Same Coverage, Less Bloat: Accelerating Binary-only Fuzzing with Coverage-*preserving* Coverage-guided Tracing

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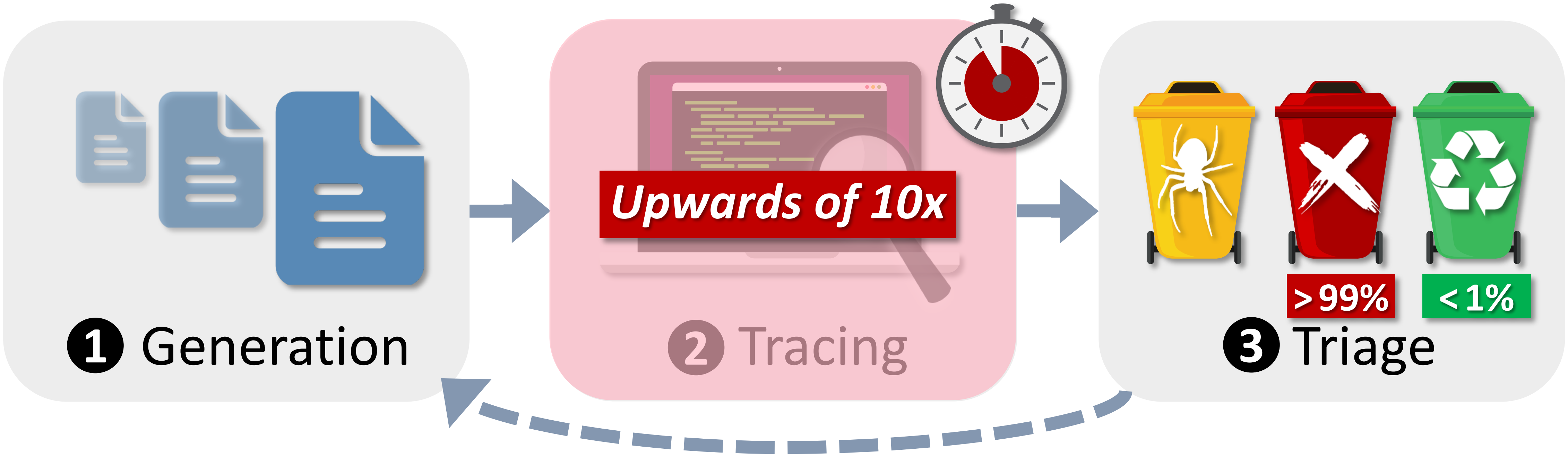
Background

Software Fuzz-testing (Fuzzing)

- Today's leading **automated bug-finding** approach
- **Uncover bugs** by bombarding program with inputs
- **Coverage-guided search:** breed only the ***winners***
  - Measure each input's code coverage via **tracing**
  - Keep and mutate only those reaching ***new*** code

Coverage-guided Fuzzing



On average, **fewer than 1 in 10,000 inputs** reach ***new*** code coverage
For ***binary-only*** fuzzing, compounded by **upwards of 10x slower** speed

