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Chair for
Software Security

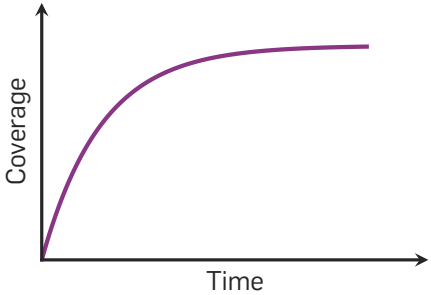
StorFuzz: Using Data-Diversity to Overcome Fuzzing Plateaus

Leon Weiß Tobias Holl Kevin Borgolte

Ruhr University Bochum

April 16, 2026
48th International Conference on Software Engineering (ICSE)

Fuzzing Plateaus



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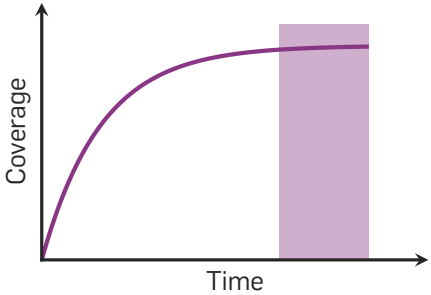

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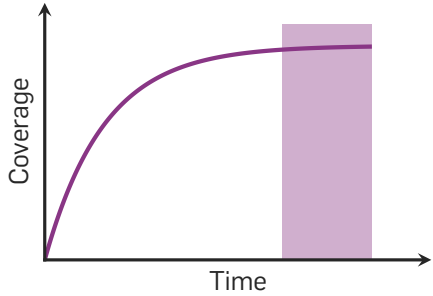
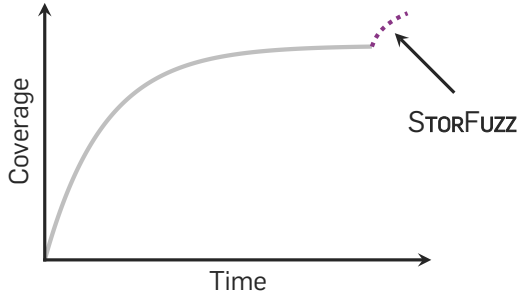


When we reach fuzzing plateaus we usually have **not** covered all code yet.

Fuzzing Plateaus



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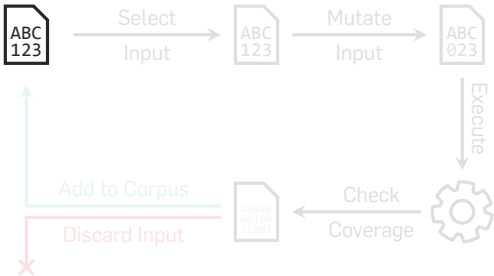
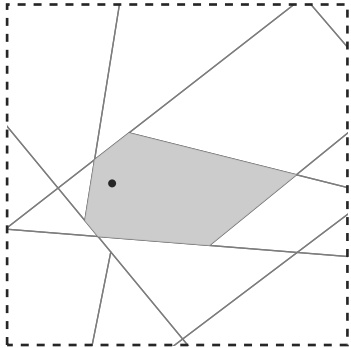
Fuzzing — Conceptually





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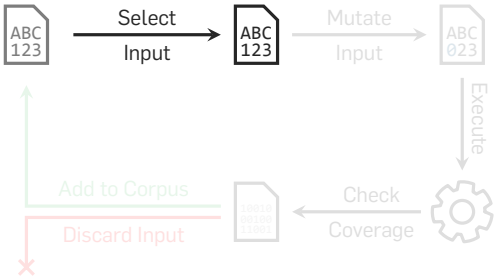

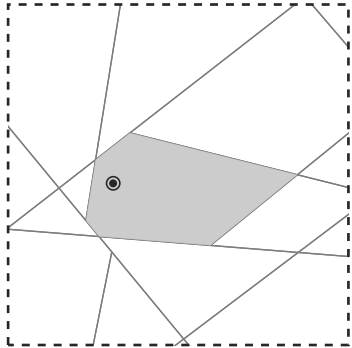

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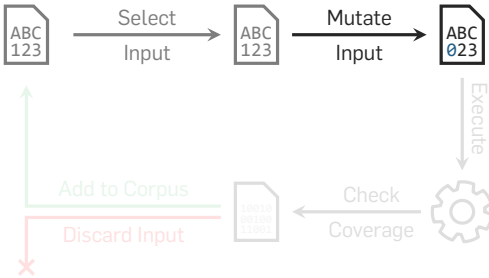

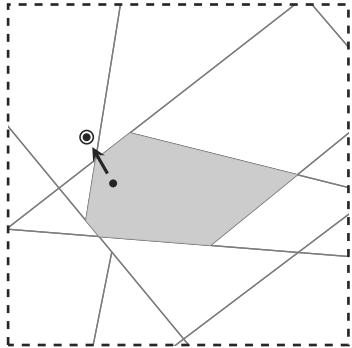

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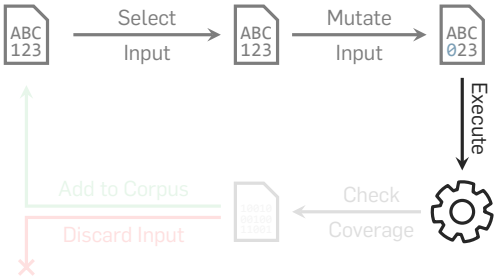

