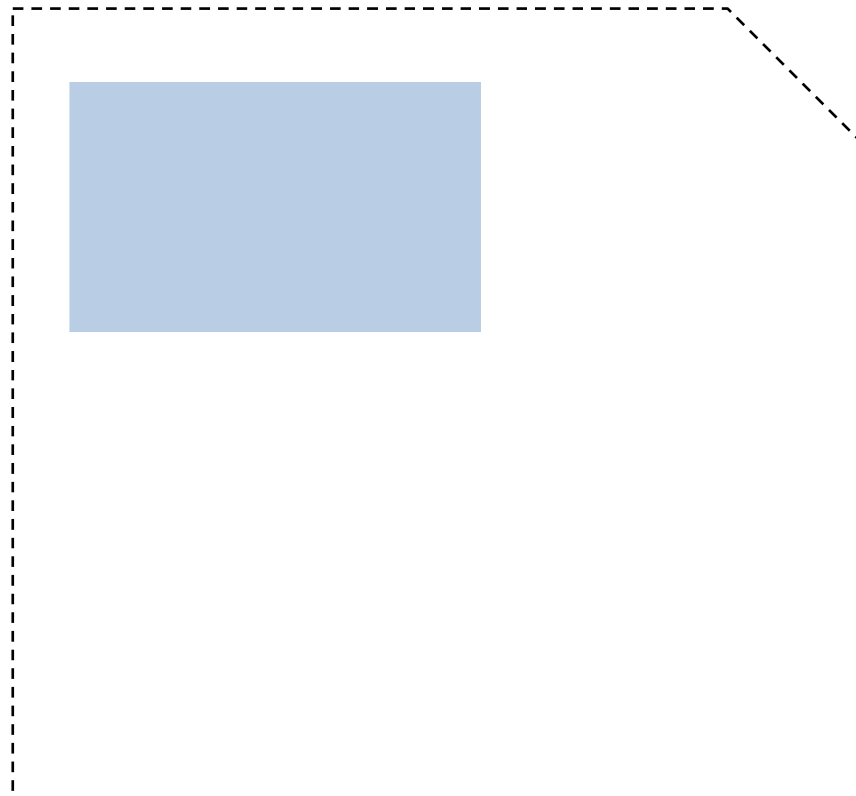

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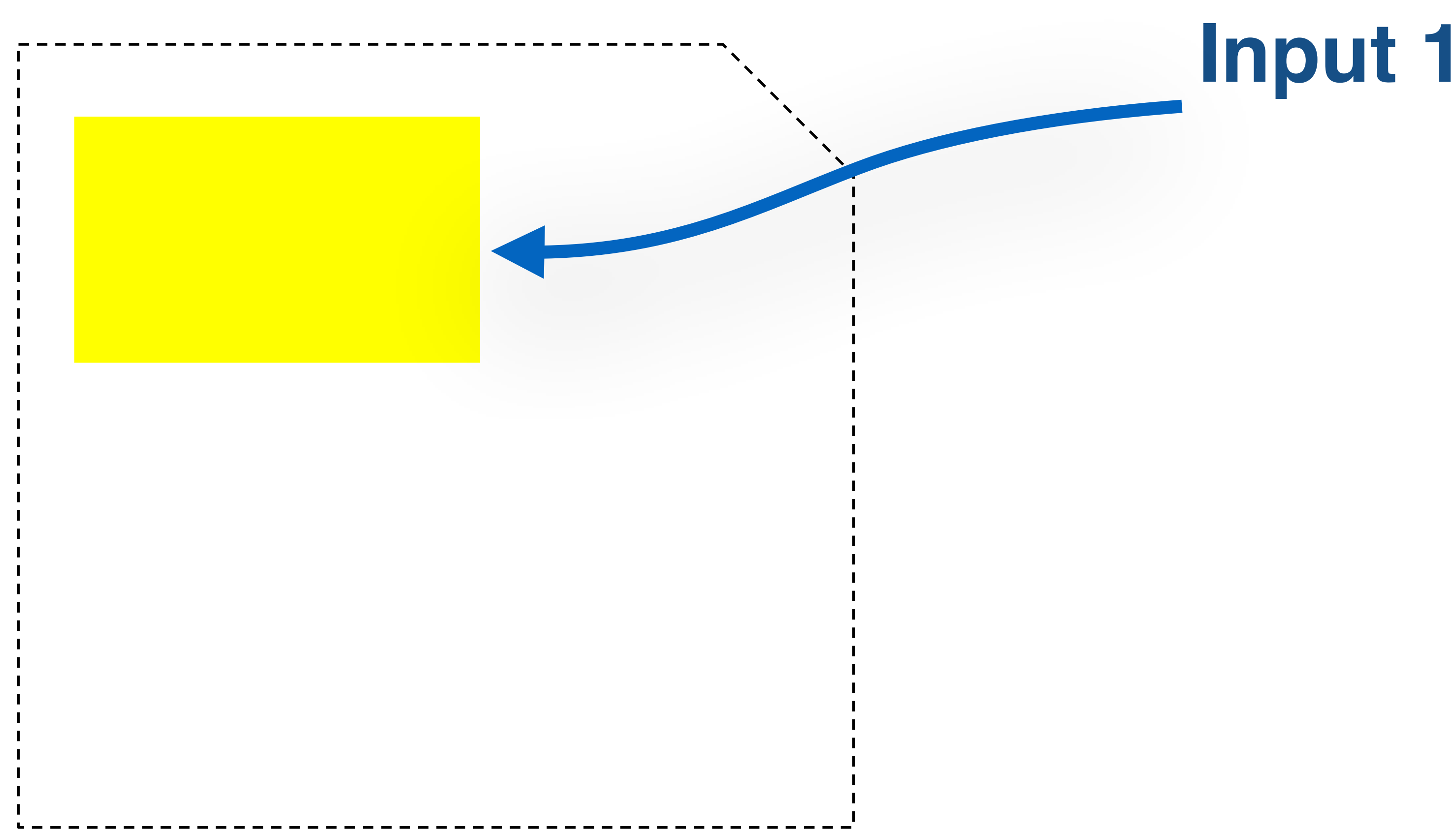


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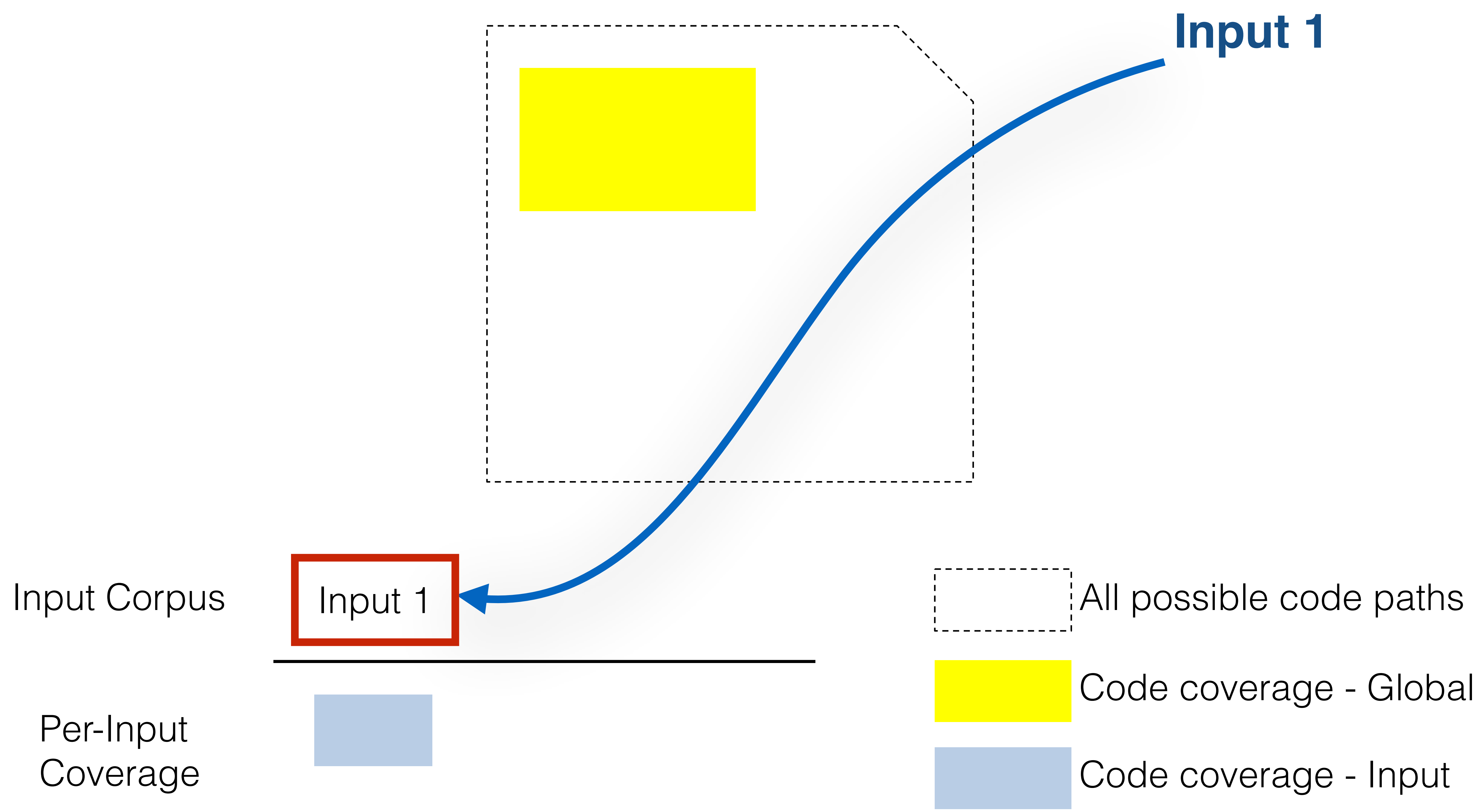
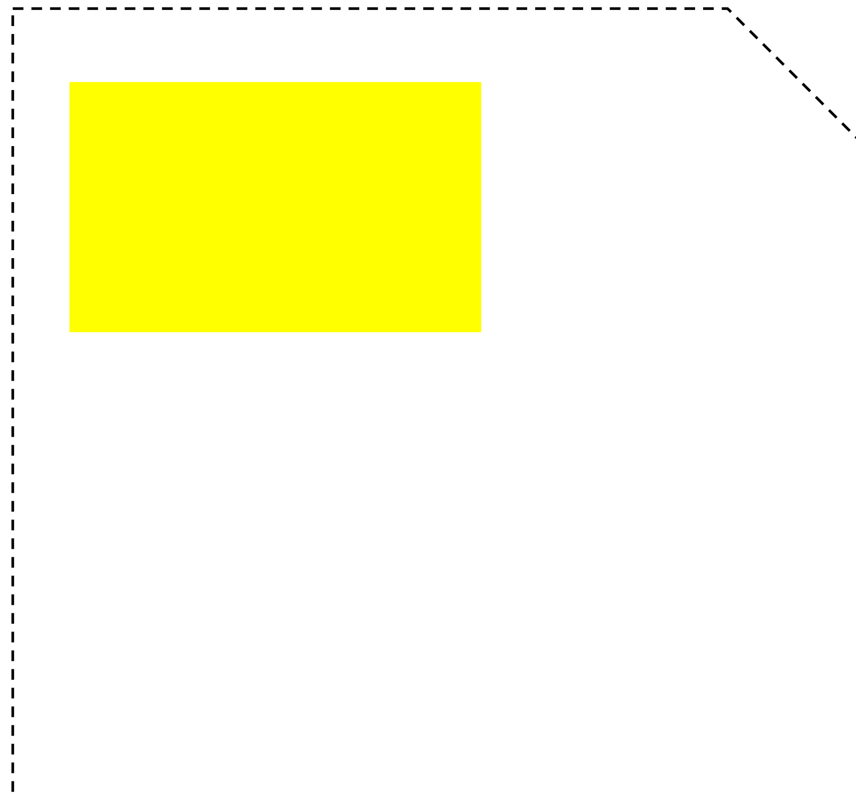


# Code Coverage - Single-App

**Input 2**



Input Corpus — Input 1

Per-Input Coverage

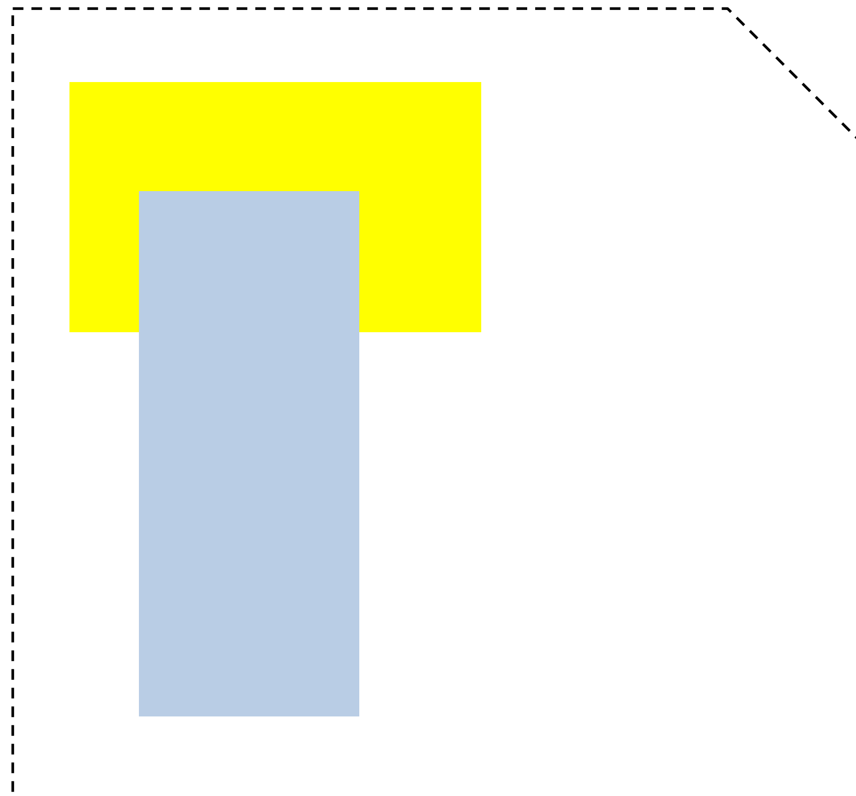
All possible code paths

Code coverage - Global

Code coverage - Input

# Code Coverage - Single-App

**Input 2**

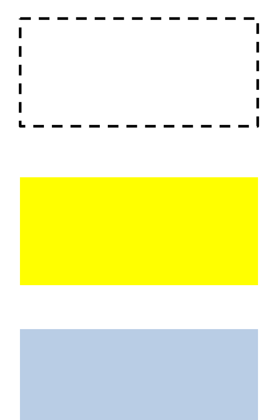


Input Corpus

Input 1

Per-Input Coverage





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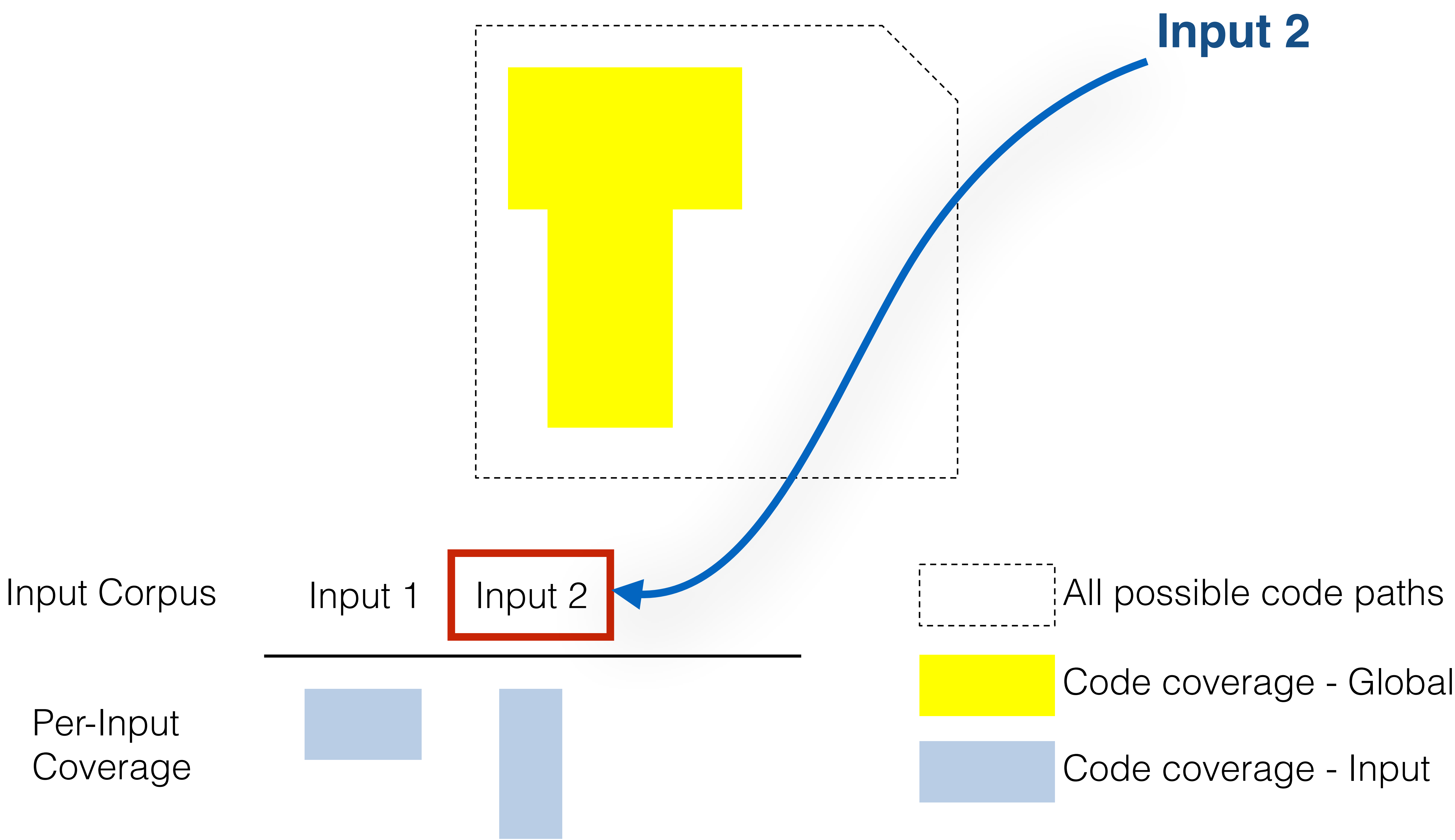