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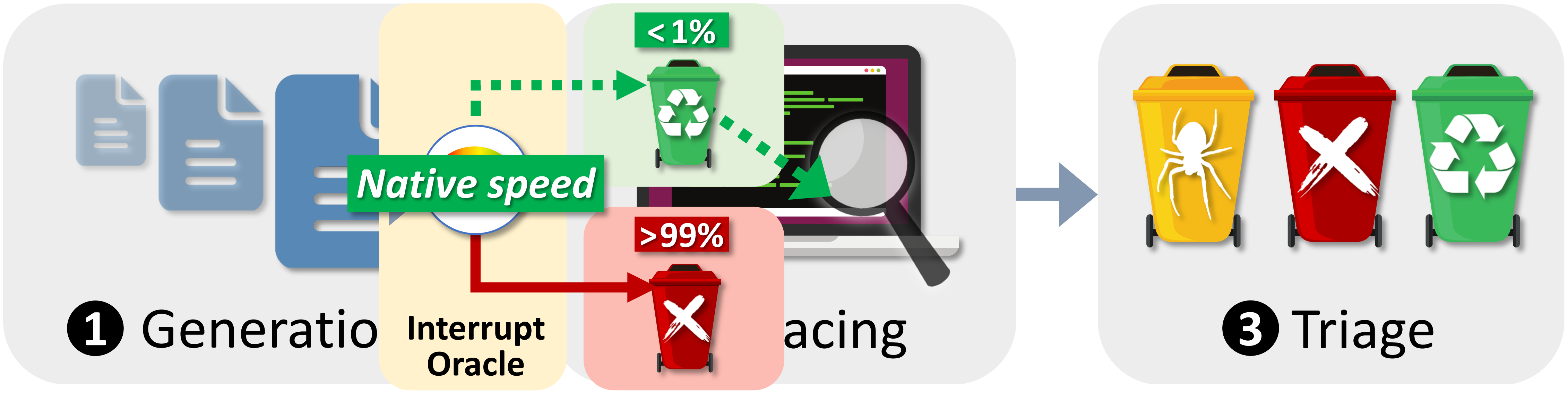
Coverage-guided Tracing (CGT)



Filter-out the **99.9%** of useless inputs at **native speed *without*** tracing
Overhead **approaches** 0% = **orders-of-magnitude faster** binary fuzzing