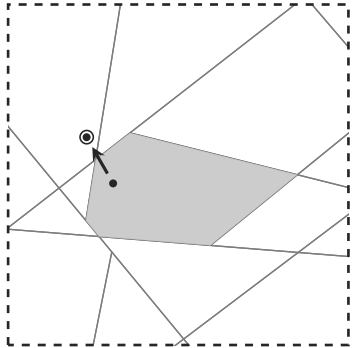

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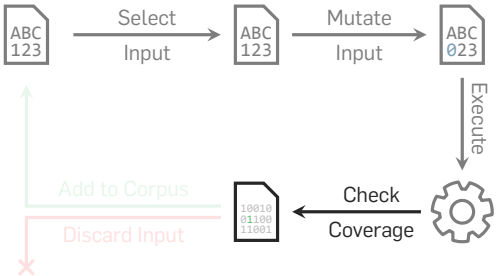

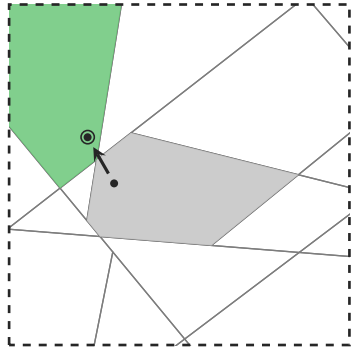

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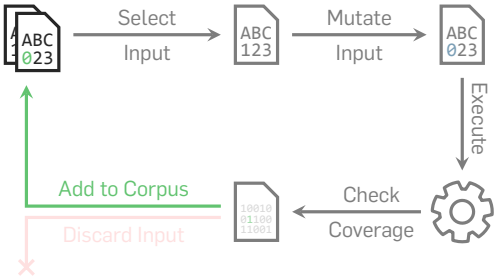

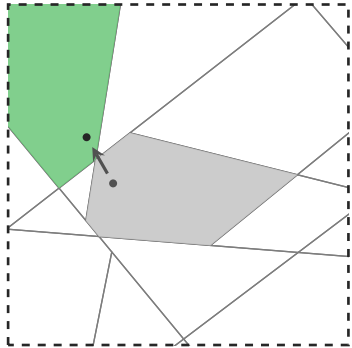

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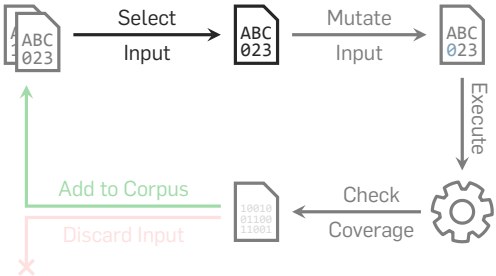

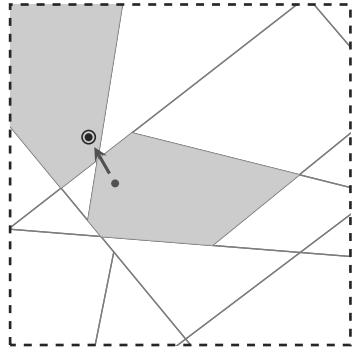

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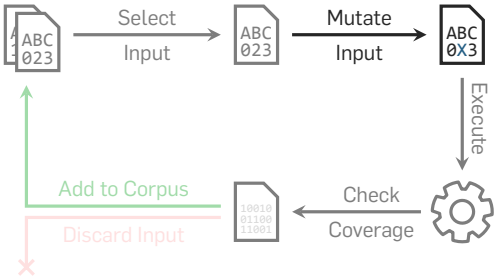

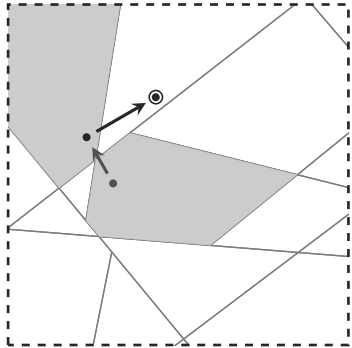

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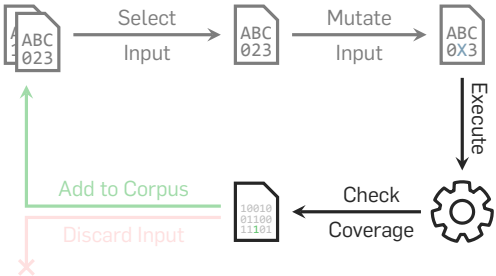