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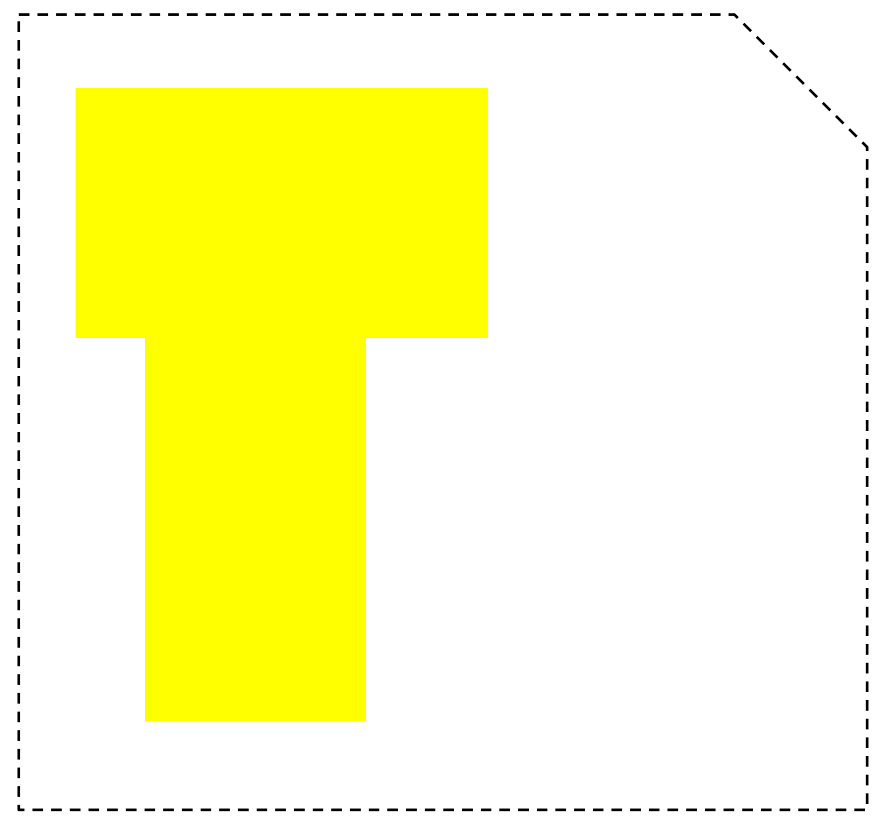
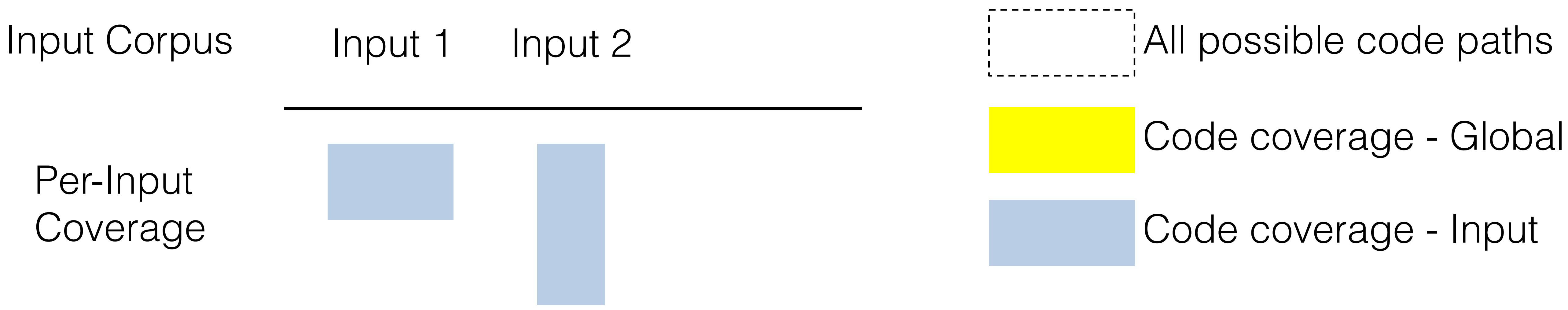
**Input 3**





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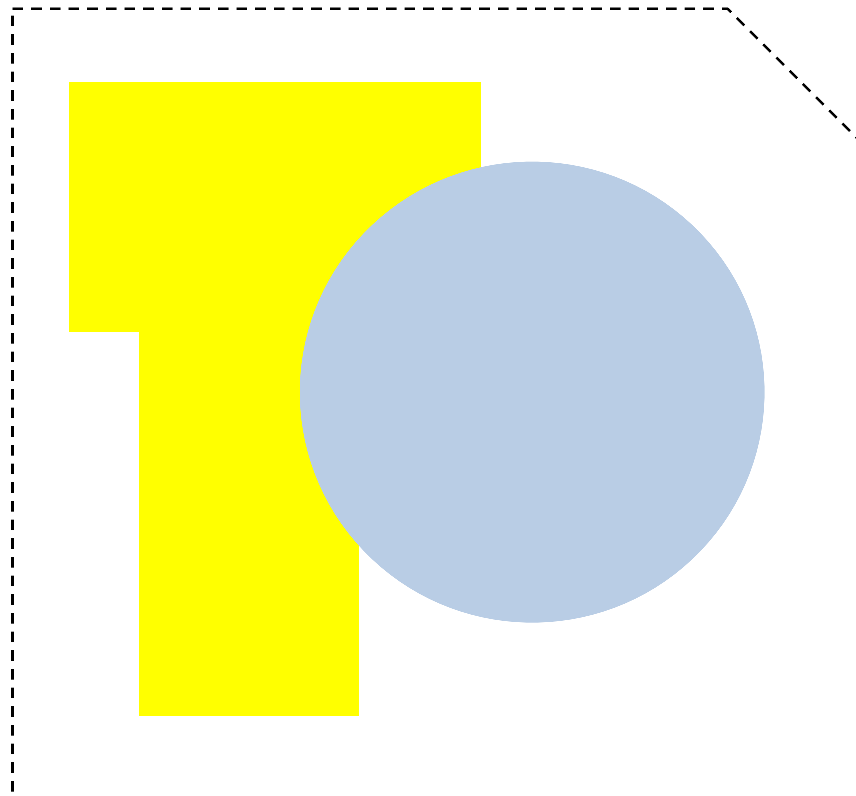

Input Corpus | Input 1 | Input 2

Per-Input Coverage



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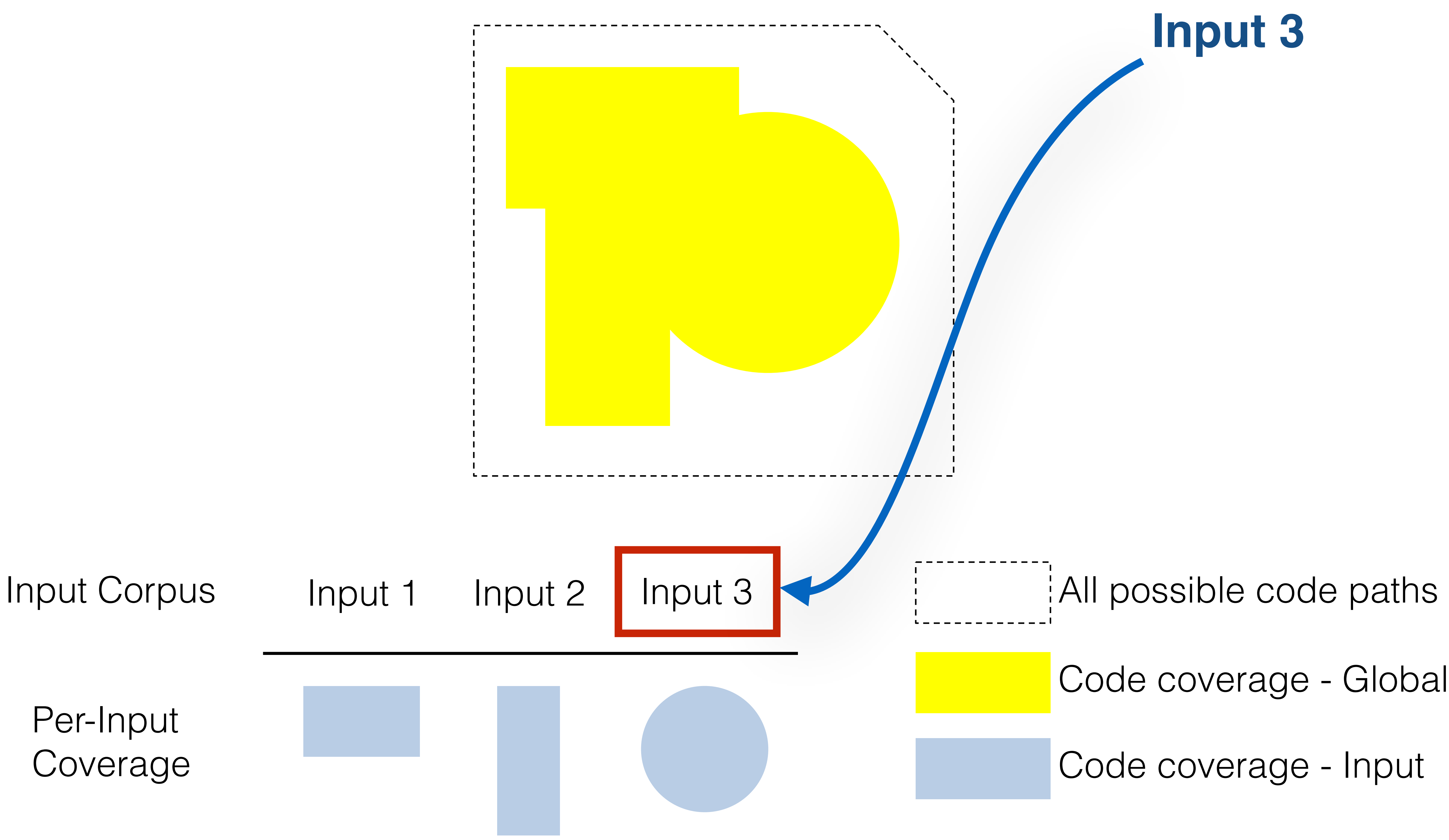

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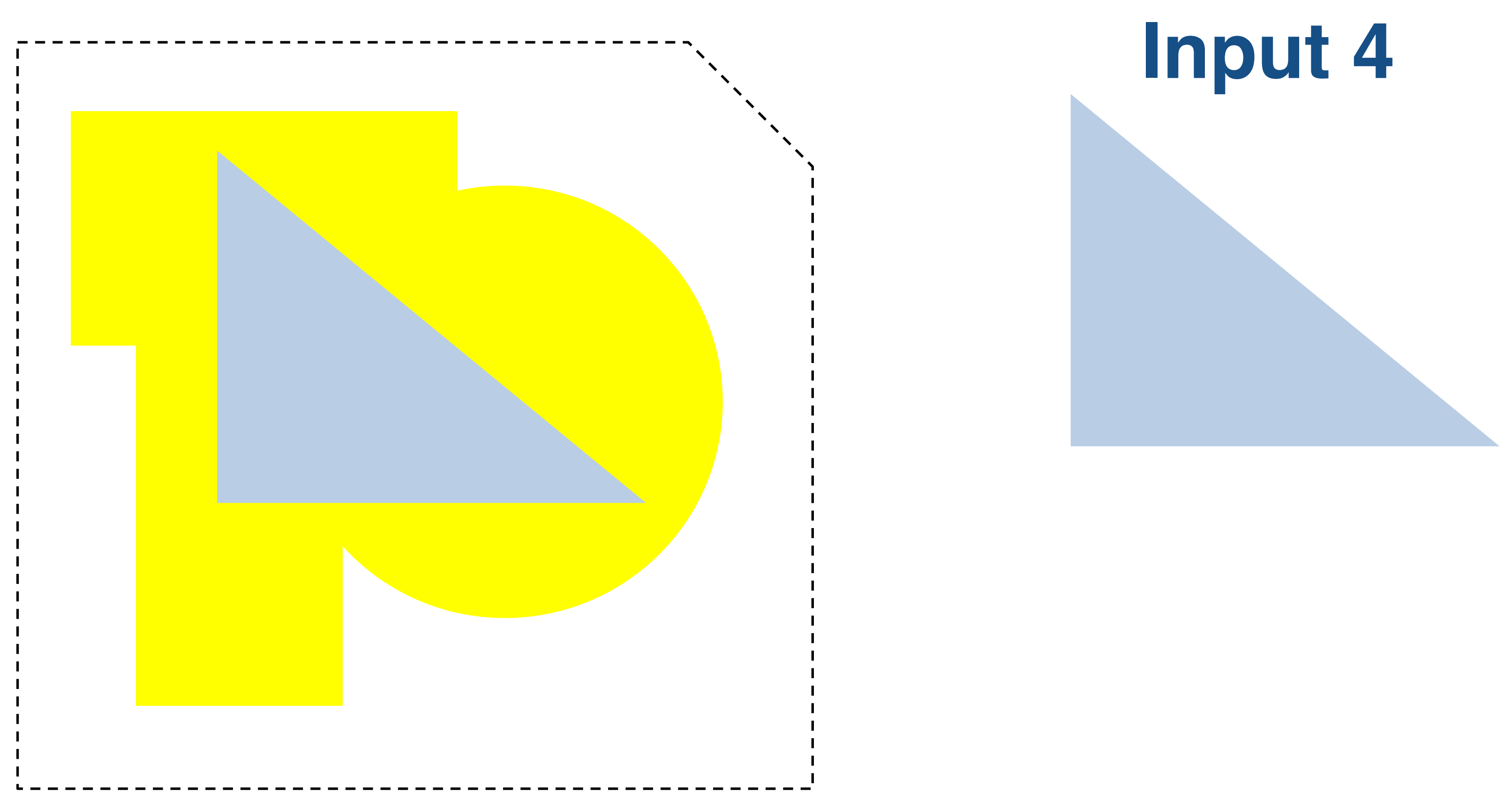


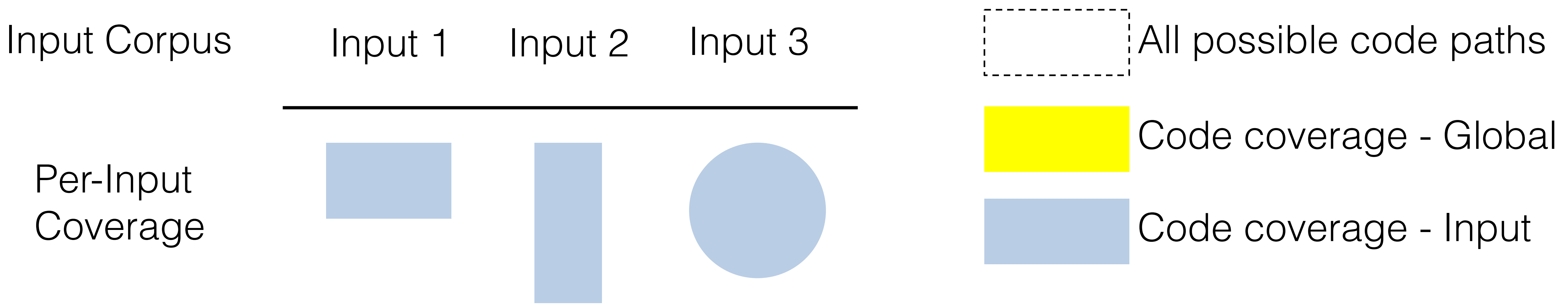

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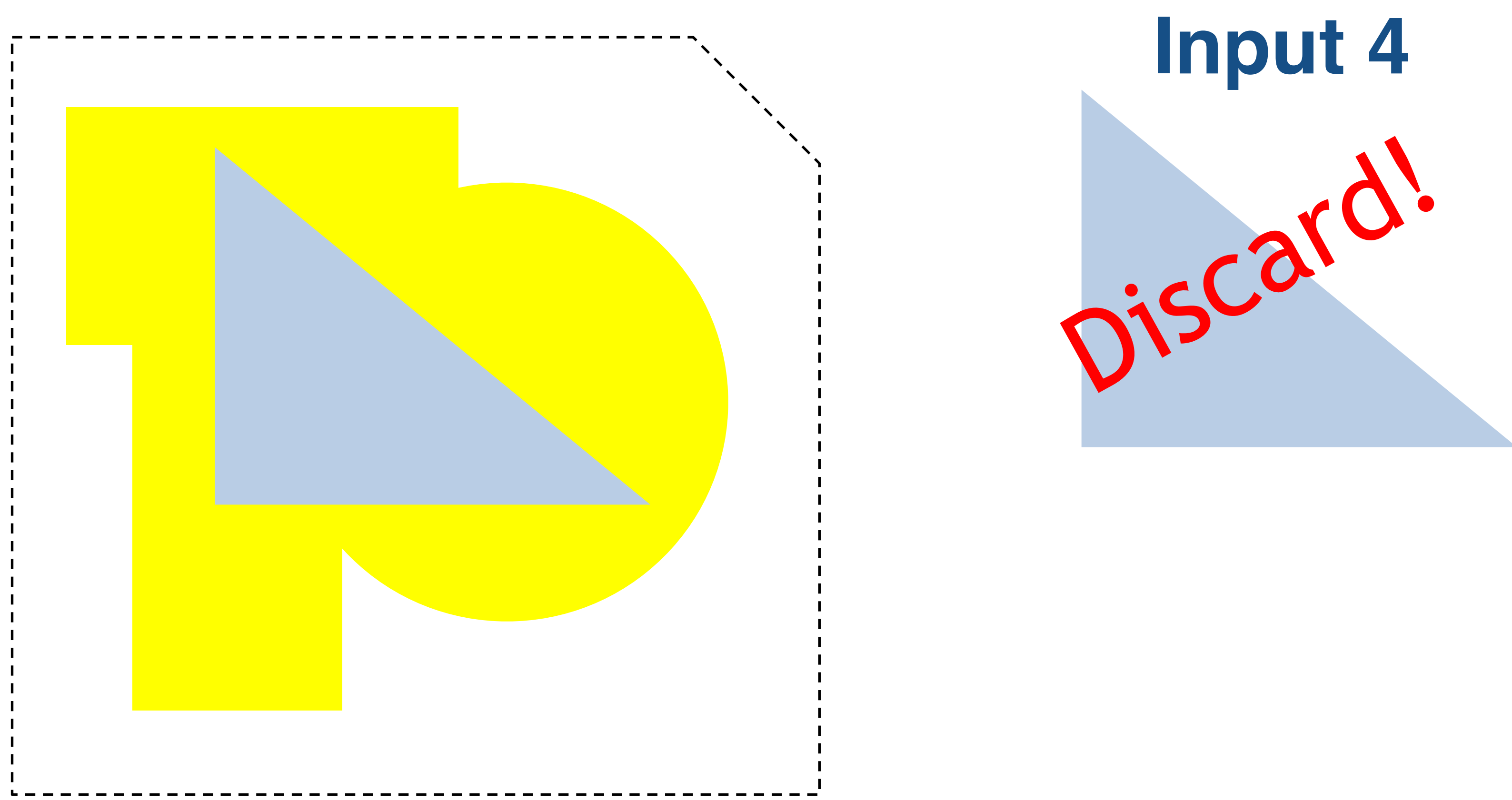
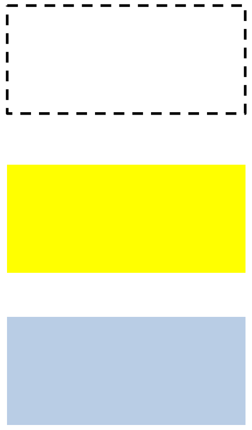



Input Corpus | Input 1 | Input 2 | Input 3

Per-Input Coverage





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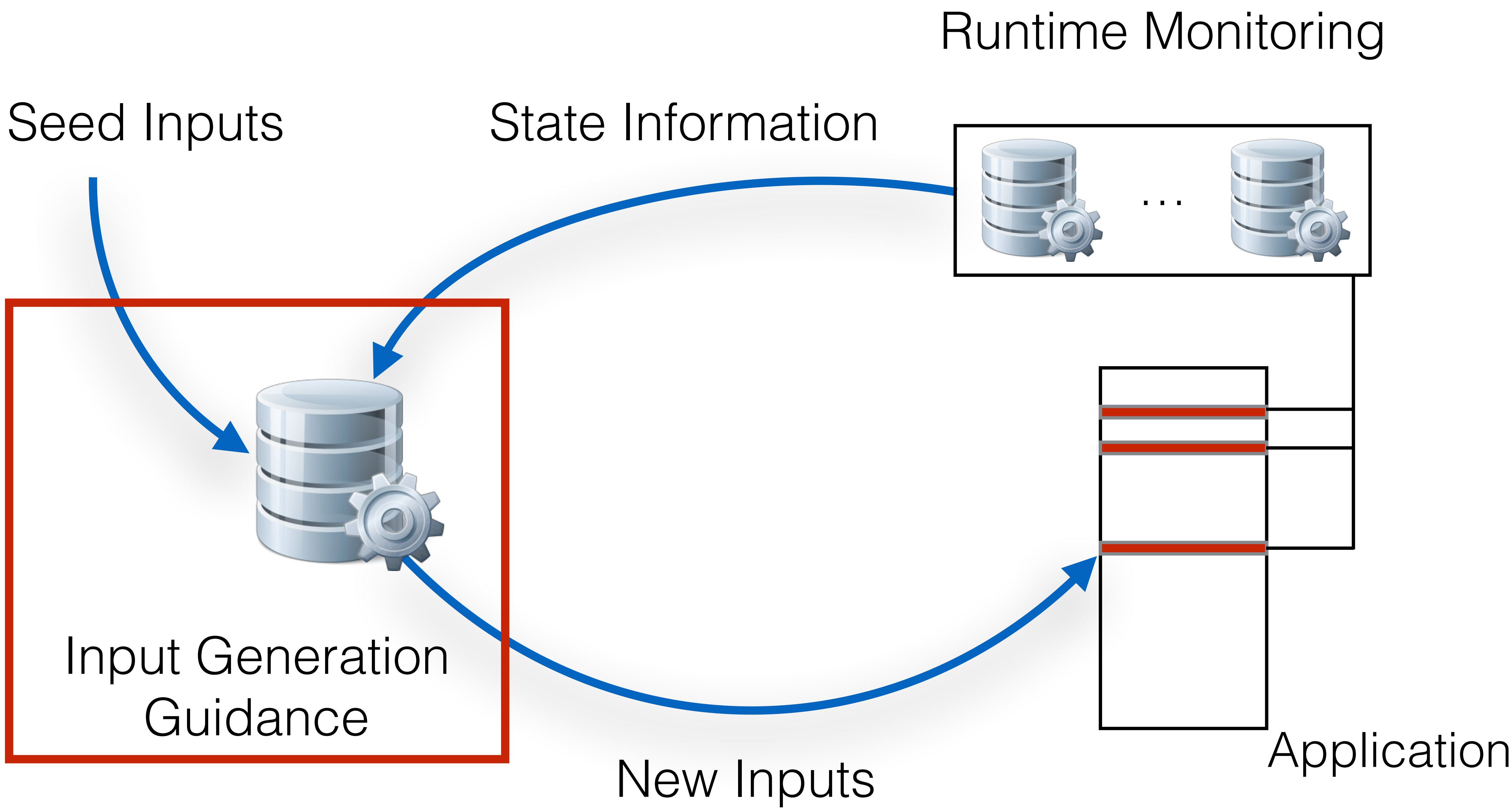
# Domain-Independent Evolutionary Testing



# Evolutionary Differential Testing - Multiple-Apps

What are the options to driving input generation?