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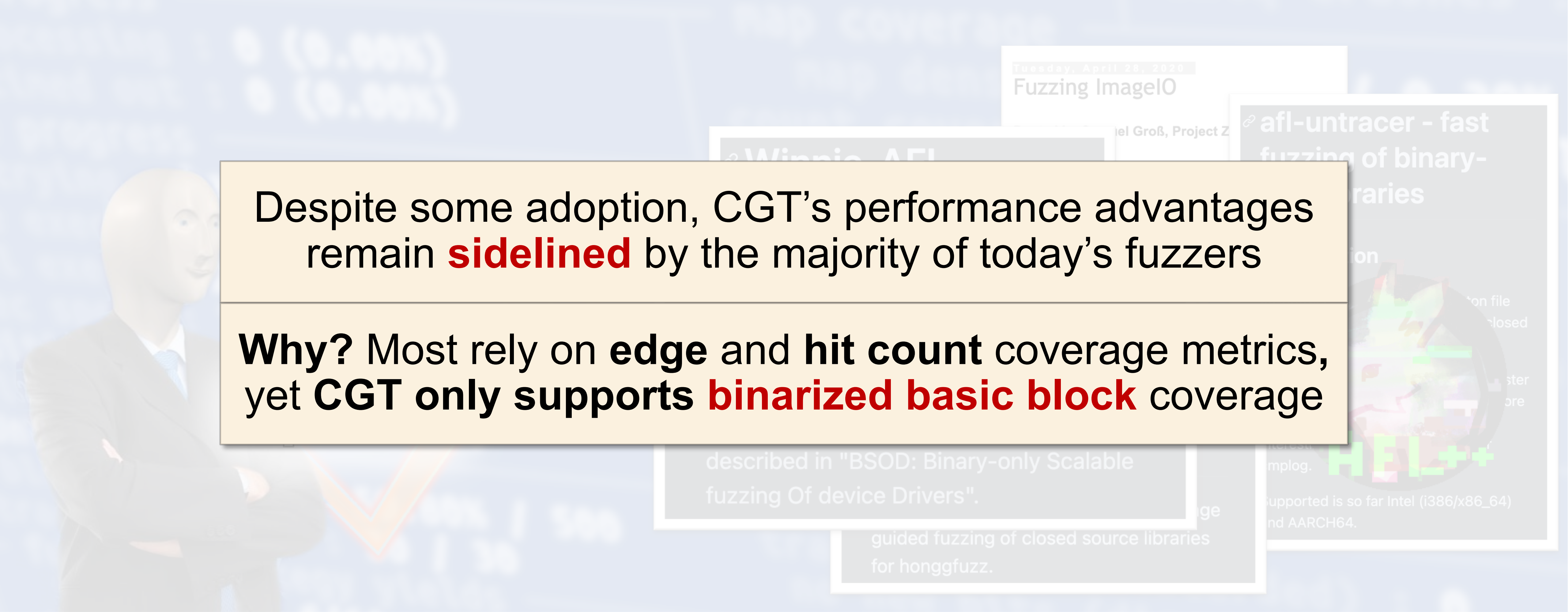
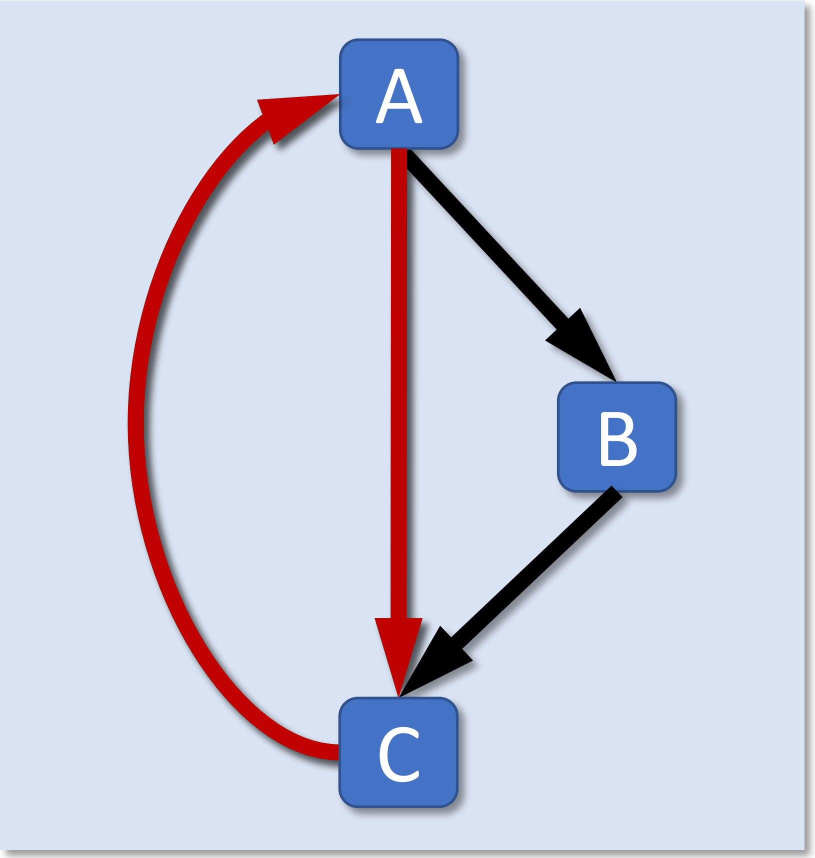
Adoption of Coverage-guided Tracing



Despite some adoption, CGT's performance advantages remain **sidelined** by the majority of today's fuzzers

Why? Most rely on **edge** and **hit count** coverage metrics, yet **CGT only supports binarized basic block** coverage