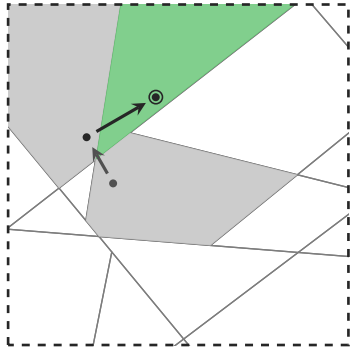

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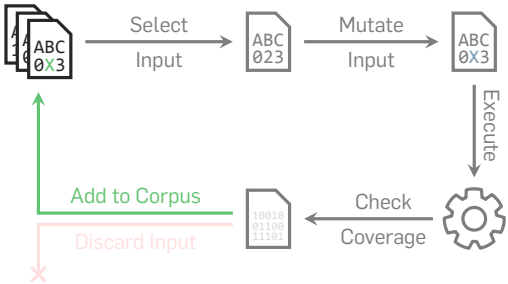

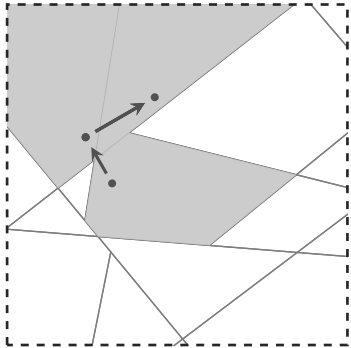

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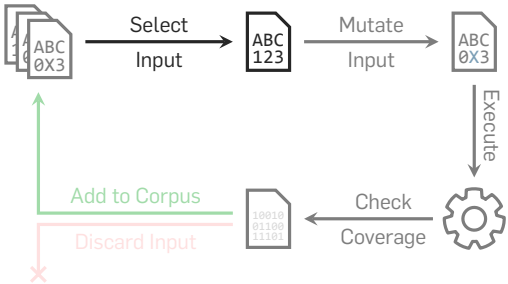

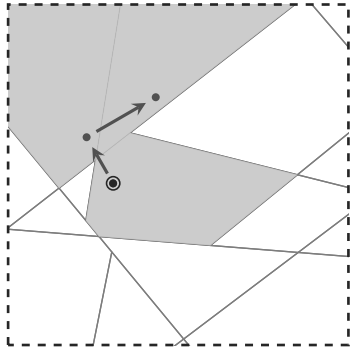

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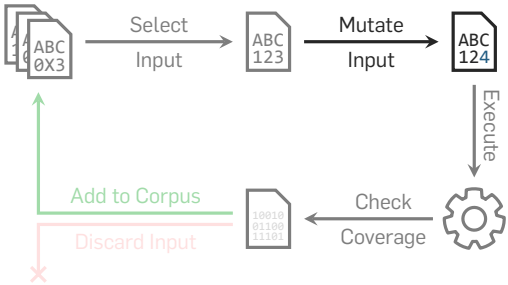

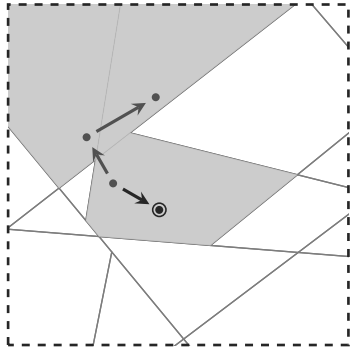

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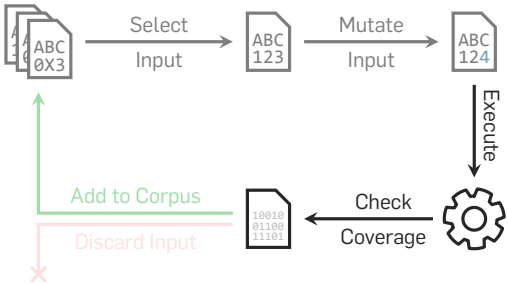

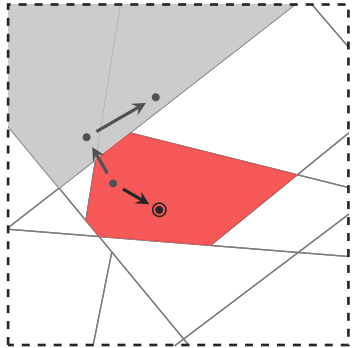

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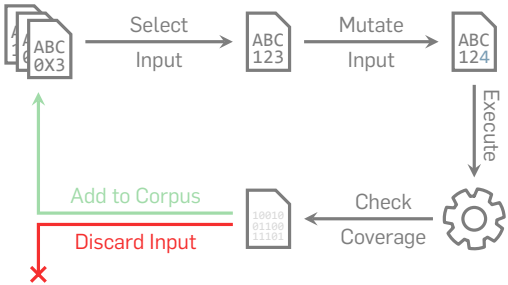

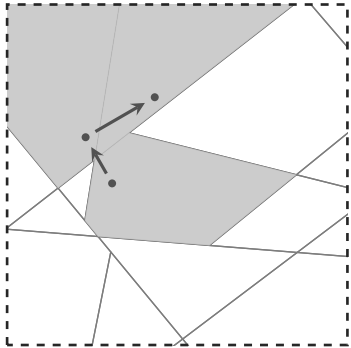

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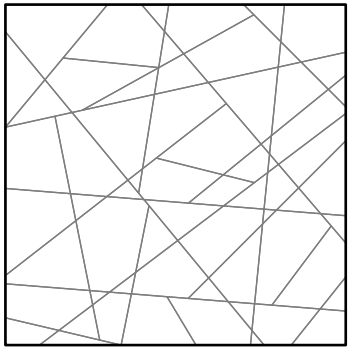