1. Use program states solely from single application, like most modern fuzzers

2. Use global program states combined across all applications

3. Re-design guidance engine geared towards differential testing

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1. Use program states solely from single application, like most modern fuzzers

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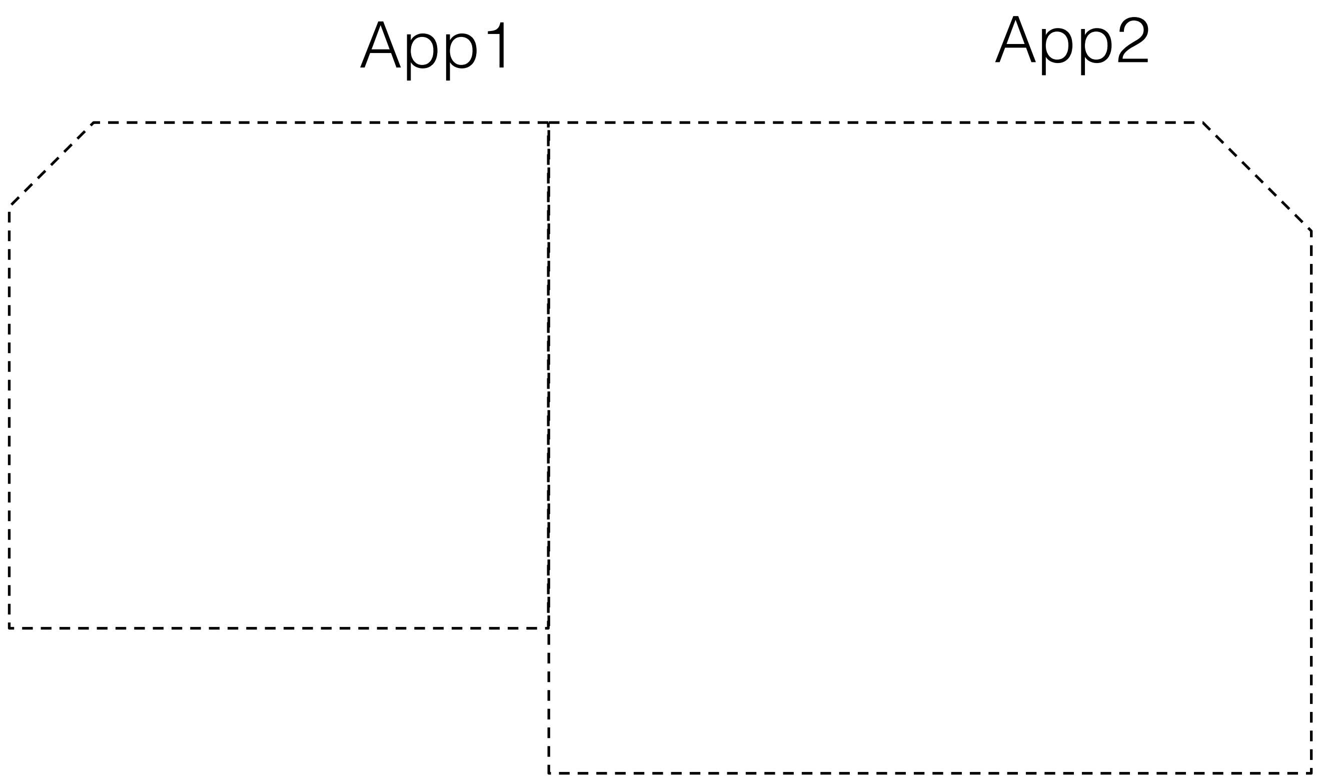
# Key Insight

Techniques that work well in the context of single application testing may not be optimal for differential testing!

# Multi-App Code Coverage




Input Corpus

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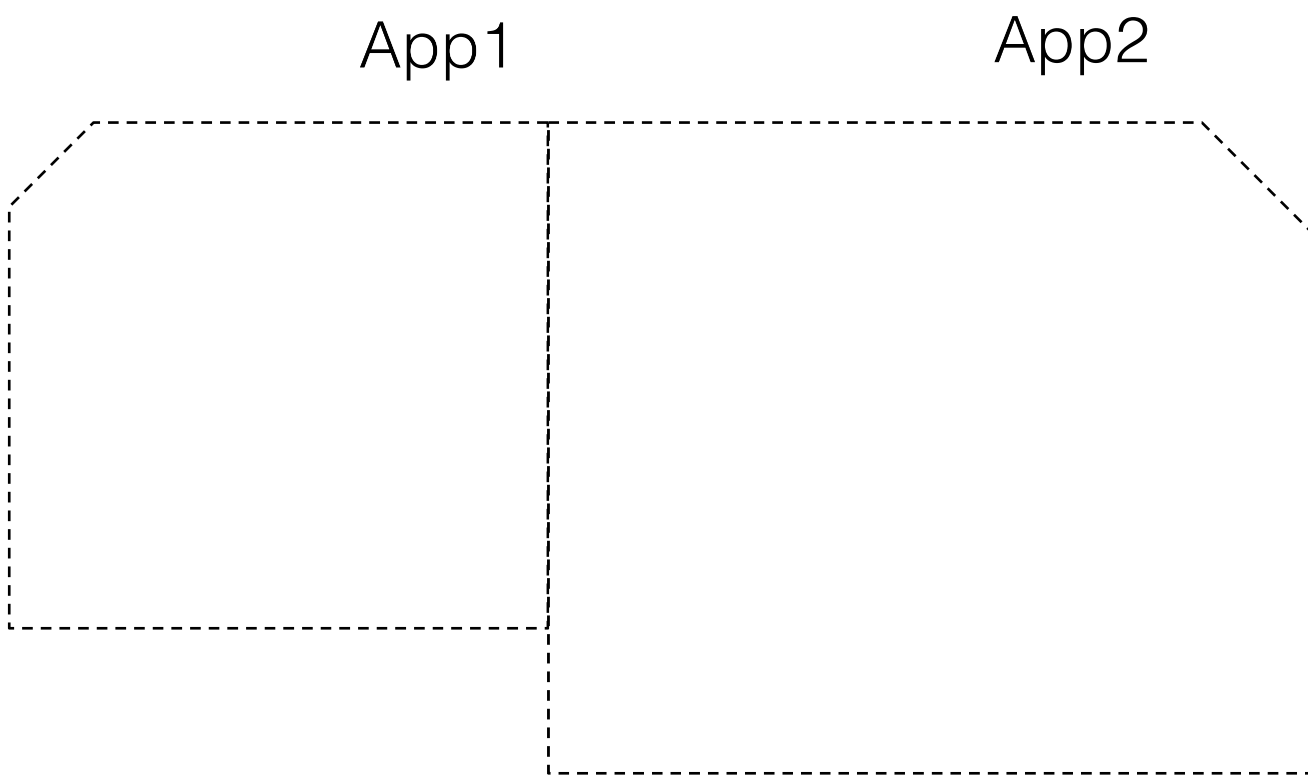


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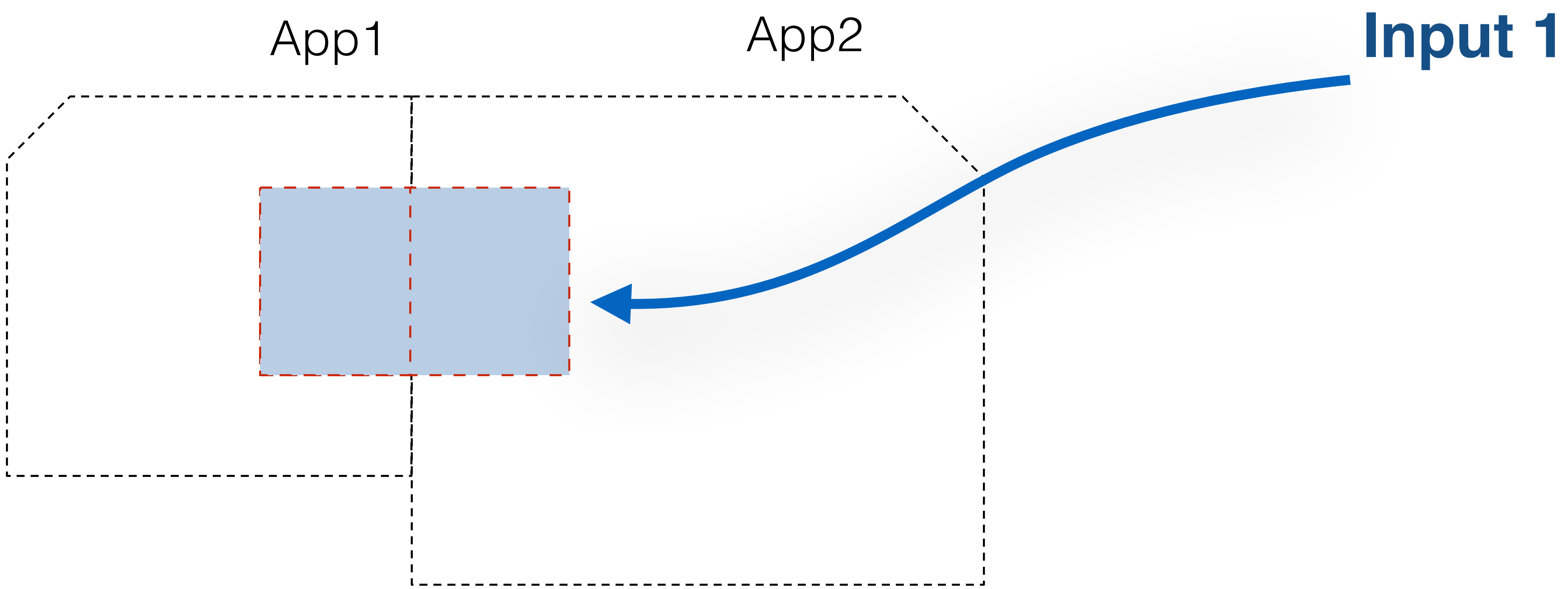


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Per-Input
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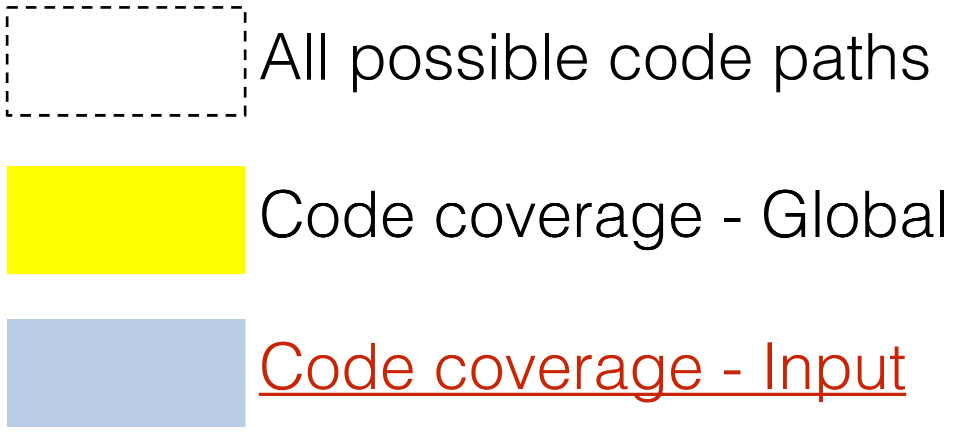

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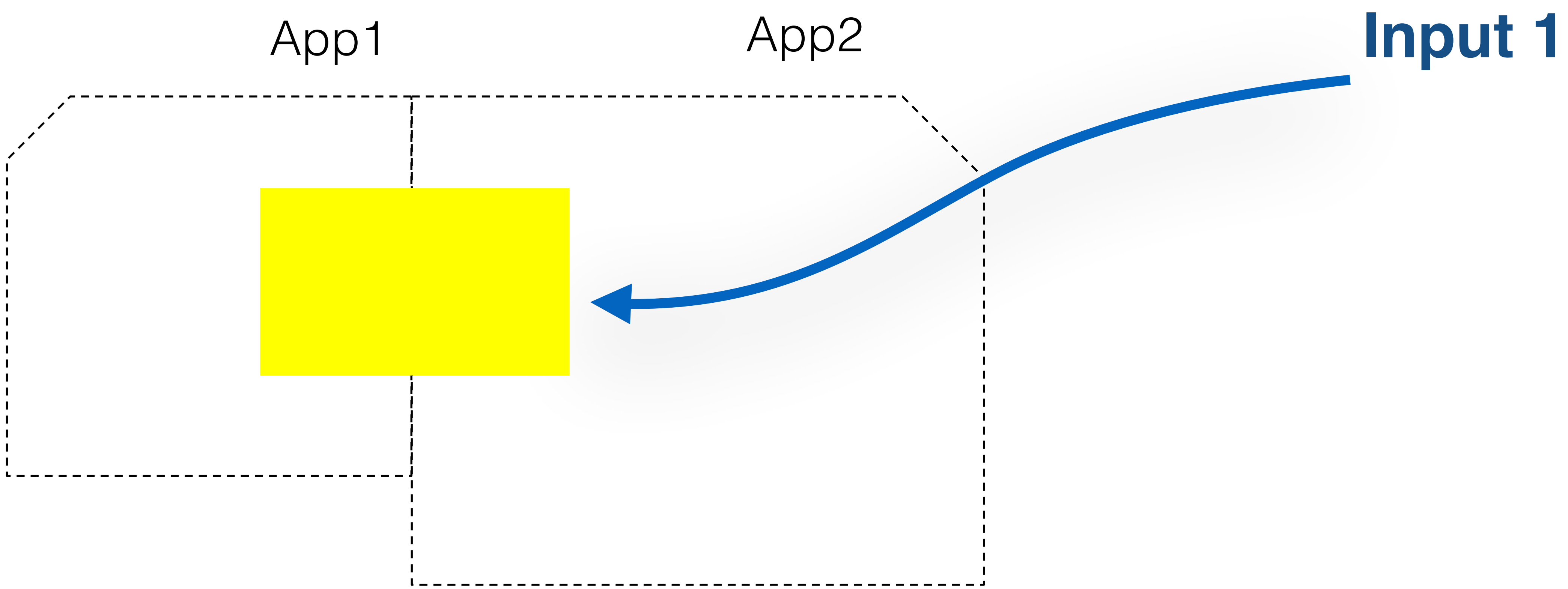


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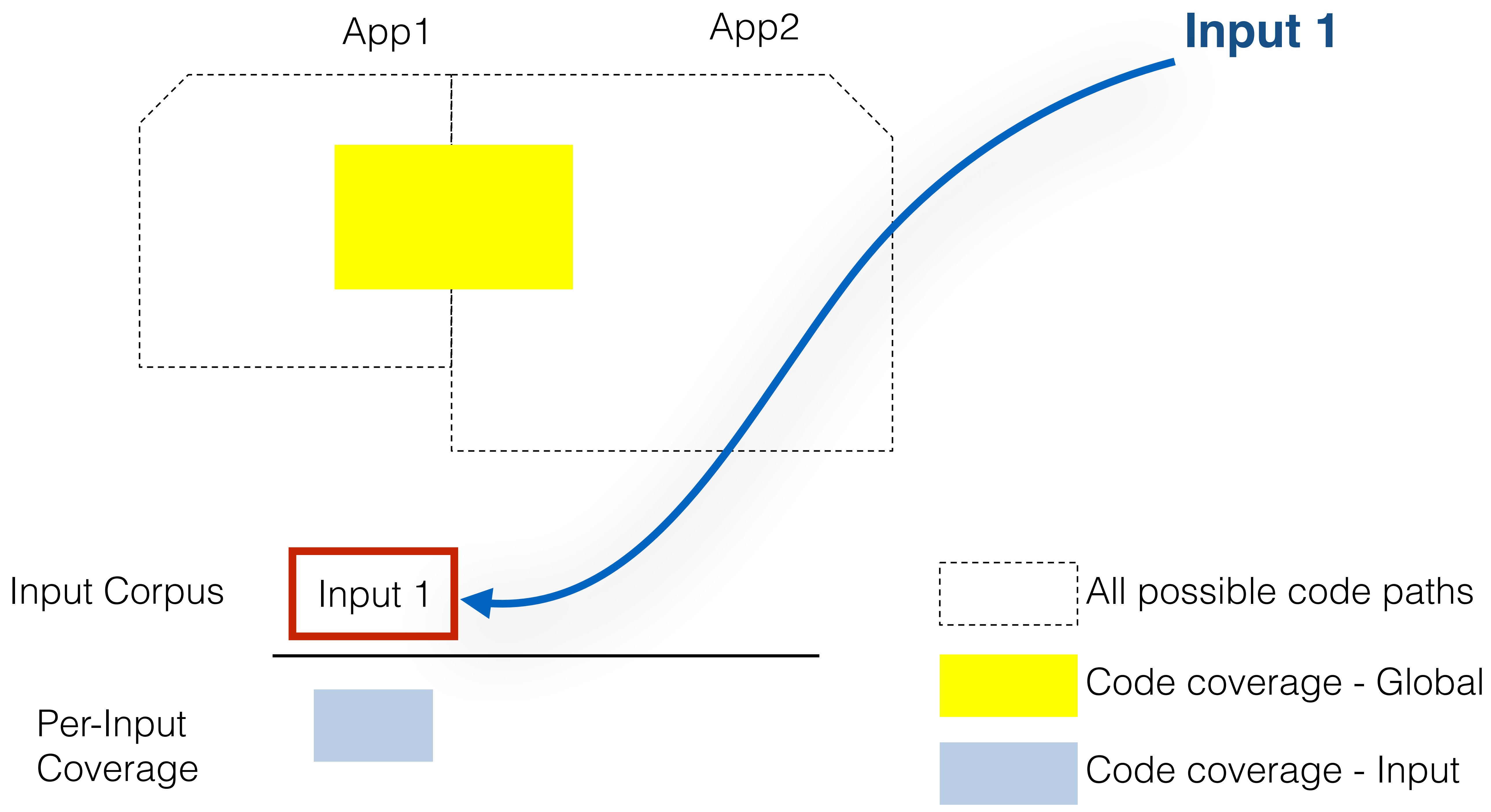