The Code Coverage Dilemma



For *critical* edge **A→C:**

Edge Coverage

- Will capture ***every*** **edge** irrespective of path taken

CGT: Block-level Coverage

- If path **A→B→C** seen first, ***can't*** discern edge **A→C**

For *back* edge **C→A:**

Hit Counts

- Will capture ***each*** **count** backwards edge is taken

CGT: Binarized Counts

- ***Can't*** discern ***any*** **count** edge **C→A** is re-taken

The Code Coverage Dilemma

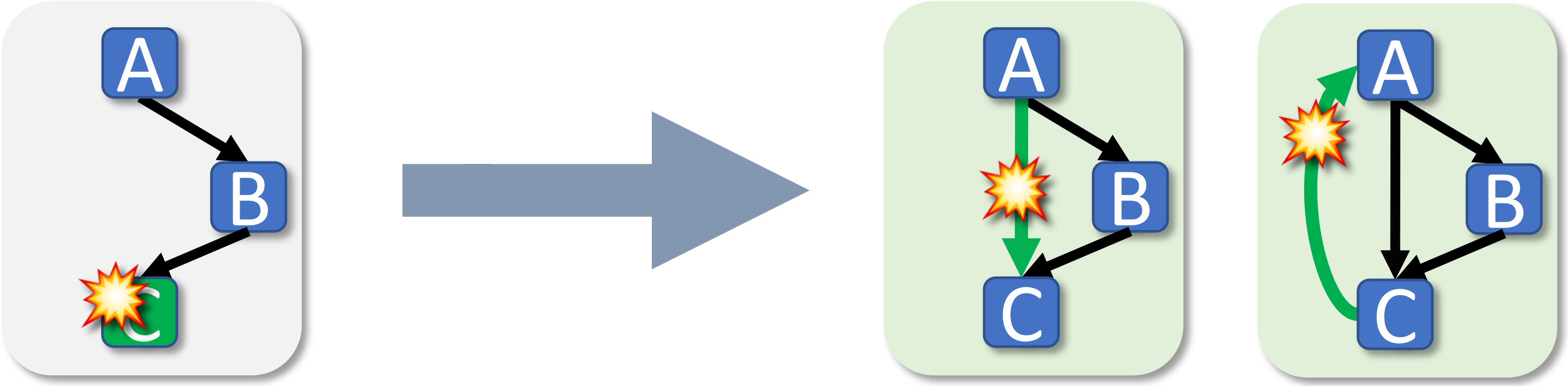
Name	Covg	Hits	Name	Covg	Hits	Name	Covg	Hits
AFL	Edge	✓	EnFuzz	Edge	✓	ProFuzzer	Edge	✓
AFL++	Edge	✓	FairFuzz	Edge	✓	QSYM	Edge	✓
AFLFast	Edge	✓	honggFuzz	Edge	✗	REDQUEEN	Edge	✓
AFLSmart	Edge	✓	GRIMORE	Edge	✓	SAVIOR	Edge	✓
Angora	Edge	✓	lafIntel	Edge	✓	SLF	Edge	✓
CollAFL	Edge	✓	libFuzzer	Edge	✓	Steelix	Edge	✓
DigFuzz	Edge	✓	Matryoshka	Edge	✓	Superion	Edge	✓
Driller	Edge	✓	MOpt	Edge	✓	TIFF	Block	✓
Eclipser	Edge	✓	NEUZZ	Edge	✓	VUzzer	Block	✓

Is it possible to uphold the **high speed of CGT** while **meeting existing fuzzers' coverage demands**?

Coverage-*preserving* Coverage-guided Tracing

Guiding Principle

How can CGT's **lightweight, interrupt-driven coverage** support finer-grained **edge and hit count** coverage?



To extend **CGT beyond binarized block coverage**, we must find ways to make these **finer-grained control-flows *self-report*** their coverage

Conventional Edge Coverage at Block Level

Resolving **critical edges**

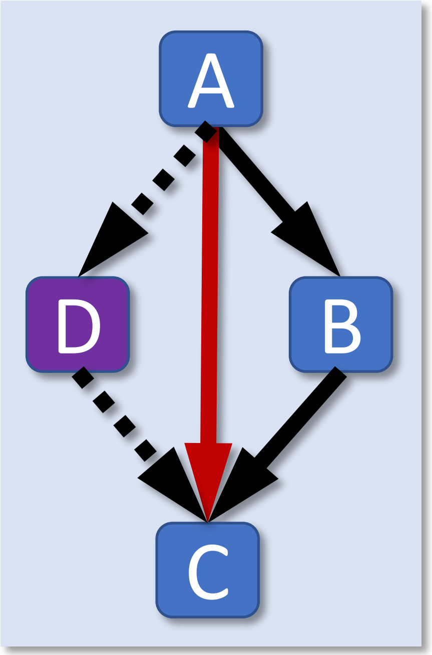
- Edges whose start, end have **2+** out, in edges (respectively)
- If *non-critical* path is first, *critical* edge (**A→C**) *never* seen!