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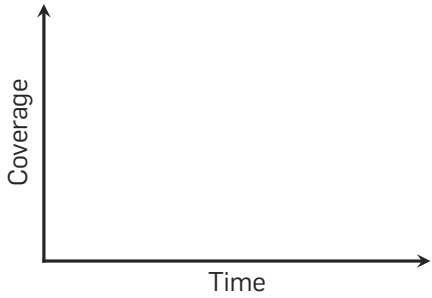

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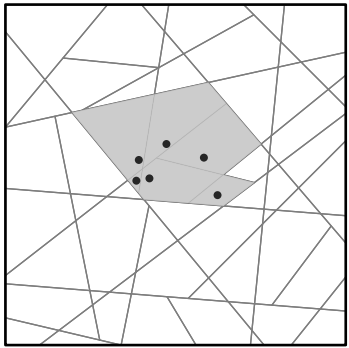

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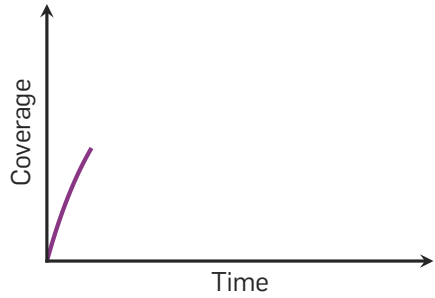

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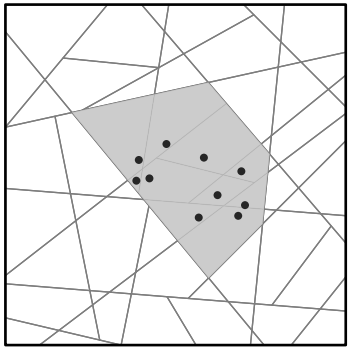

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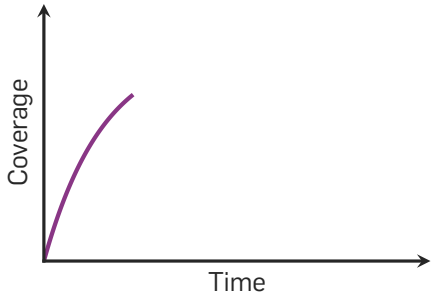

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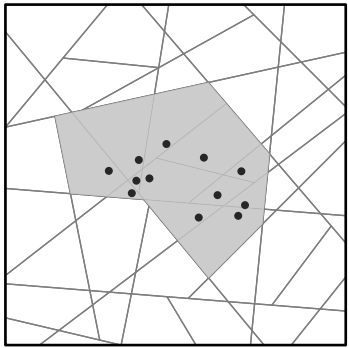

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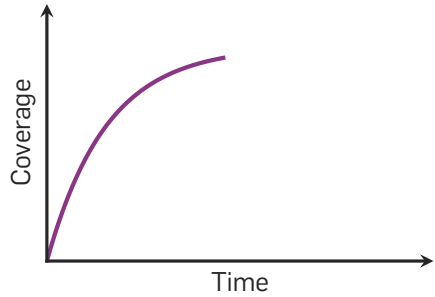

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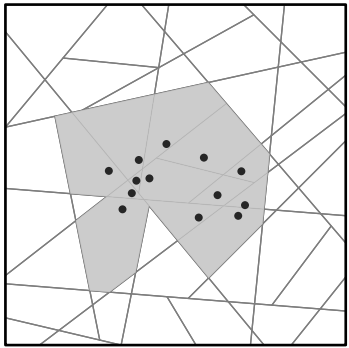

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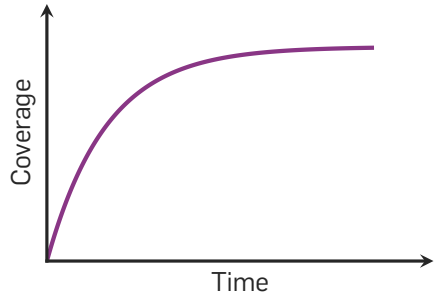

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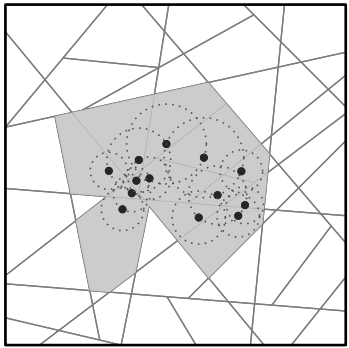

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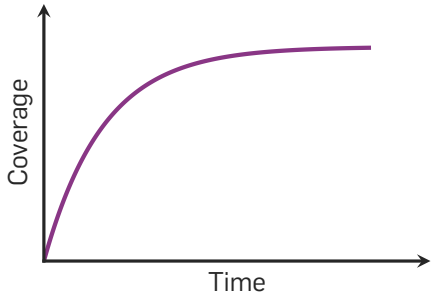
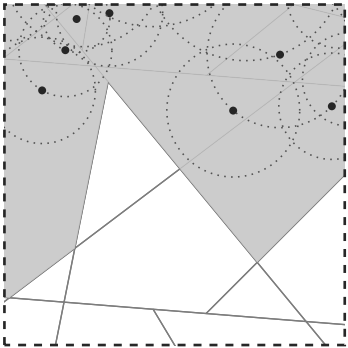


Plateaus are caused by **poorly placed** inputs so **mutations cannot reach new code**.