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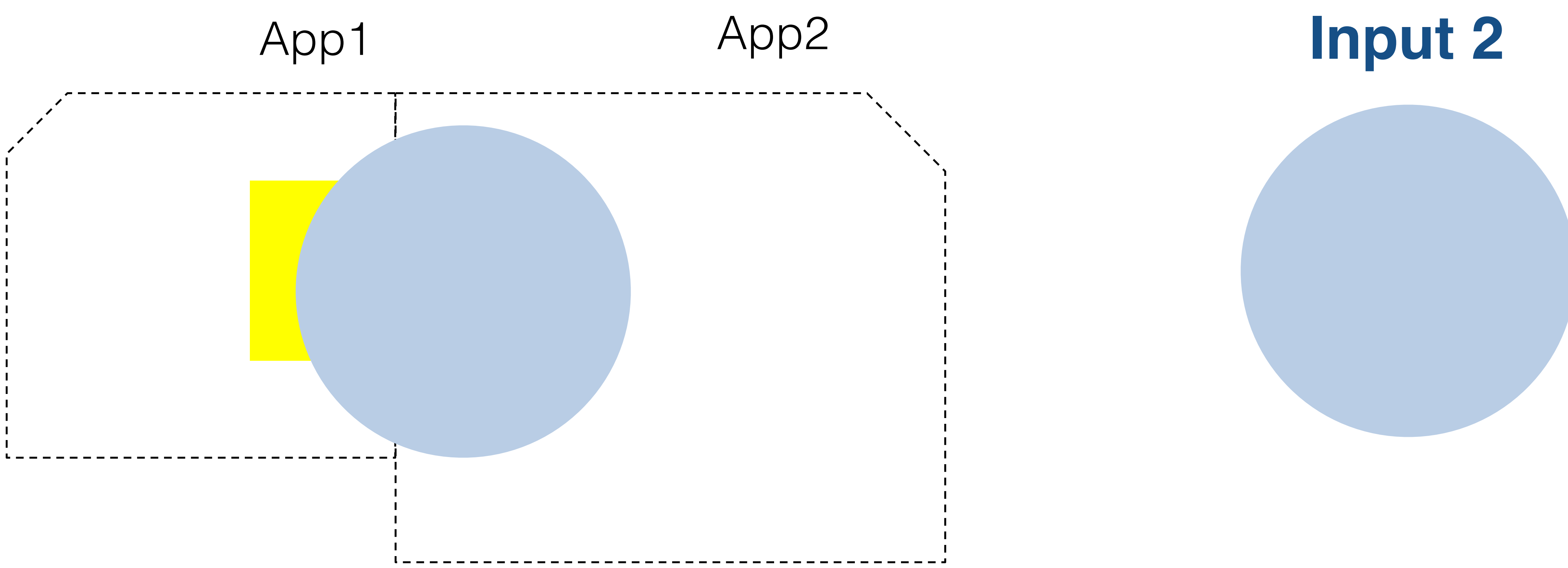
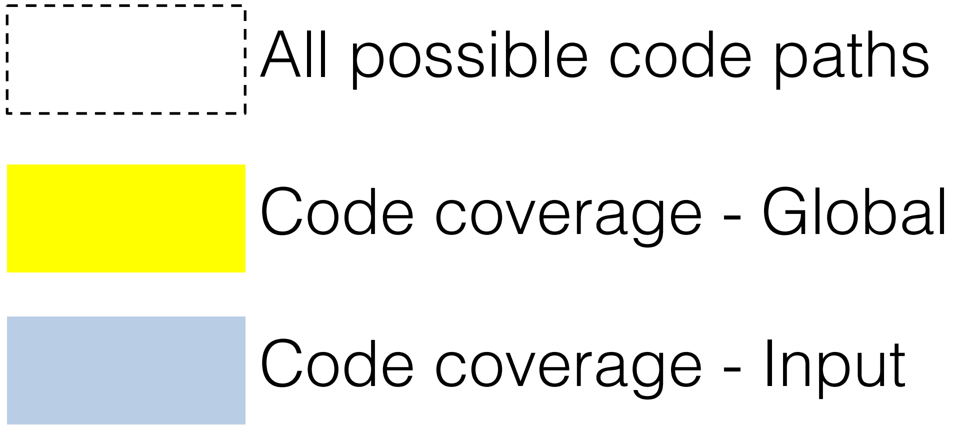



Input Corpus — Input 1

Per-Input Coverage



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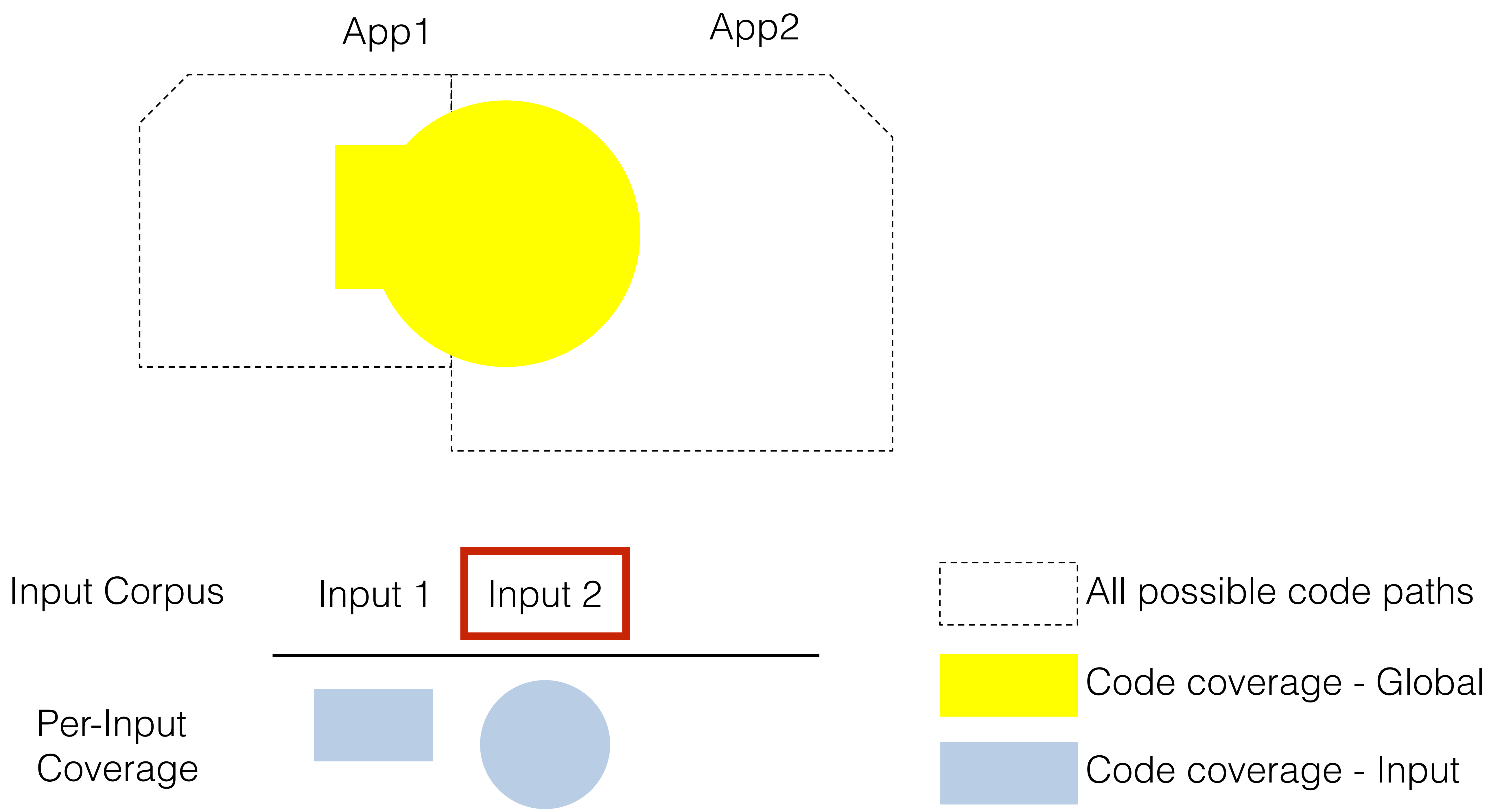

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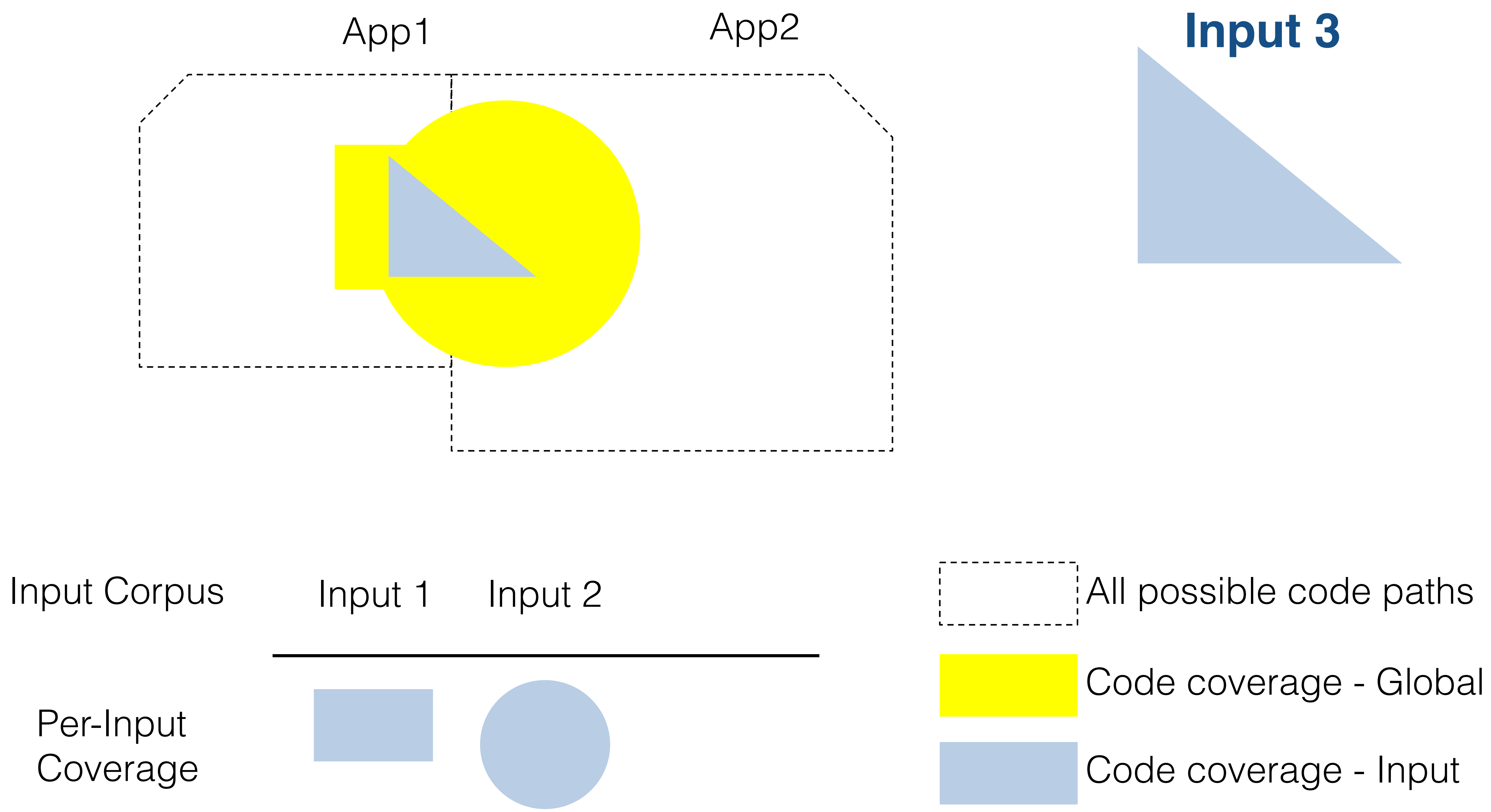

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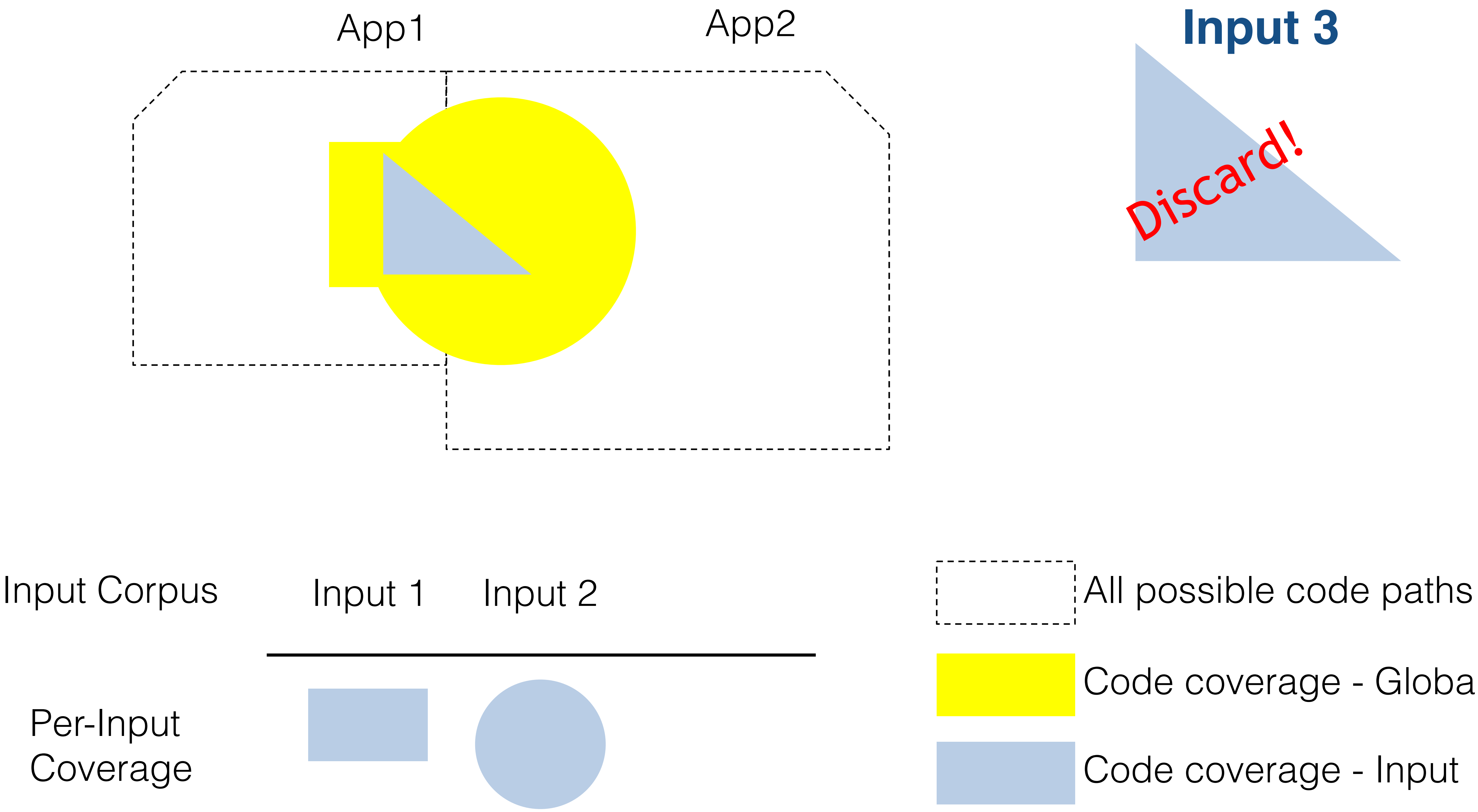

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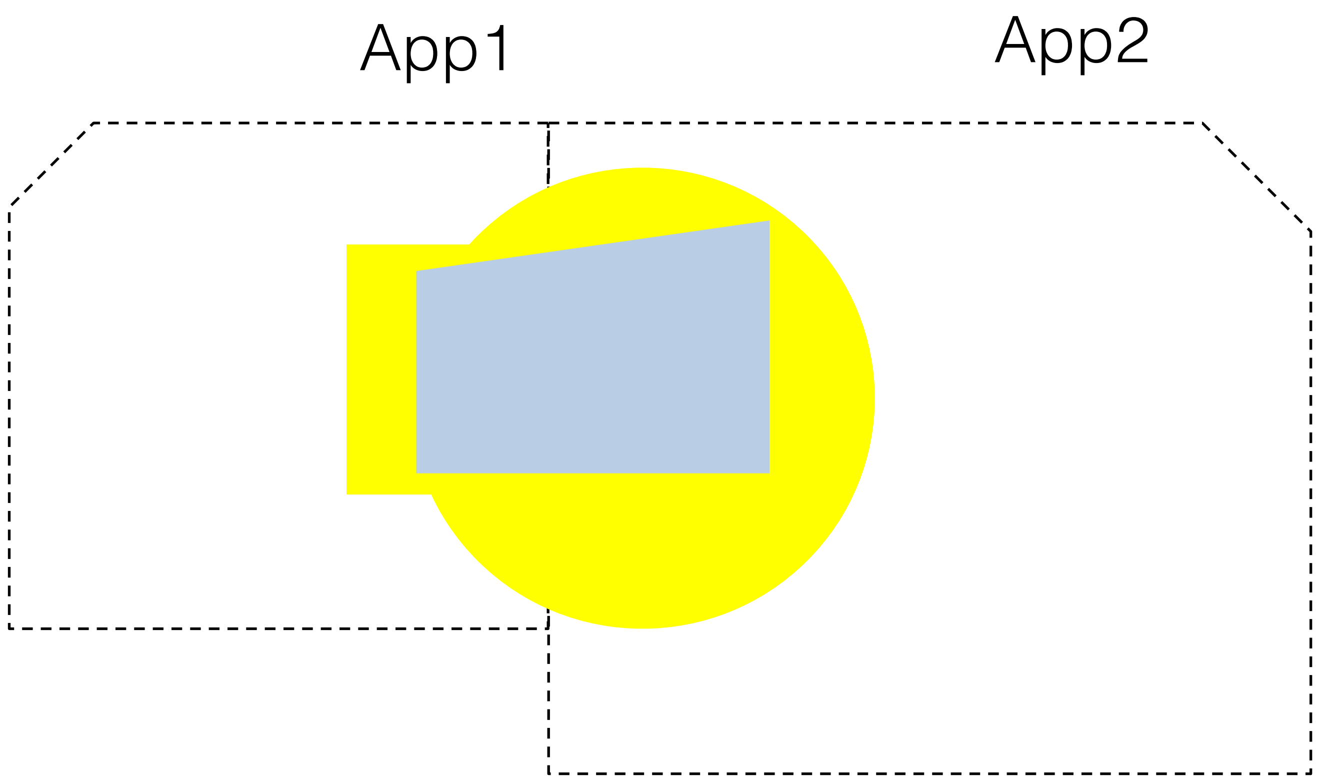