Naive approach: **split** each with new dummy block

- Covering a dummy (**D**) implicitly covers its critical edge
- To facilitate CGT, add interrupts on every dummy

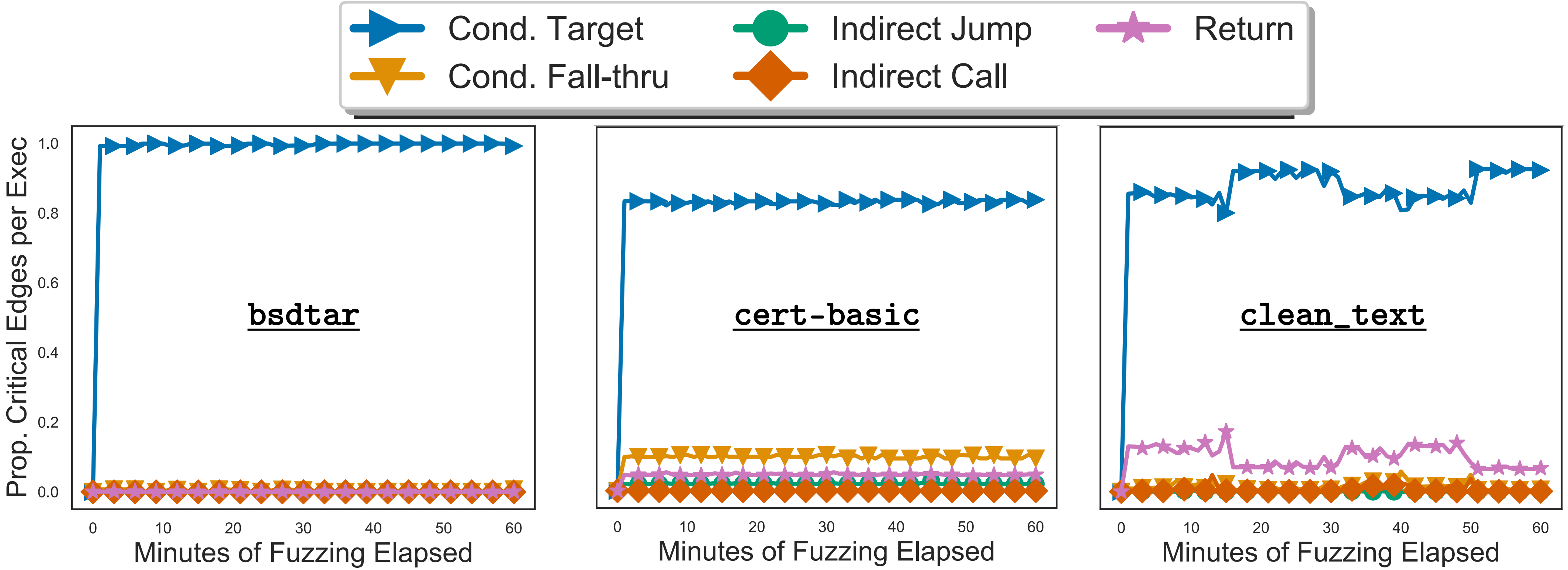
Problem: splitting adds **30–40%** more basic blocks

- Accumulates **more and more overhead** over native speed



Splitting each critical edge with new basic blocks will **deteriorate** CGT's performance

How do critical edges manifest?