Overcoming the Plateau



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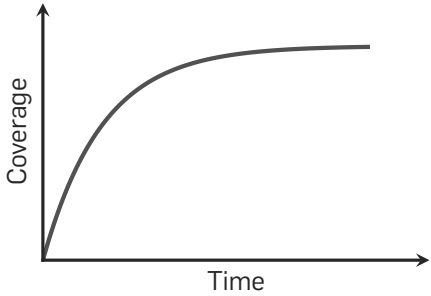

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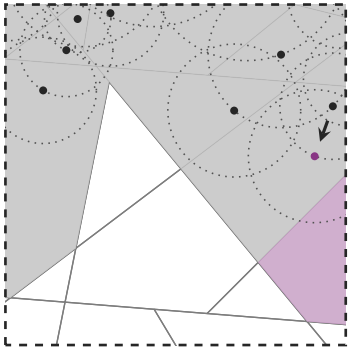

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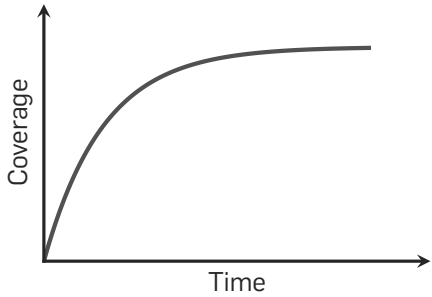

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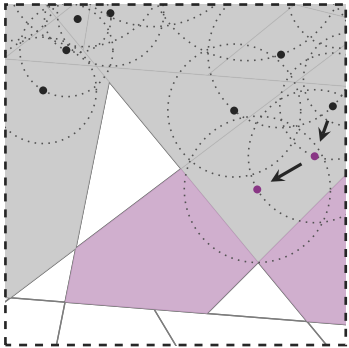

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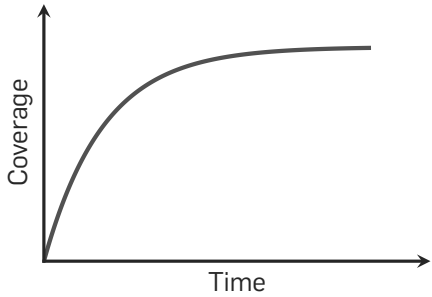

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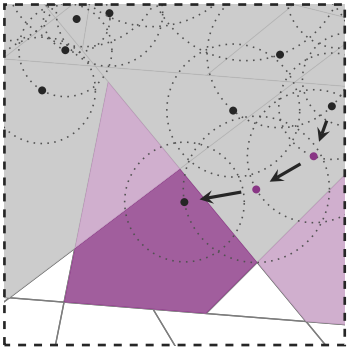

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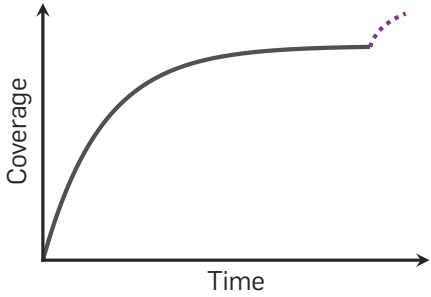

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- We want to reward **diversity in program behavior** during fuzzing.
- Behavior at runtime is decided by the program itself, its **state**, and the given input.
- State is the combination of current location within the program and **stored values**.

StorFuzz uses **diversity** in the target's **stored values** as a measure for **diversity in state**.

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- Some values are **not** related to state.
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- State related variables only hold a **limited amount** of information.

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- Meaningful state is encoded in **long-lived** data.
- StorFuzz uses compile-time instrumentation to collect coverage on **stores to memory**.
- Some values are **not** related to state.
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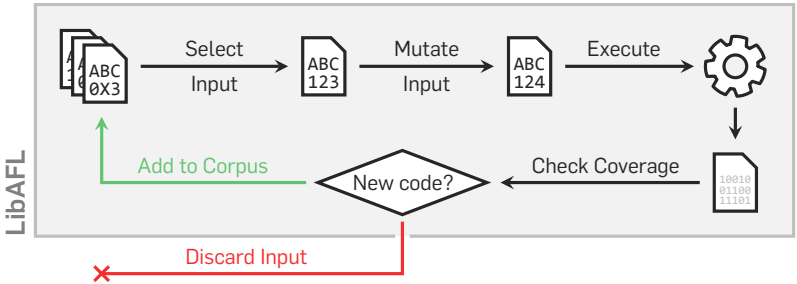
- Each individual instruction stores to the **same variable** over time.
- StorFuzz combines the reduced value and the **ID of the store instruction** into coverage.