**Input 4**



Input Corpus    Input 1    Input 2

Per-Input Coverage

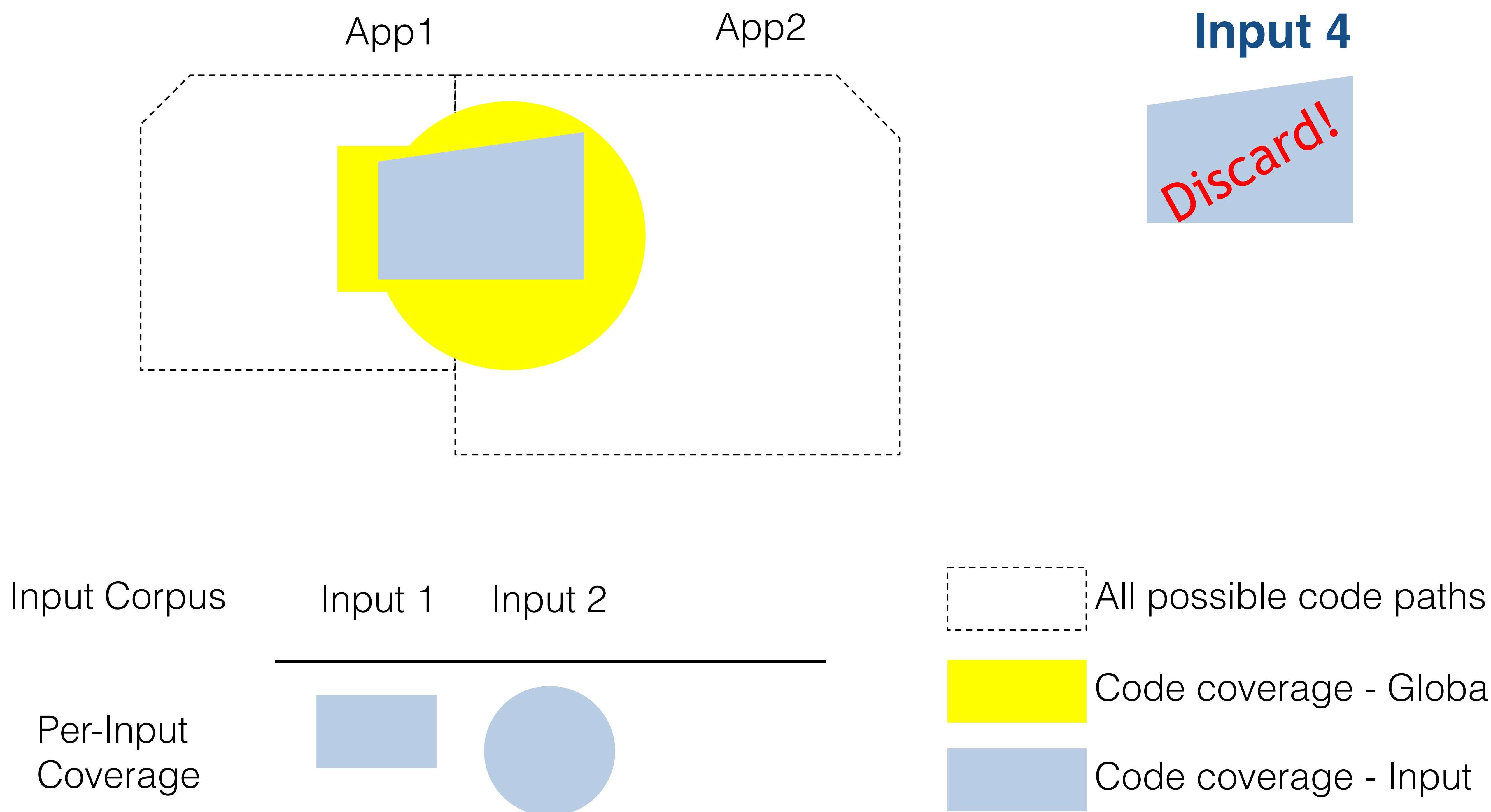


All possible code paths

Code coverage - Global

Code coverage - Input

# Multi-App Code Coverage



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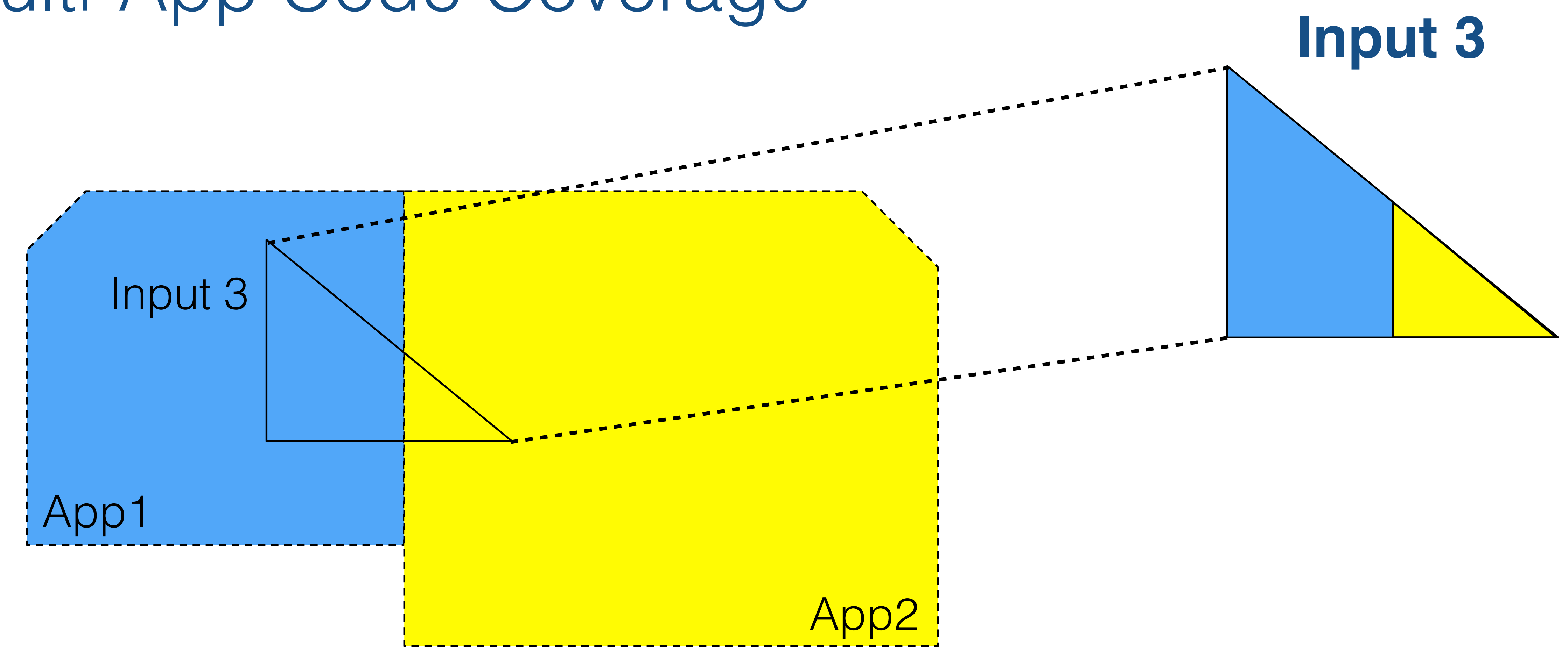

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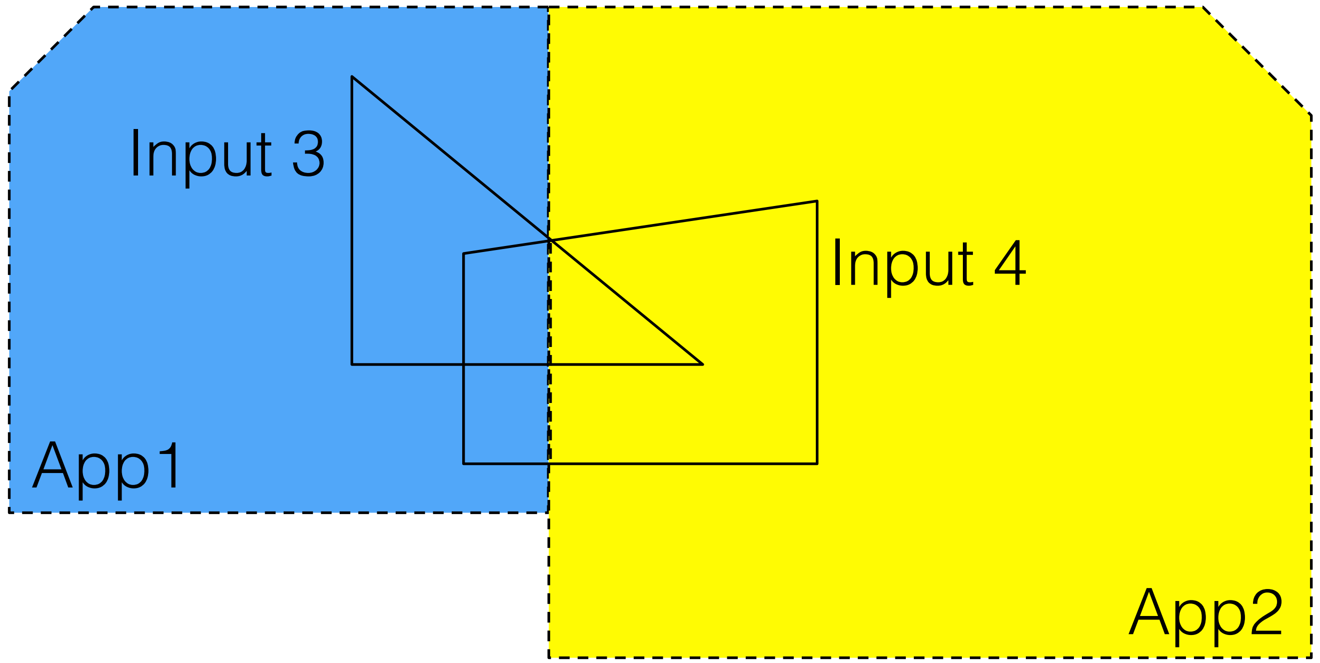


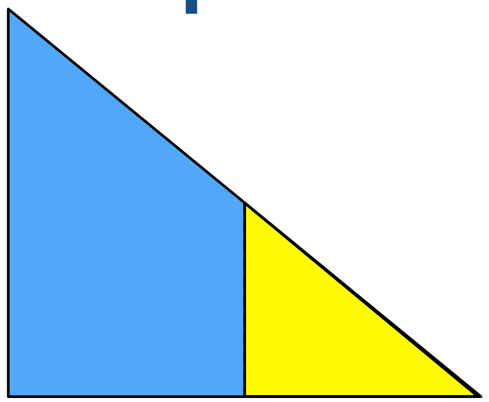


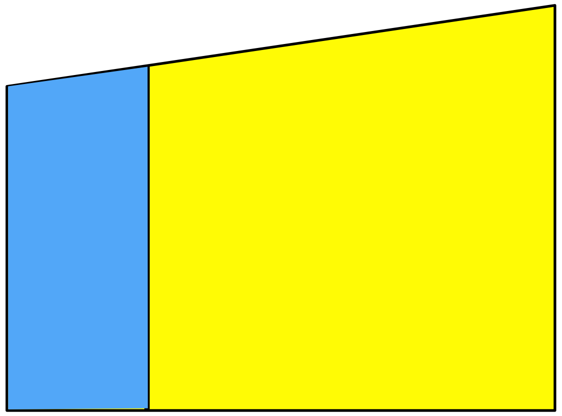

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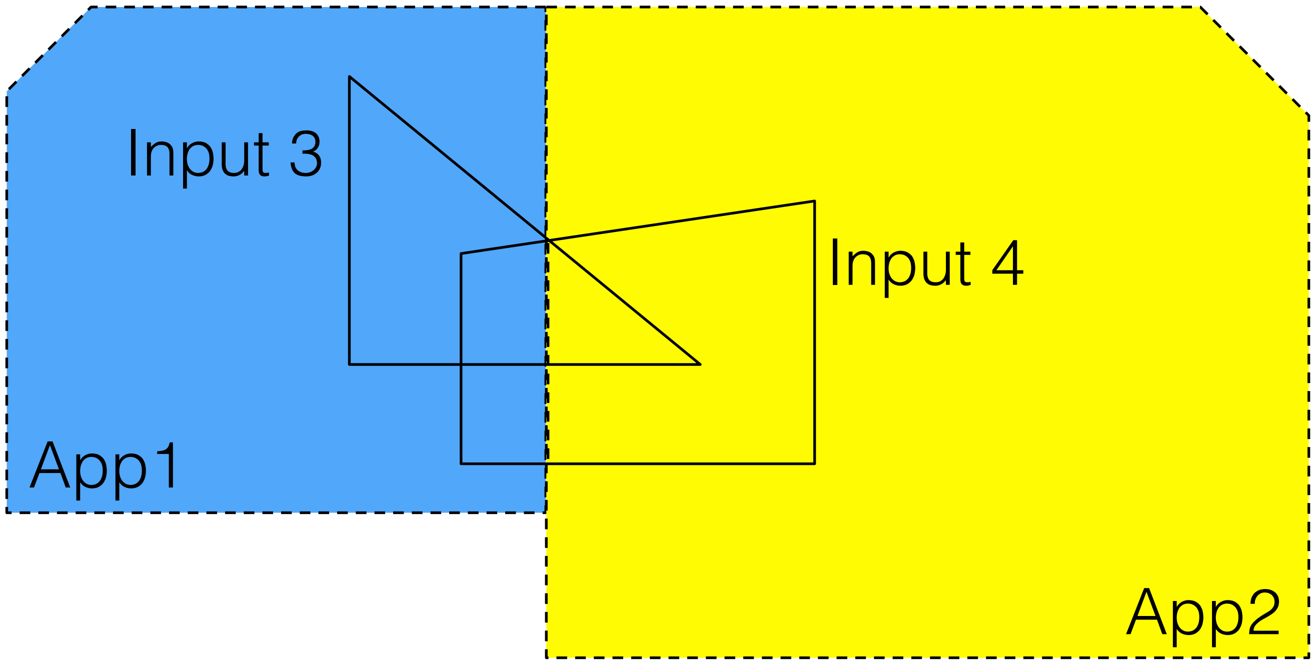


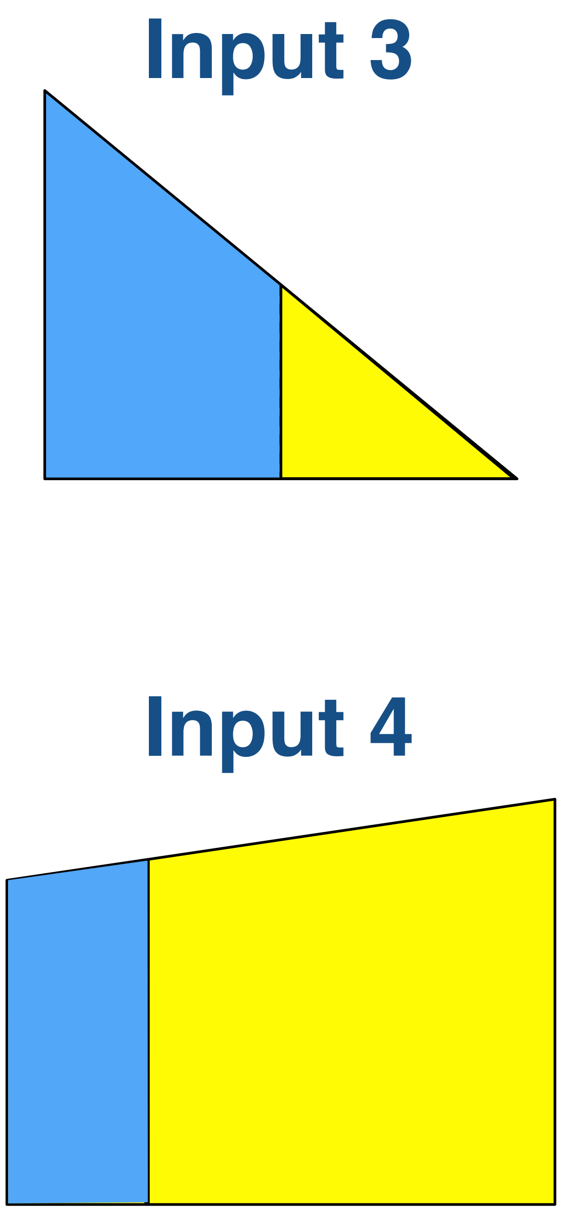


- These inputs exercise disproportionate code regions in the two apps
- This disproportion might imply differences in handling logic
- Retaining them in corpus speed up process of finding discrepancies

Relative program behavior is important in this context!

δ-diversity: a new approach to guided differential testing

# Differential Testing under δ-diversity

- Obtain State Information
  - White-box (e.g., at compile time)
  - Gray-box (e.g., using Dynamic Binary Instrumentation)
  - Black-box (e.g., only examining system response to inputs)
- Behavioral Diversity

# Differential Testing under δ-diversity

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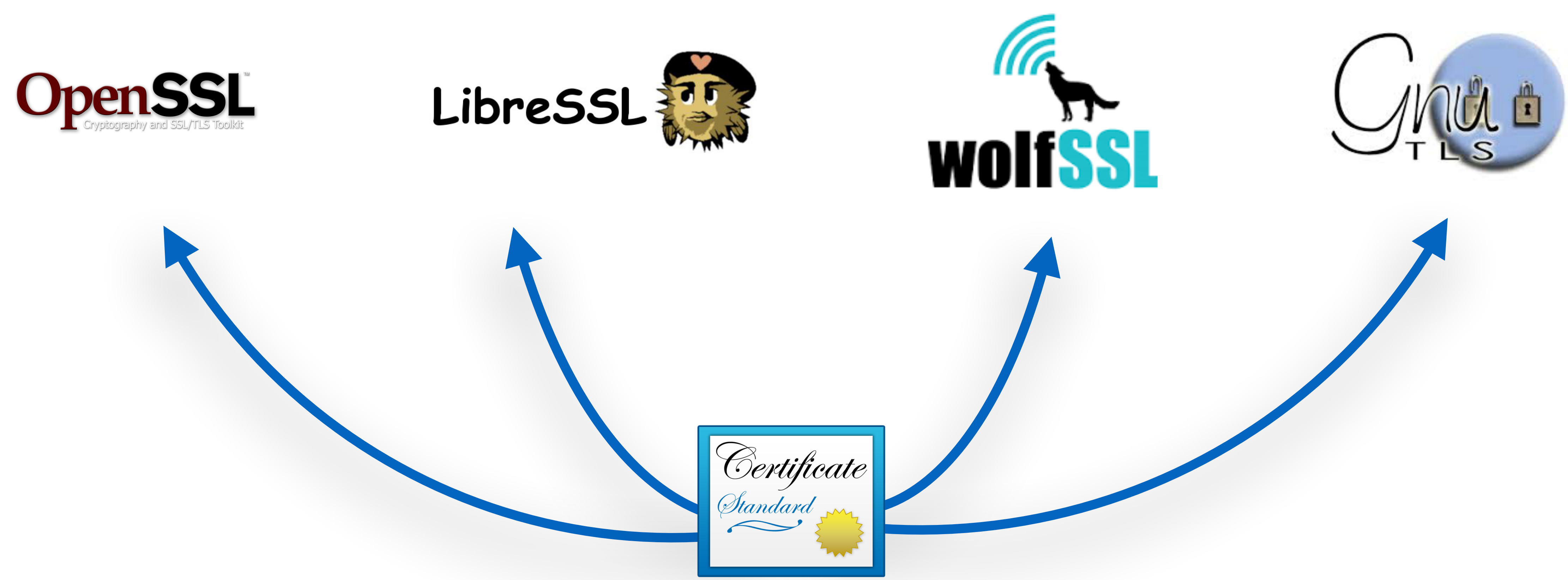