Observation: **89%** of fuzzer-covered critical edges are **conditional jump target** branches

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Optimizing Common-case Critical Edges

Observation: conditional jumps' **targets** are **self-encoded**

- Jump instruction encoding:

```
[ opcode ] [ PC-relative displacement ]
```

- To resolve a jump to a target address:

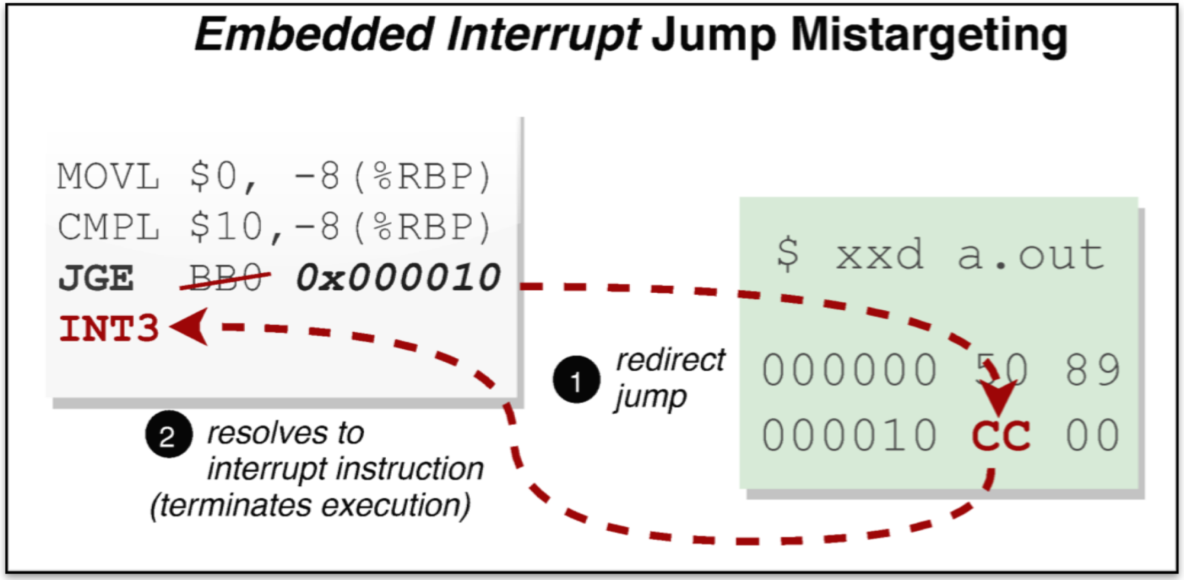
```
[        ] =
```

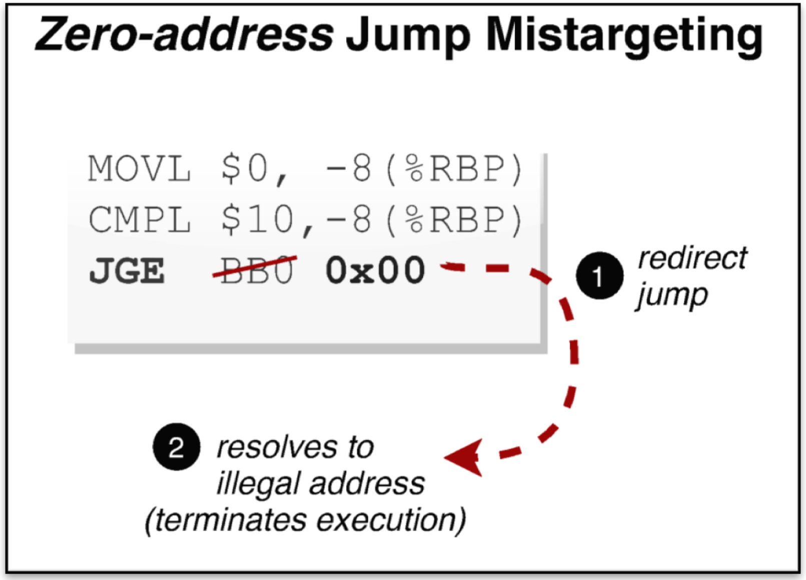
Intuition: rewrite and force execution to an *interrupt*!