StorFuzz — Fuzzing



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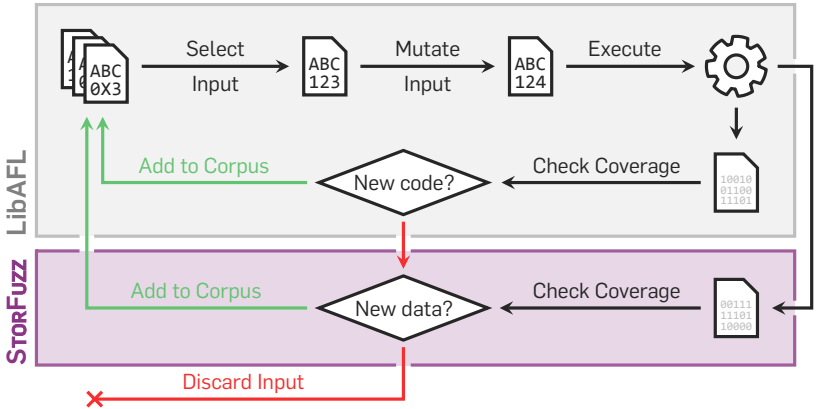

Data coverage is an **addition** to code coverage **for diversification**.

Evaluation

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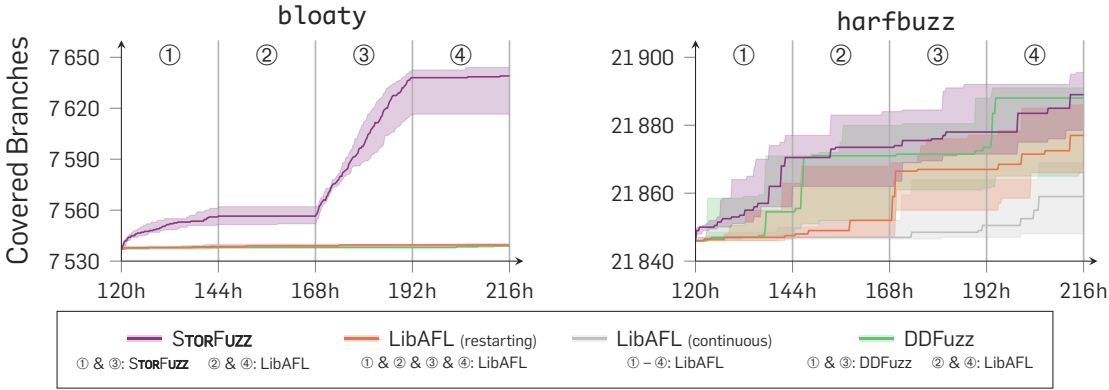
- In a separate evaluation we compare to **WingFuzz** (based on **libFuzzer**).

Evaluation — Escaping the Plateau

Benchmark	StorFuzz	LibAFL (baseline)	DDFuzz
bloaty	7 556.5 (+19.5)	7 538.5 (+1.5)	7 538 (+1)
curl	11 569.5 (+15.5)	11 557 (+3)	11 557 (+3)
freetype2	18 054.5 (+11.5)	18 044.5 (+1.5)	18 045 (+2)
harfbuzz	21 870.5 (+24.5)	21 847.5 (+1.5)	21 854.5 (+8.5)
libxml2	16 314 (+3)	16 311.5 (+0.5)	16 313 (+2)
libxslt	12 158.5 (+23.5)	12 143.5 (+8.5)	12 139 (+4)
mbedtls	4 419 (+1)	4 418 (+0)	4 418 (+0)
openh264	9 841 (+2)	9 839 (+0)	9 839 (+0)
openthread	4 651 (+70)	4 637.5 (+56.5)	4 583.5 (+2.5)
proj4	11 119 (+9)	11 112 (+2)	11 111 (+1)
sqlite3	21 592 (+47)	21 578.5 (+33.5)	21 582 (+37)
Best fuzzer after 24h	11/23 benchmarks	0/23 benchmarks	0/23 benchmarks

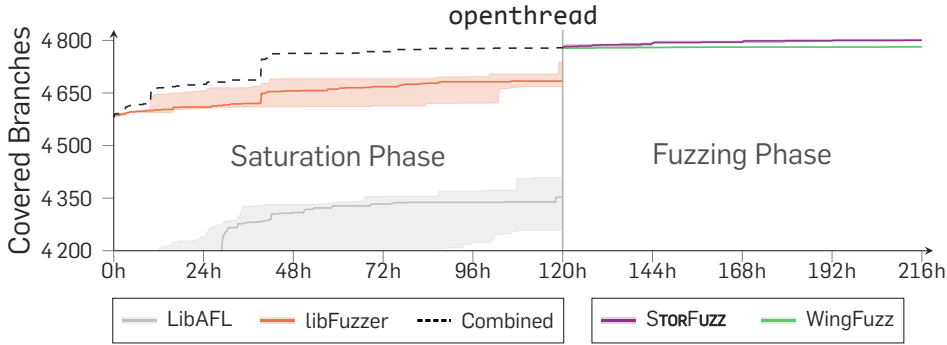
StorFuzz **escapes the plateau** better than restarting LibAFL or diversifying with DDFuzz.