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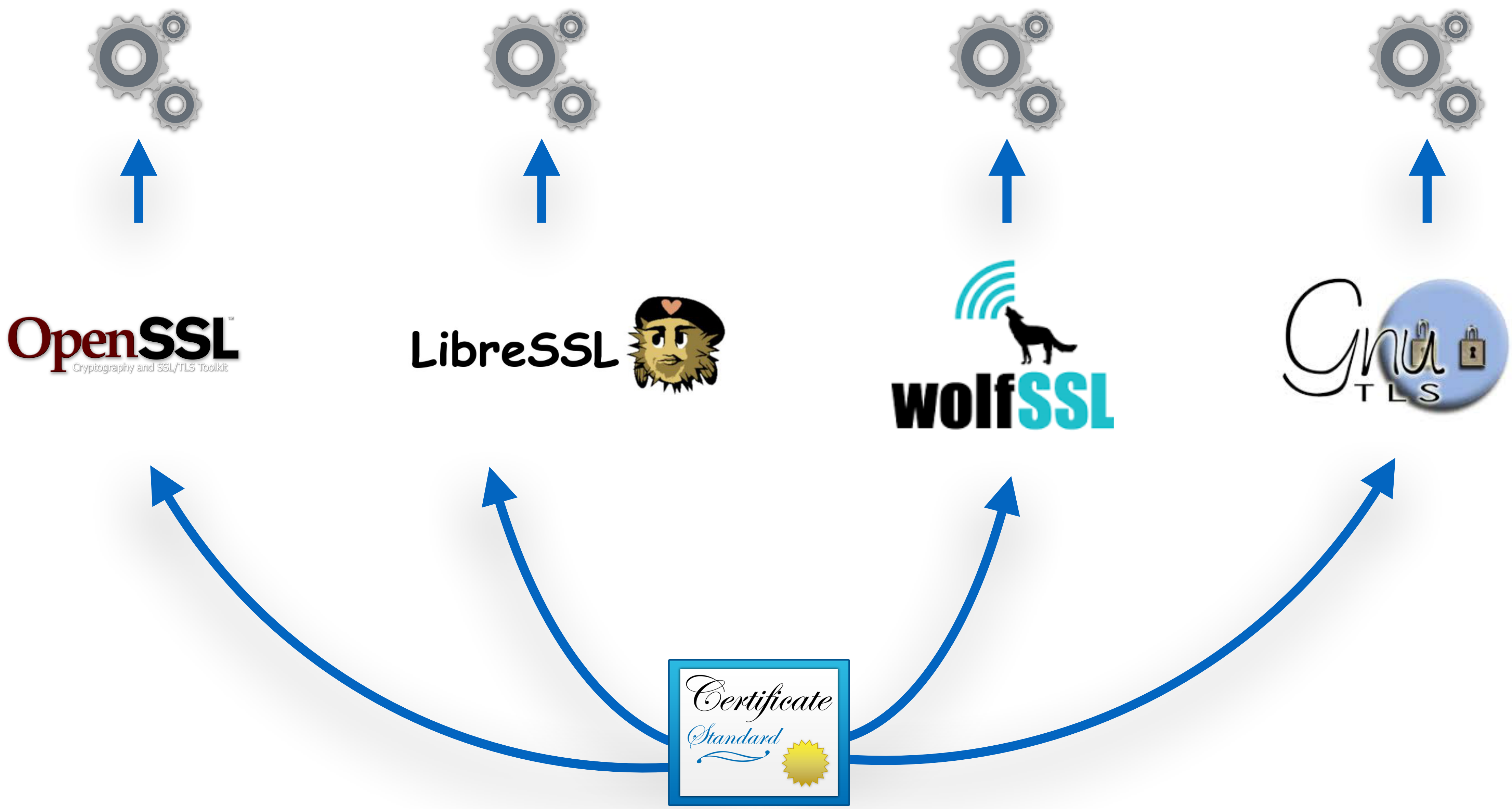
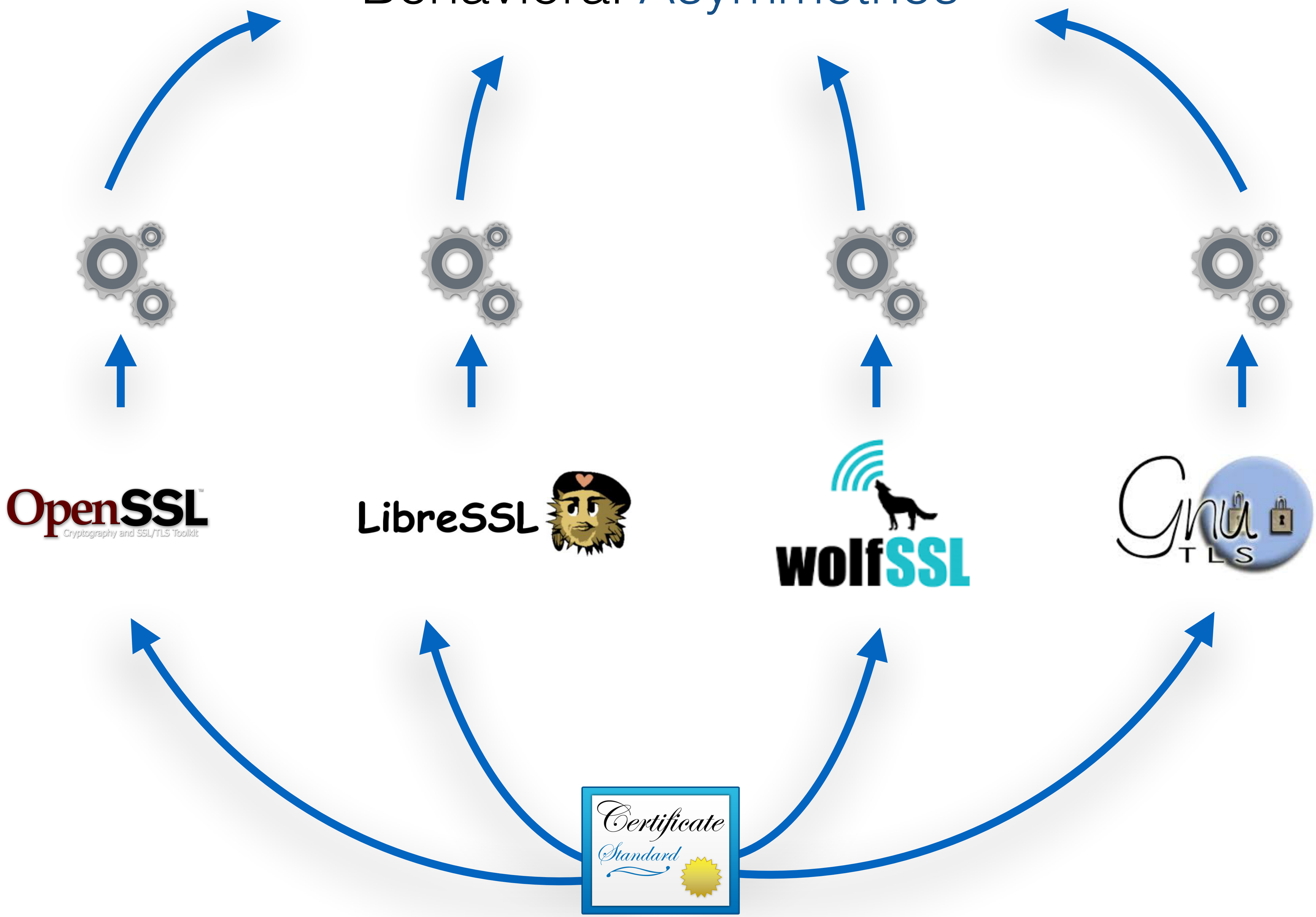


# Differential Testing under δ-diversity

Behavioral Asymmetries



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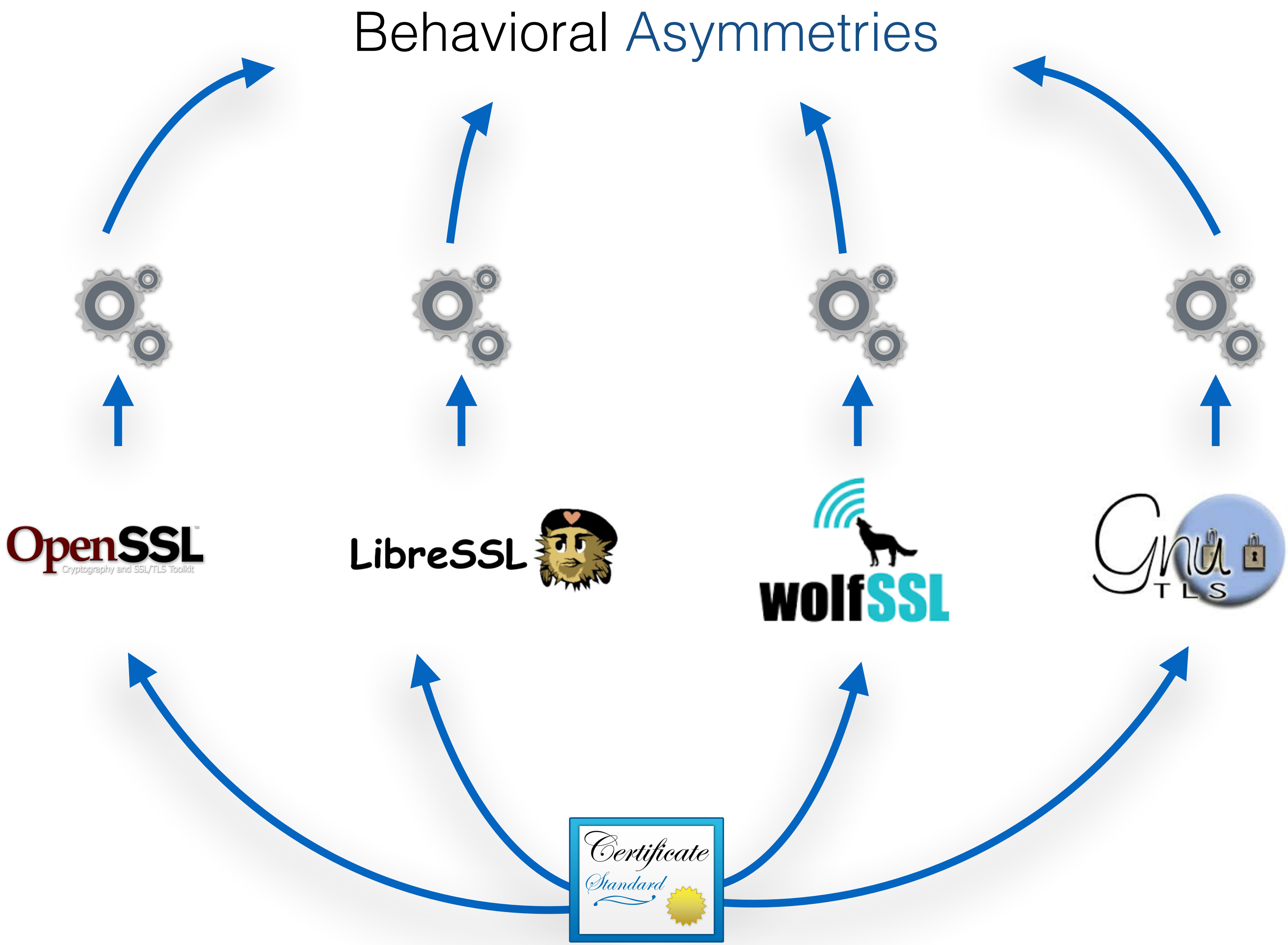
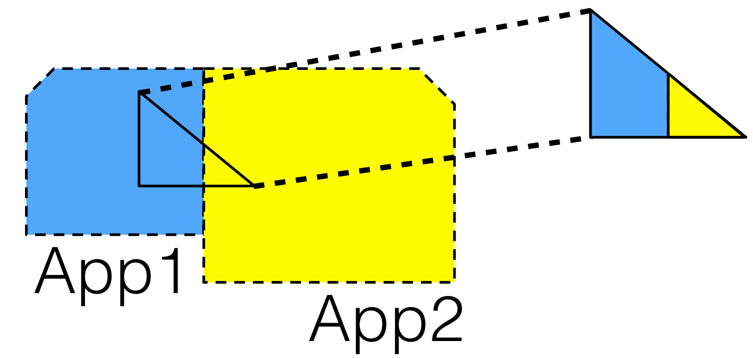
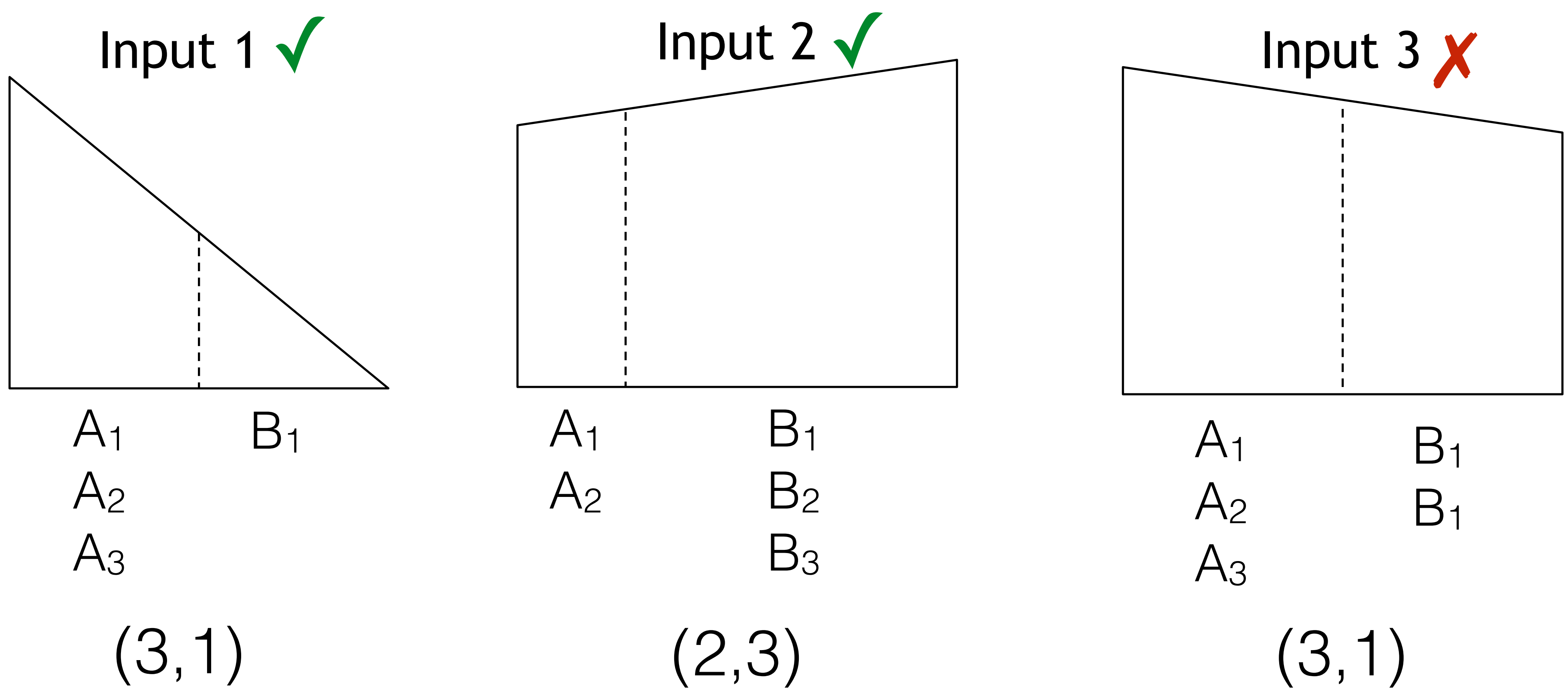


# Differential Testing under δ-diversity

- Two examples:
  - Gray-box
  - Black-box
- Both outperform code coverage

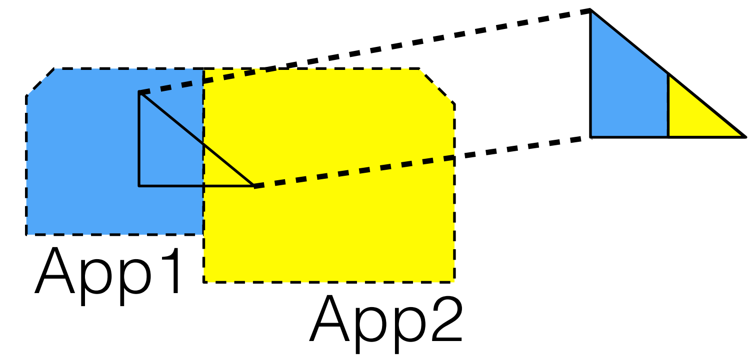
# Path δ-diversity: gray-box

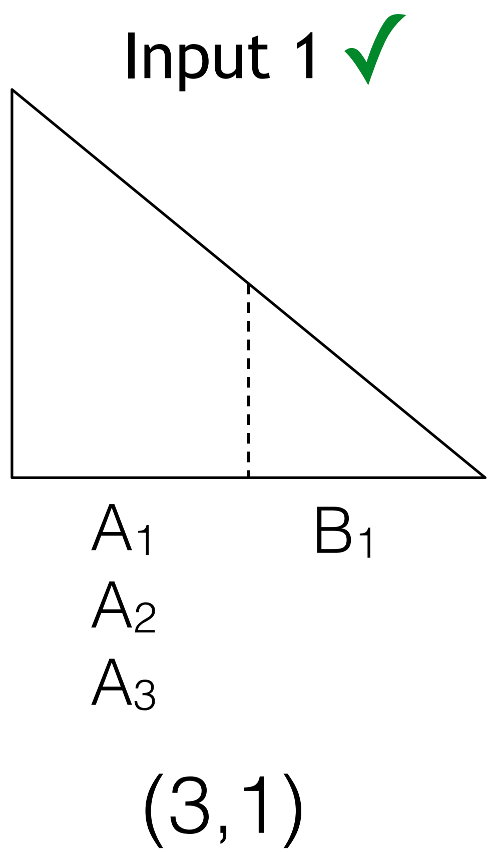


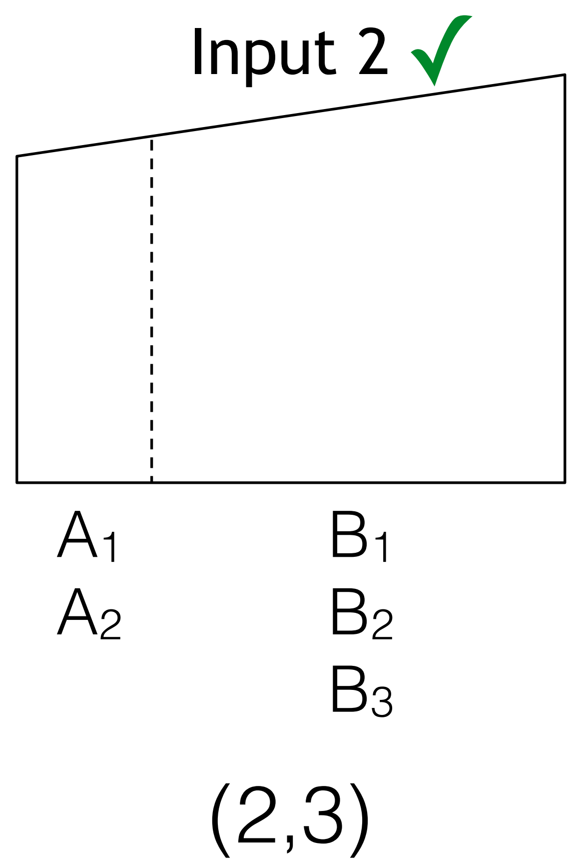



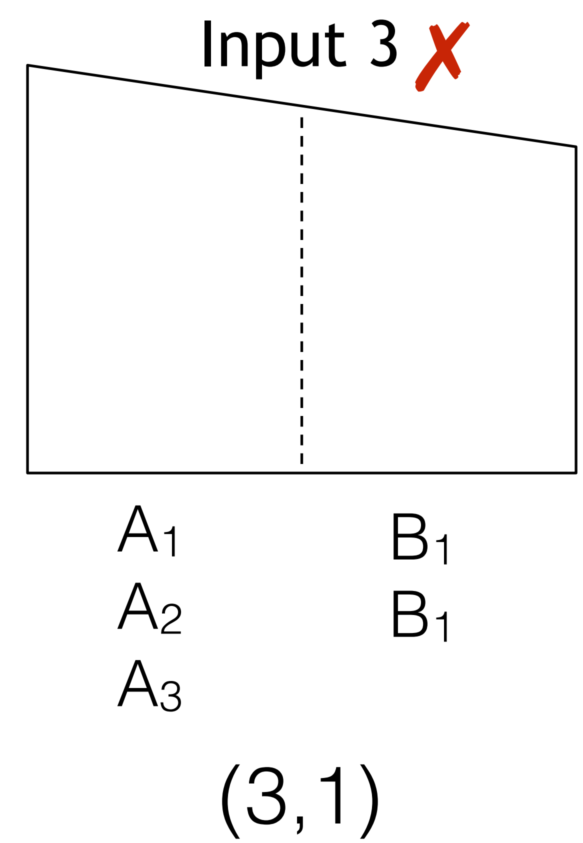

Keep track of unique edges

# Path δ-diversity: gray-box



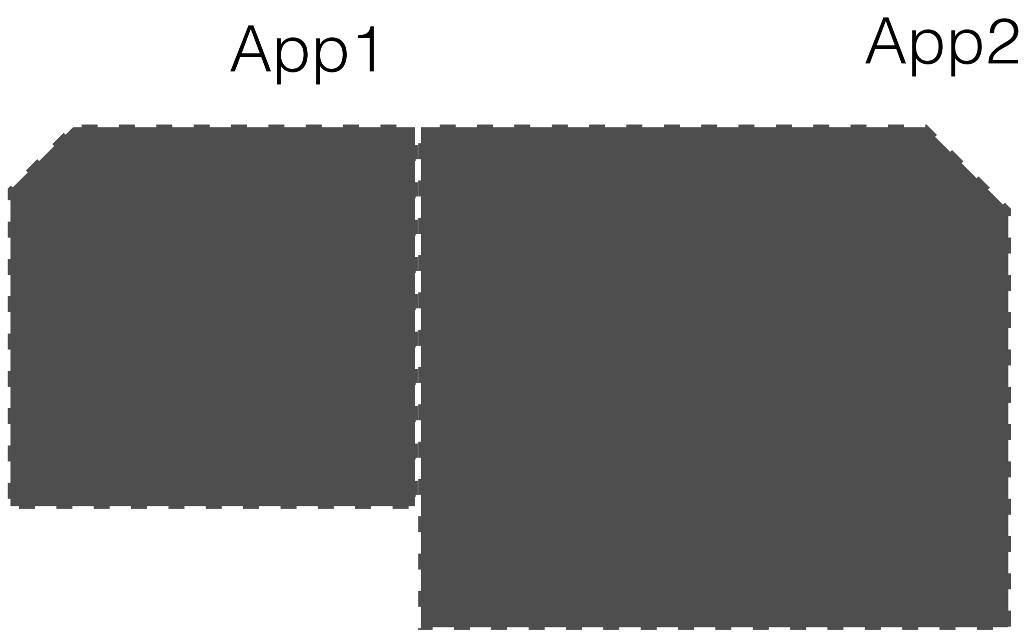




Keep track of unique edges

# Output δ-diversity: black-box




All possible ~~code paths~~

Return values
Error codes
Exception messages



| | Input | App1 | App2 |
|---|---|---|---|
| ✓ | | 0x0 | 0x0 |
| ✓ | | 0x1 | 0xdead |
| ✗ | | 0x0 | 0x0 |
| ✓ | | 0x0 | 0xbeef |
| ✓ | | 0xbabe | 0x0 |
| ✗ | | 0x0 | 0xbeef |