Evaluation — Transferring the Diversity



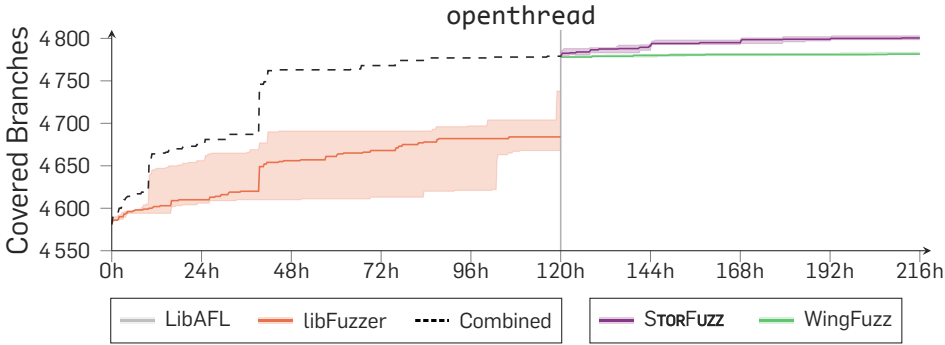
Subsequent fuzzers can effectively **pick up** on corpora diversified by StorFuzz.

Evaluation — Transferring the Diversity: WingFuzz



Both StorFuzz and WingFuzz **improve** over saturated corpora in **distinct ways**. Which of them performs better overall is **benchmark-specific**.

Evaluation — Transferring the Diversity: WingFuzz



Both StorFuzz and WingFuzz **improve** over saturated corpora in **distinct ways**. Which of them performs better overall is **benchmark-specific**.

Evaluation — Transferring the Diversity: WingFuzz

Covered in n trials	Only by StorFuzz			Only by WingFuzz		
	1+	3+	5+	1+	3+	5+
bloaty	24	6	2	58	61	66
curl	14	6	4	18	8	8
freetype2	8	4	1	21	13	9
harfbuzz	51	30	37	15	8	3
libxml2	13	5	3	26	6	5
libxslt	28	22	11	23	14	7
openssl				17	2	1
openthread	48	25	25	11	2	1
proj4	4	12	11	118	50	25
re2				7	4	4
sqlite3	88	31	30	128	31	28

Unique branches covered in at least 1, 3 and 5 trials (for all benchmarks see paper).

StorFuzz and WingFuzz **complement each** other by covering **unique program parts**.

Evaluation — Bug Finding Case Study

- We tested bug finding on the most popular projects in OSS-Fuzz.
- StorFuzz discovered **50** new bugs in 7 well-known projects (VLC, PHP, ImageMagick,...).
- We found bugs in areas **already covered** by OSS-Fuzz and previously untested code.
- Some bugs were introduced **13+** years ago and were not found by **4+** years of fuzzing.

StorFuzz finds bugs both by covering **new code** and **new states** in already covered code.

Takeaways

StorFuzz uses data-diversity to overcome fuzzing plateaus, cover new code, find new bugs and complement existing fuzzers.

Paper, code, data, and slides are available at
`softsec.link/icse26.storfuzz`

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

CASA
Securing the Digital Society

WWTF
Vienna Science and Technology Fund

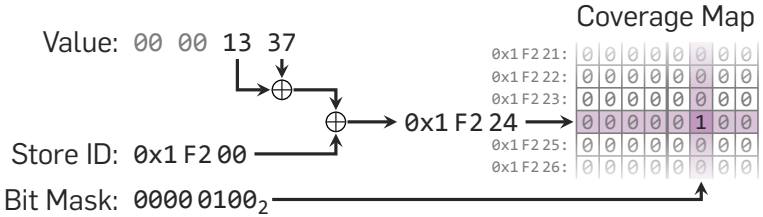
StorFuzz — Value Reduction

- StorFuzz uses a **simple** and **inexpensive** approach.
- Reduction is **directly injected** into the binary near the store.

```
uint8_t value_reduction(uint64_t v) {
    return (v & 0xFF) ^ ((v & 0xFF00) >> 8)
}
```

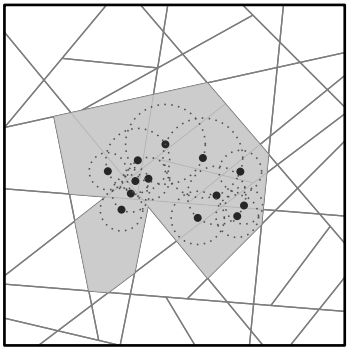
- Other reduction widths are possible (see ablation study).
- Experiments showed the default (8 Bits) performs best in the **general case**.

StorFuzz — Coverage Map



- StorFuzz optimizes the data coverage map by using **each bit** as its own entry.
- The store ID (fixed per store instruction) is split into **two parts**:
  1. Index into the coverage map.
  2. Bit mask to address single bit.
- Recording is done using a **single** `or` of the bit mask with the indexed byte.

Other Concepts of Escaping the Plateau



Restarts with Dropouts

(Schiller et al. [1])

Input Space

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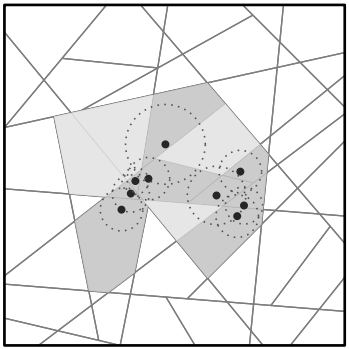

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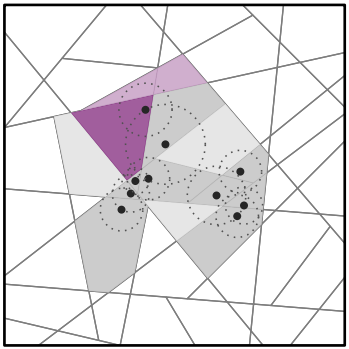

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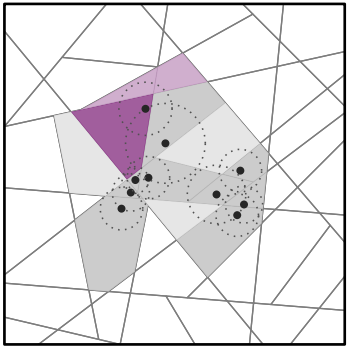
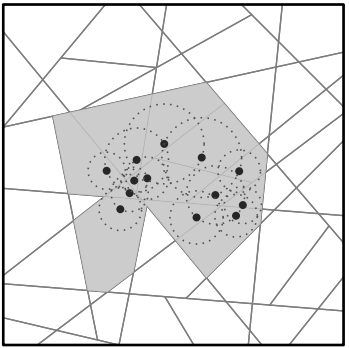


Input Space

Larger Mutation Steps

(e.g., Constraint Solving)



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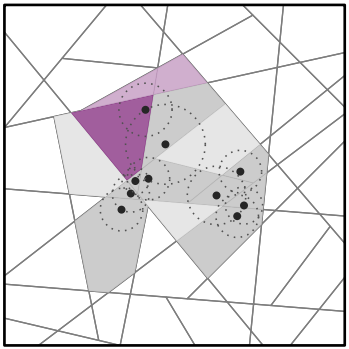

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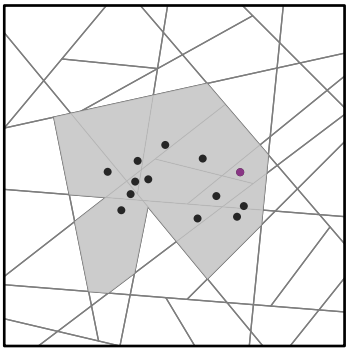

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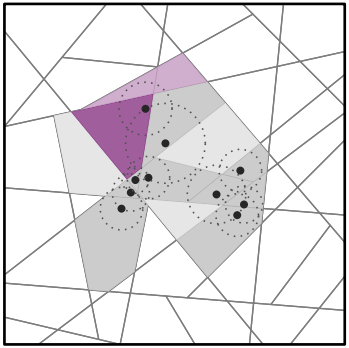

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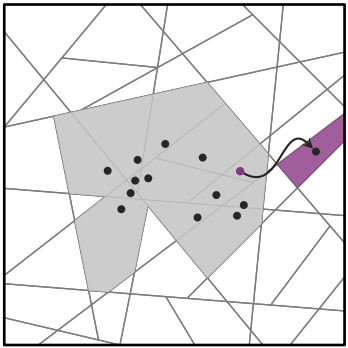

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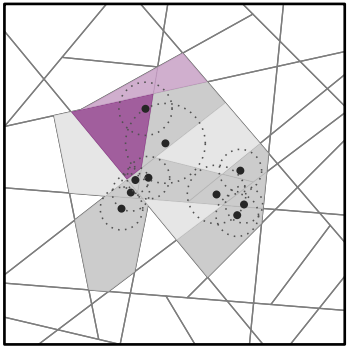

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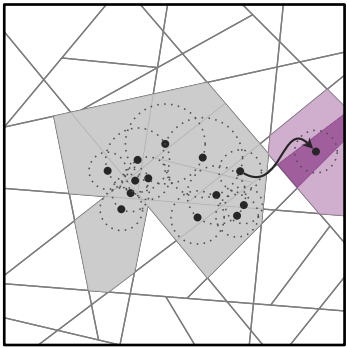

Input Space

Ablation Study

- We performed an ablation study for individual components:
  - Value reduction
  - Threshold for bulk operations
  - Exclusion of plain copies
- We include the data in the artifact.

The default choices in StorFuzz work best in the **general case**. Fine-tuning to an individual benchmark is possible and could improve results further.

References

[1] N. Schiller, X. Xu, L. Bernhard, N. Bars, M. Schloegel, and T. Holz. “Novelty Not Found: Exploring Input Shadowing in Fuzzing through Adaptive Fuzzer Restarts”. In: *ACM Transactions on Software Engineering and Methodology* 34.3 (Mar. 2025). DOI: 10.1145/3712186.