# δ-diversity

- Domain Independence
- Efficient differential guidance

# Implementation

- NEZHA prototype
- Gray-box and black-box δ-diversity metrics
    - Path δ-diversity (fine & coarse)
    - Output δ-diversity
- Domain-independent input generation
    - Evolutionary, feedback-guided
- Built upon libFuzzer with NEZHA-specific hooks
- 1545 lines of C++

# Use cases

- SSL libraries
- PDF readers
- ClamAV & XZ Parsers

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# Certificate Verification Discrepancies

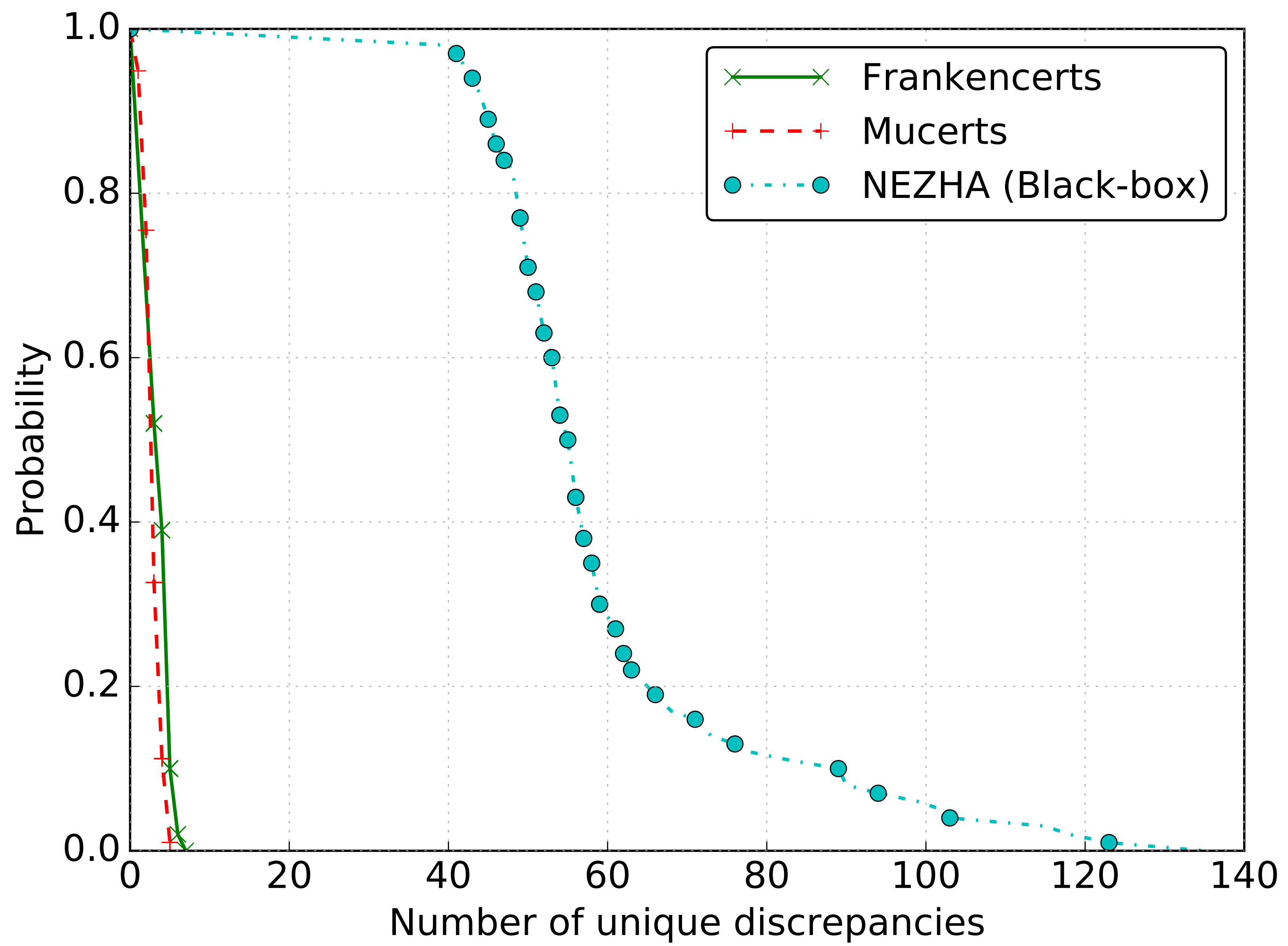
One library accepts one certificate, while another rejects it with an error code.

| | LibreSSL | BoringSSL | wolfSSL | mbedTLS | GnuTLS |
|---|---|---|---|---|---|
| OpenSSL | 10 | 1 | 8 | 33 | 25 |
| LibreSSL | - | 11 | 8 | 19 | 19 |
| BoringSSL | - | - | 8 | 33 | 25 |
| wolfSSL | - | - | - | 6 | 8 |
| mbedTLS | - | - | - | - | 31 |

Unique pair-wise discrepancies (based on error code tuples)

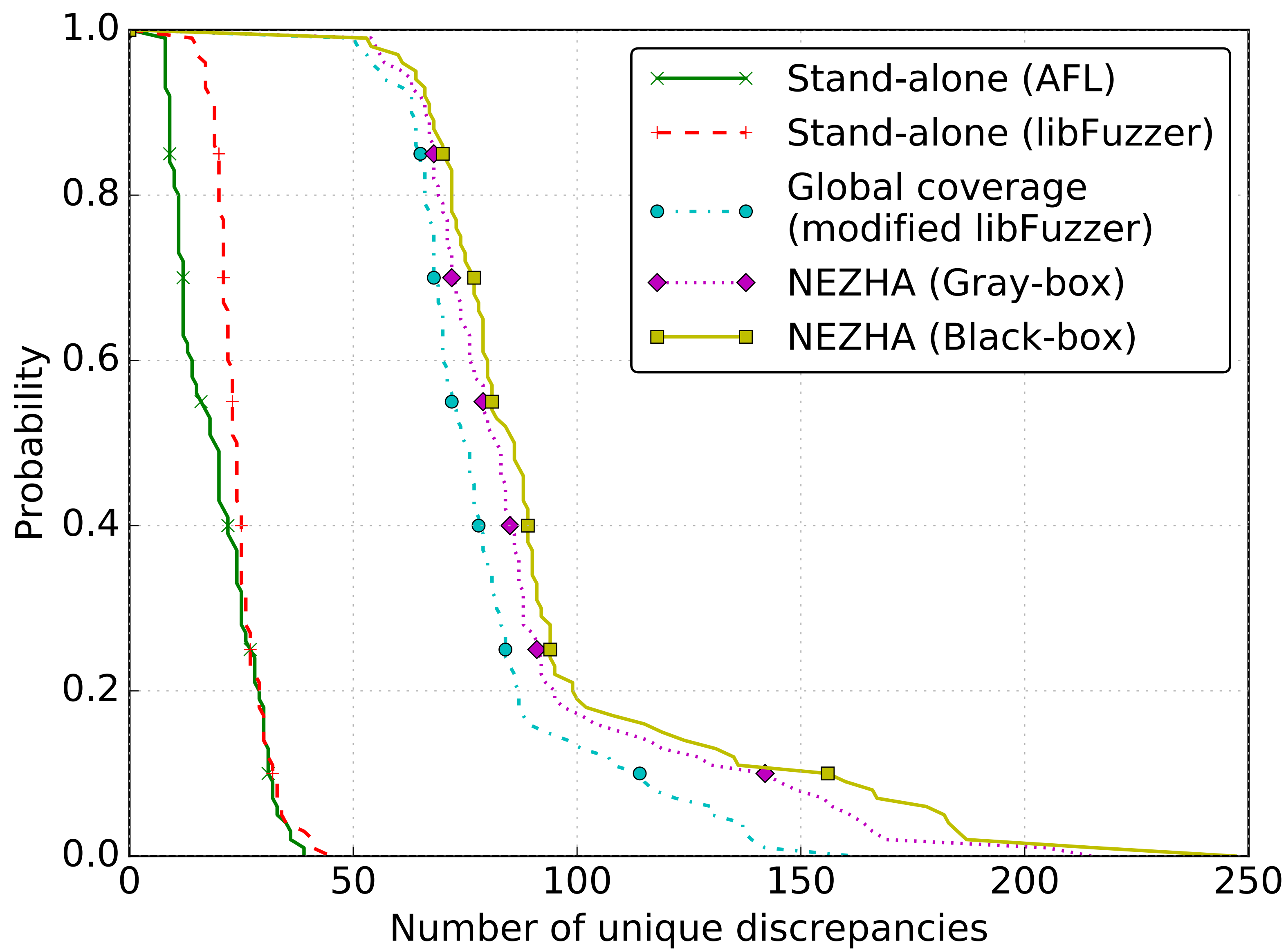
# NEZHA vs domain-specific frameworks

- 52x more discrepancies than *Frankencerts*
- 27x more discrepancies than *Mucerts*



# NEZHA vs popular evolutionary fuzzers

- Adapted popular evolutionary fuzzers for differential testing
    - Code coverage in single application
    - Global code coverage
- 6x more discrepancies than testing on a single application
- 30% more discrepancies than modified libFuzzer



Sample Bugs uncovered by NEZHA

*(disclosed and patched)*

# Experimental Setting

| Application Category | Tests |
|---|---|
| SSL Libraries | OpenSSL, LibreSSL, BoringSSL, GnuTLS, wolfSSL, mbedTLS |
| PDF Readers | Evince PDF, MuPDF, Xpdf |
| Parsers | ClamAV vs binutils<br>ClamAV vs xz |

# BUG 1: Malicious ELF can evade ClamAV detection

CLAMAV (ELF parsing engine)

```
static int cli_elf_fileheader(...) {
  ...
  switch(file_hdr->hdr64.e_ident[4]) {
    case 1:
      ...
    case 2:
      ...
    default:
      ...
      return CL_EFORMAT;
  ...
```

# BUG 1: Malicious ELF can evade ClamAV detection

CLAMAV (ELF parsing engine)

```
static int cli_elf_fileheader(...) {
  ...
  switch(file_hdr->hdr64.e_ident[4]) {
    case 1:
      ...
    case 2:
      ...
    default:
      ...
      return CL_EFORMAT;
  ...
```

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LINUX ELF loader

```
static int load_elf_binary(struct linux_binprm *bprm) {
  ...
  retval = -ENOEXEC;
  if (memcmp(loc->elf_ex.e_ident, ELFMAG, SELFMAG) != 0)
    goto out;
  if (loc->elf_ex.e_type != ET_EXEC &&
       loc->elf_ex.e_type != ET_DYN)
    goto out;
  if (!elf_check_arch(&loc->elf_ex))
    goto out;
  ...
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# BUG 2: LibreSSL misinterprets time in ASN.1 format

Time fields can be formatted in 2 ways:

**UTC**: YYMMDDHHMMSSZ (13 char long)

**GMT**: YYYYMMDDHHMMSSZ (15 char long)

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LibreSSL ignores the ASN.1 time format tag, and determines format based on length of field

# BUG 2: LibreSSL misinterprets time in ASN.1 format

```
int asn1_time_parse(..., size_t len, ..., int mode) {
  ...
  int type = 0;
  ...
  /* Constrain to valid lengths. */
  if (len != UTCTIME_LENGTH && len != GENTIME_LENGTH)
    return (-1);
  ...
  switch (len) {
  case GENTIME_LENGTH:
    // mode is "ignored" -- configured to 0 here
    if (mode == V_ASN1_UTCTIME)
      return (-1);
    ...
    type = V_ASN1_GENERALIZEDTIME;
  case UTCTIME_LENGTH:
    if (type == 0) {
      if (mode == V_ASN1_GENERALIZEDTIME)
        return (-1);
      type = V_ASN1_UTCTIME;
    }
    // parse time as UTCTIME
```

LibreSSL ignores the ASN.1 time format tag, and determines format based on length of field

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  ...
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  ...
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    if (mode == V_ASN1_UTCTIME)
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    ...
    type = V_ASN1_GENERALIZEDTIME;
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LibreSSL ignores the ASN.1 time format tag, and determines format based on length of field

*Jan 1 01:01:00 2012 GMT can interpreted as Dec 1 01:01:01 2020 GMT*

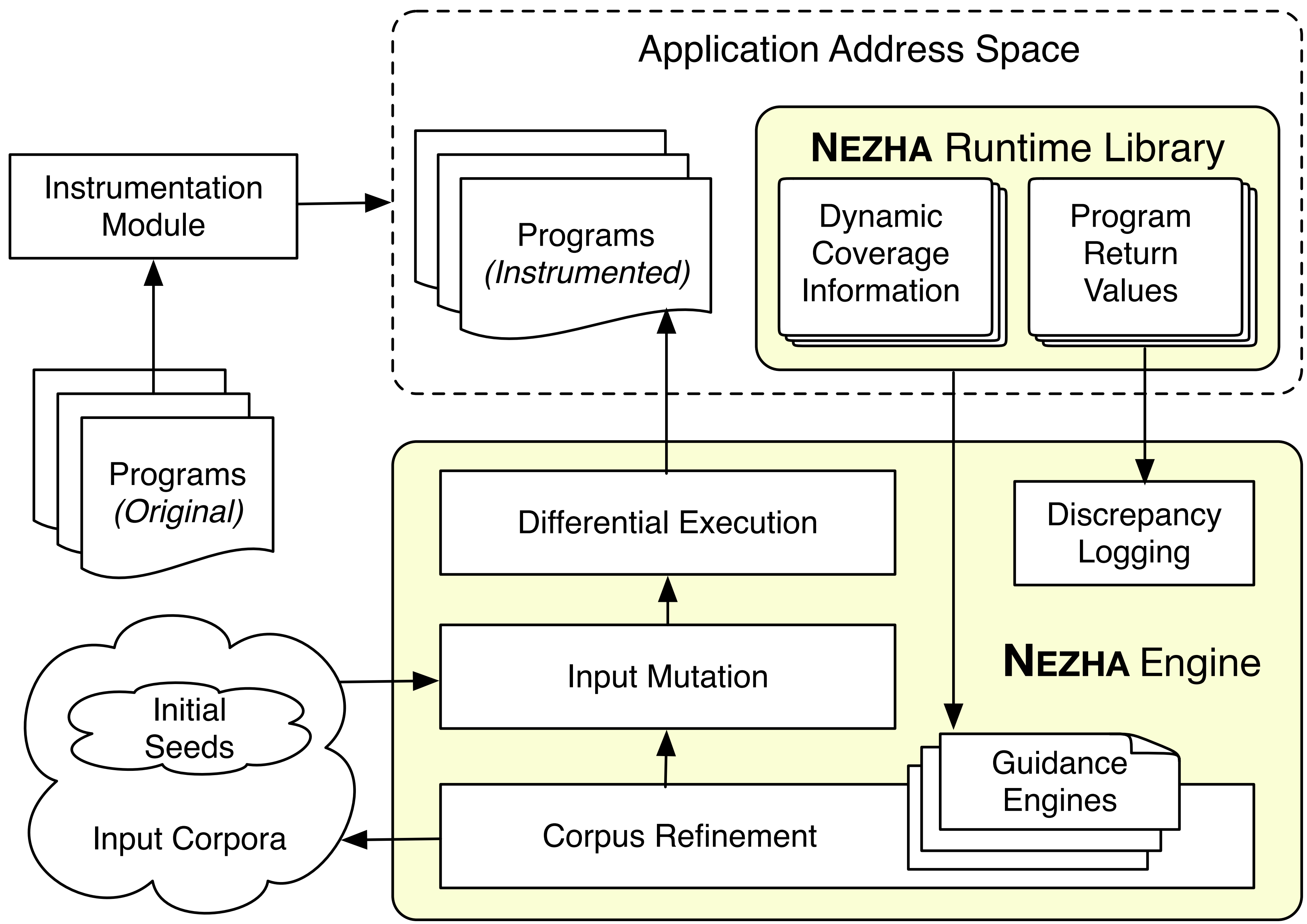
# Conclusions

- δ-diversity outperforms code coverage for differential testing
- NEZHA: Domain independent, efficient differential testing
- Differential testing should be integrated, when possible, into the testing cycle

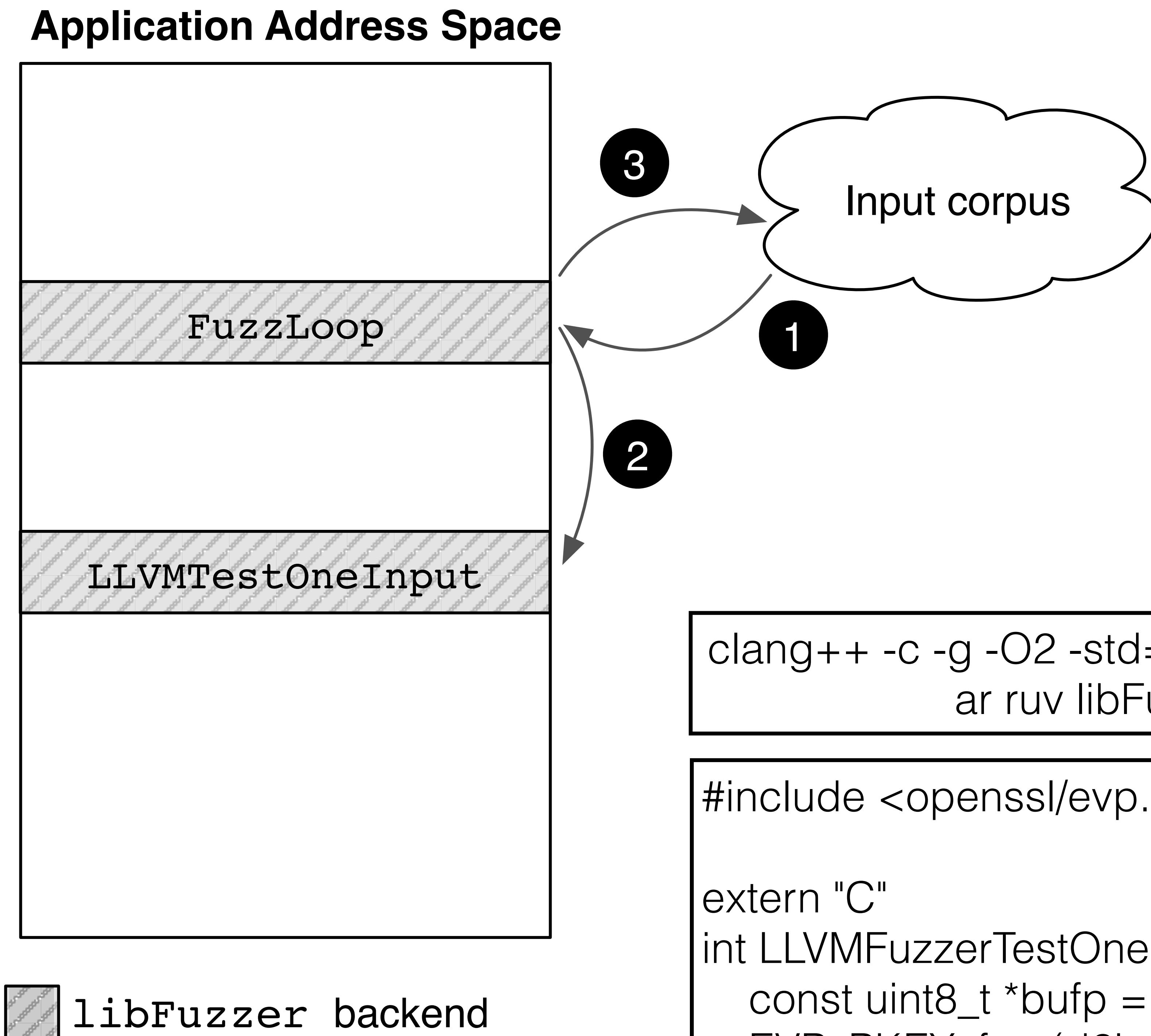
https://github.com/nezha-dt

# Backup Slides

# NEZHA: Architecture



# NEZHA: Architecture

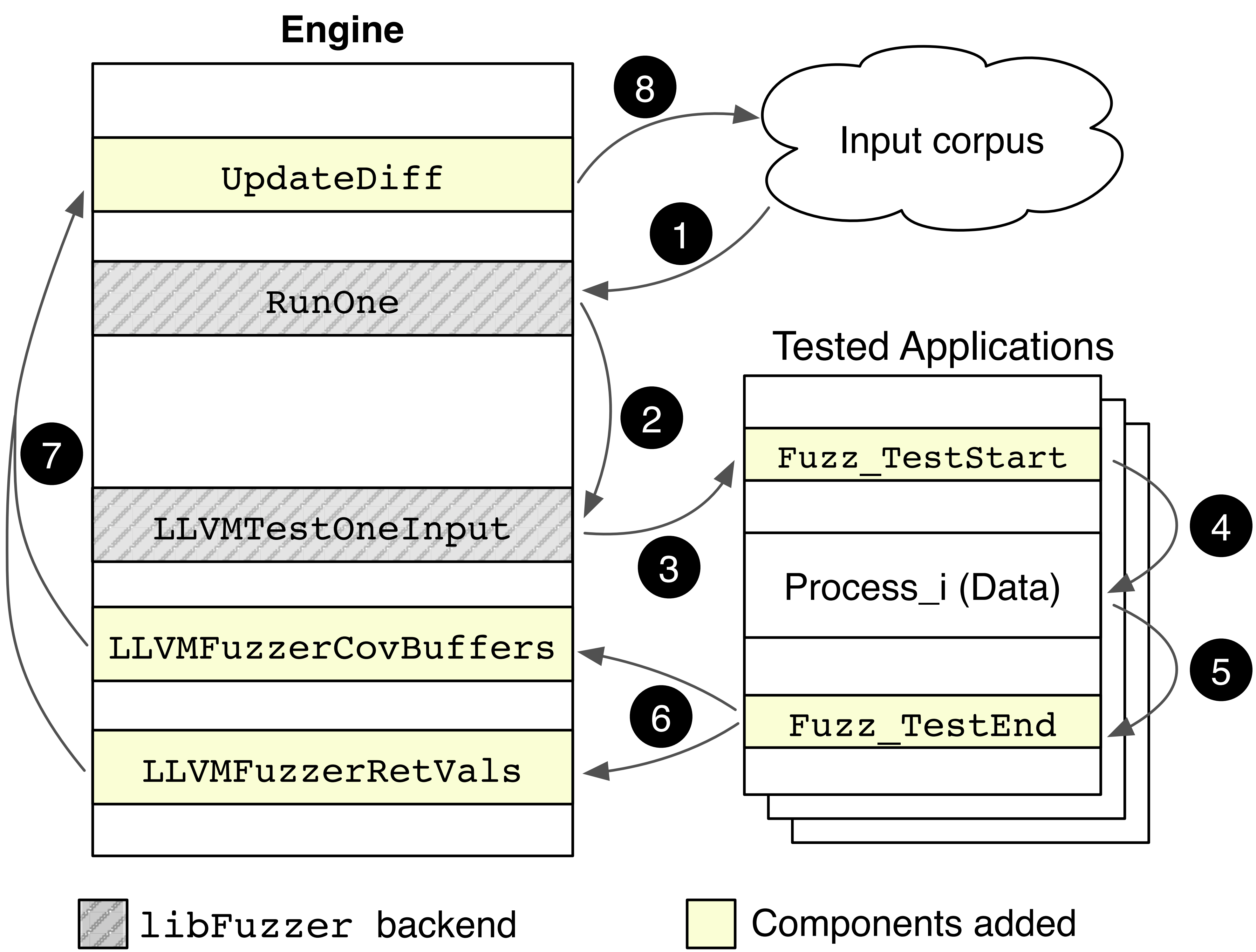



```
clang++ -c -g -O2 -std=c++11 Fuzzer/*.cpp -IFuzzer
ar ruv libFuzzer.a Fuzzer*.o
```

```
#include <openssl/evp.h>

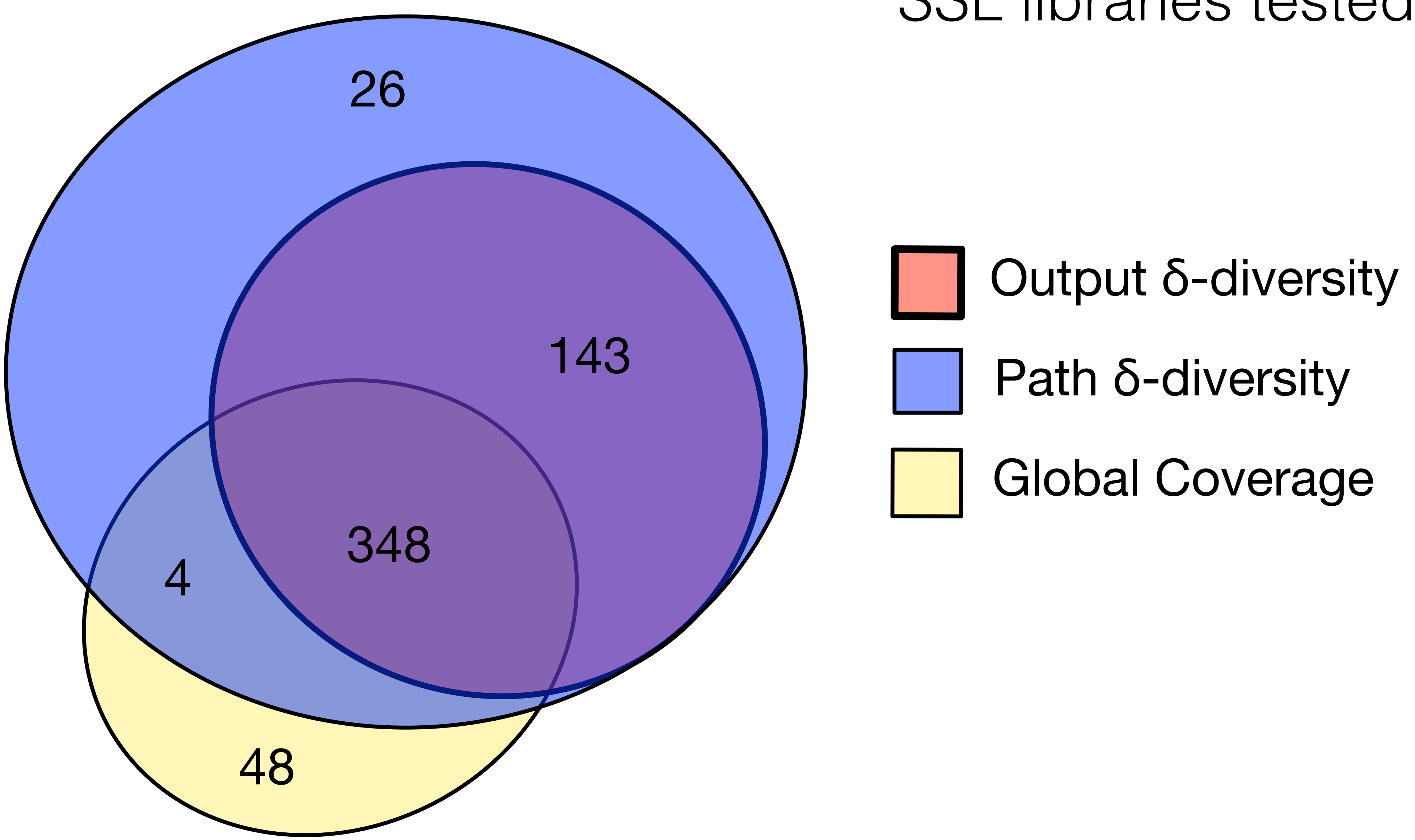
extern "C"
int LLVMFuzzerTestOneInput(const uint8_t *buf, size_t len) {
    const uint8_t *bufp = buf;
    EVP_PKEY_free(d2i_AutoPrivateKey(NULL, &bufp, len));
    return 0;
}
```

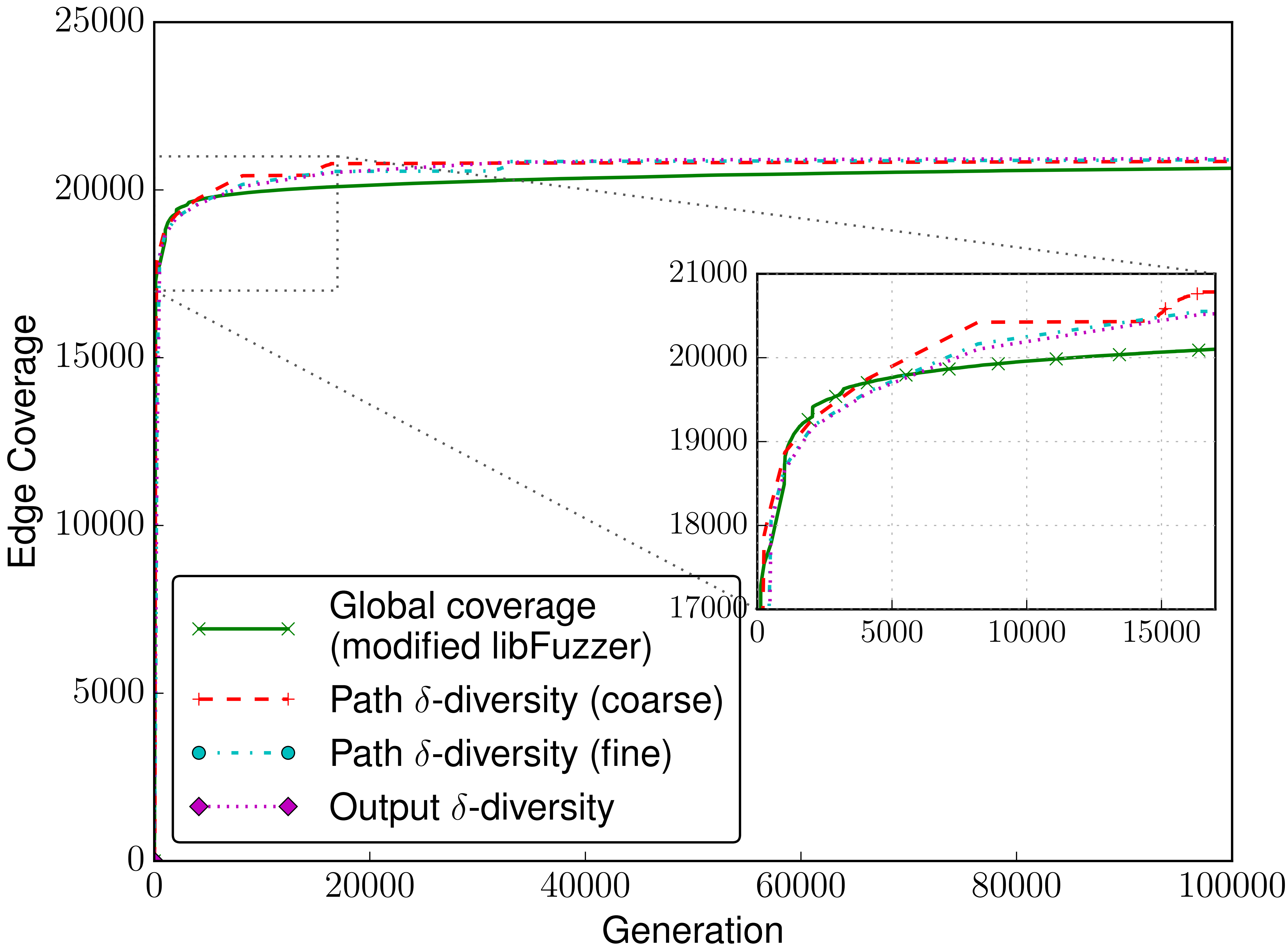
# NEZHA: Architecture



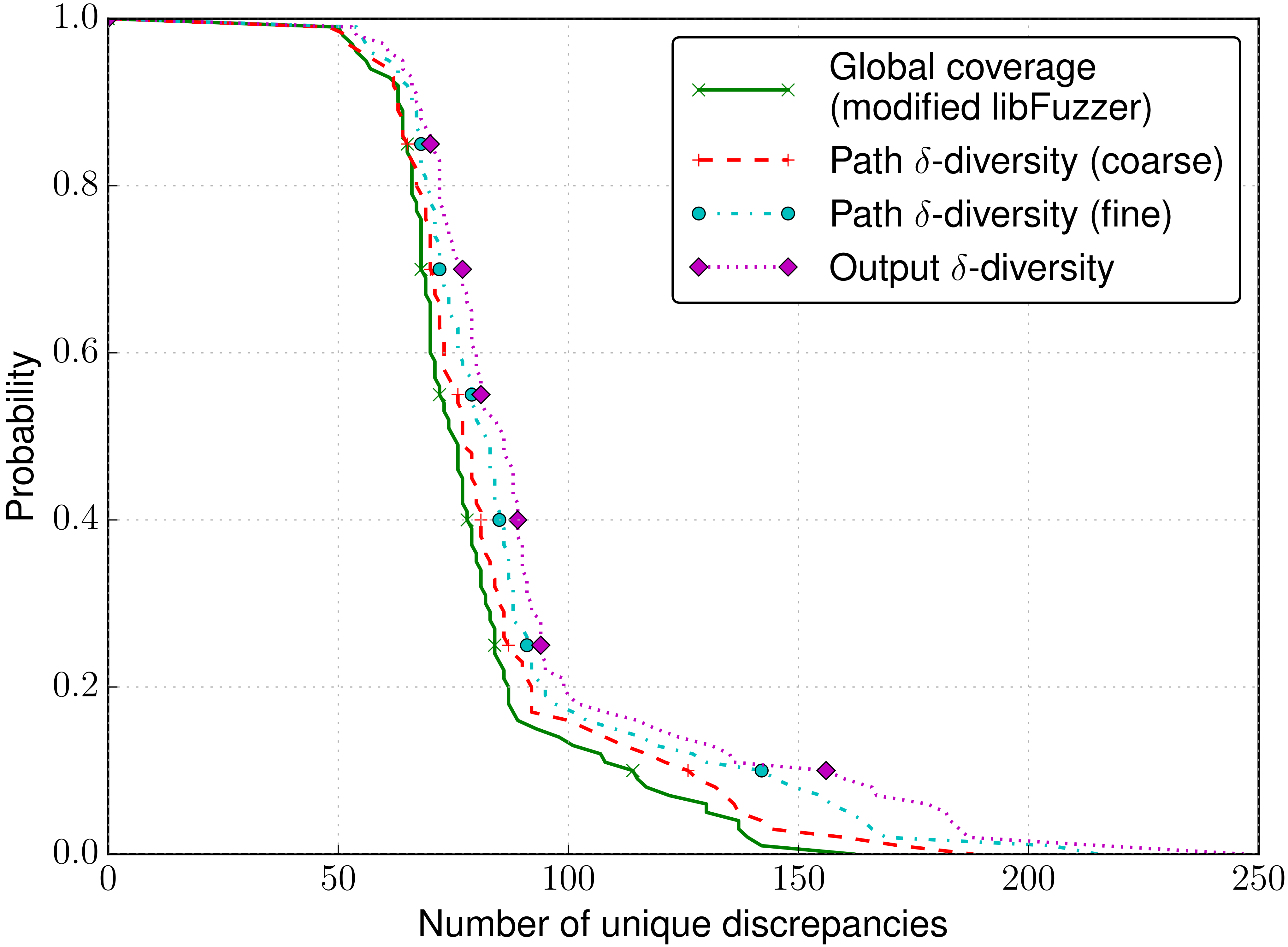
# Discrepancy Distribution for SSL/TLS Libs

Same Inputs / Different mode
SSL libraries tested

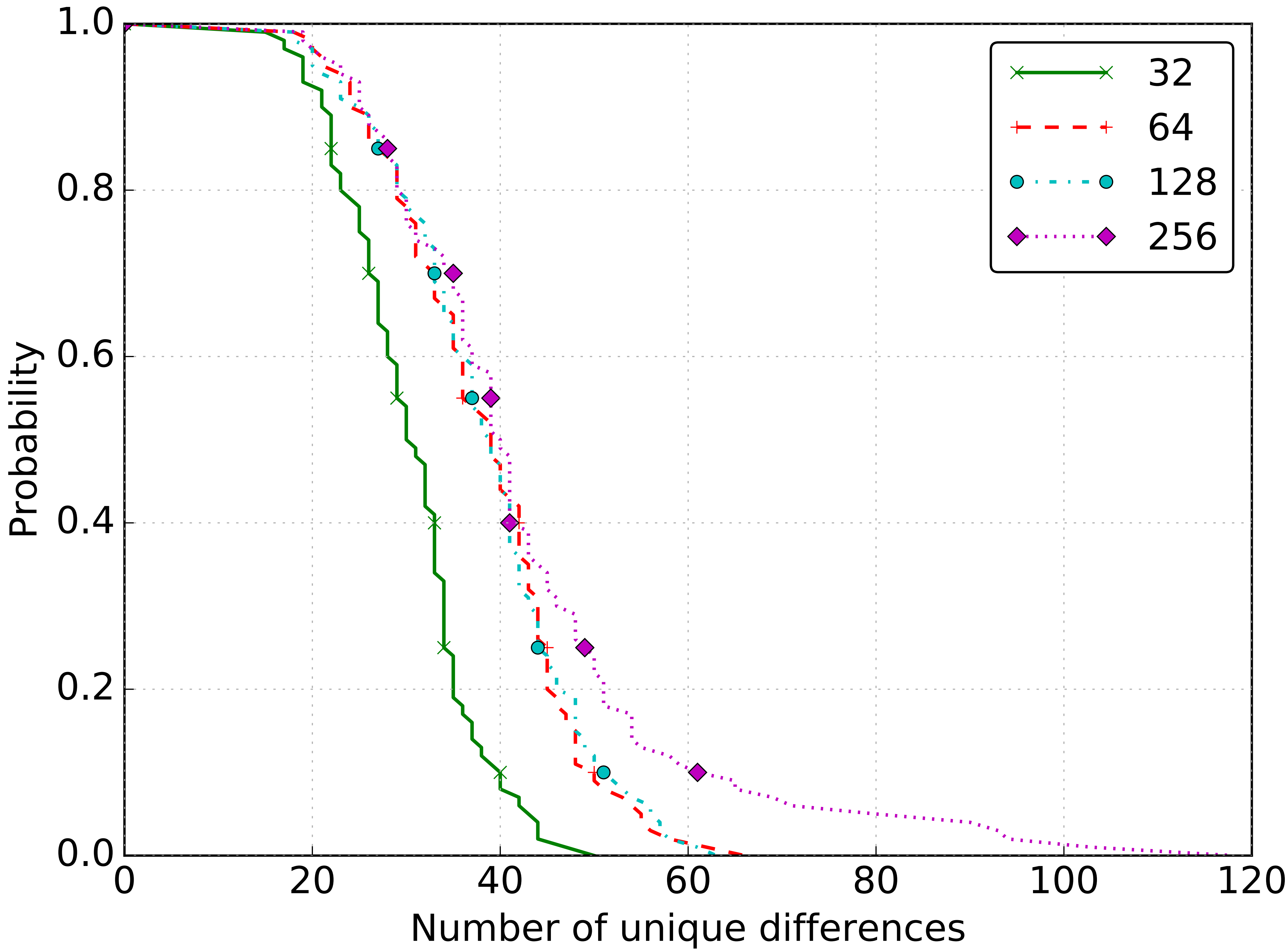




Edge Coverage
Generation
25000
20000
15000
10000
5000
0
0
20000
40000
60000
80000
100000
21000
20000
19000
18000
17000
0
5000
10000
15000
Global coverage
(modified libFuzzer)
Path δ-diversity (coarse)
Path δ-diversity (fine)
Output δ-diversity



1.0
0.8
0.6
0.4
0.2
0.0
Probability
0
50
100
150
200
250
Number of unique discrepancies
Global coverage (modified libFuzzer)
Path $\delta$-diversity (coarse)
Path $\delta$-diversity (fine)
Output $\delta$-diversity



1.0
0.8
0.6
0.4
0.2
0.0
Probability
0
20
40
60
80
100
120
Number of unique differences
32
64
128
256