> To signal the edge as taken, we can **resolve its target** to a **CGT-style interrupt**

Our Solution: Jump Mistargeting

- Modify jump target to resolve in a **CGT-style interrupt**





- Following a crash, ***restore*** displacement for future test cases

Outcome: CGT-style edge coverage **at native speed**
(i.e., **zero additional** basic blocks or instructions)

Conventional Hit Count Coverage Tracking

Most fuzzers rely on AFL-style **bucketed hit counts:**

```
[ 1 ] [ 2 ] [ 3 ] [ 4,7 ] [ 8,15 ] [ 16,31 ] [ 32,127 ] [ 128+ ]
```

Advances to **higher buckets** (e.g., `[3]`→`[4,7]`) flagged interesting

Problem: implemented within **always-on instrumentation**

- Increments each edge's unique counter **for *each* execution**

Hit count tracking's reliance on **exhaustive tracing contradicts CGT's** only-when-needed tracing mindset

Why are hit counts important?

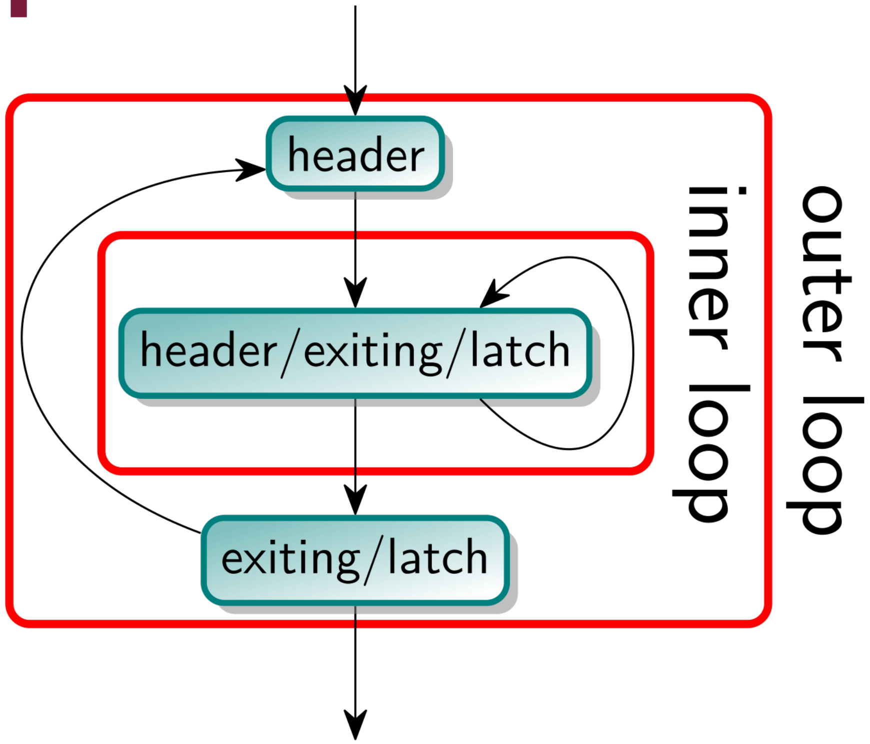
A testing property of cycles **(e.g., loops)**

Unlocking **deeper loop iterations**

- Common precedent for many critical bugs

Differentiating progress of nested loops

- Maximal consecutive iterations



Observation: Hit counts primarily guide fuzzing toward higher **loop exploration** progress

Optimizing Loop Hit Count Tracking

Observation: loops' **induction variables** **encode** their **iterations**

```
for( int i = 0; i < 100; i = i + 1 ){
```

iter 1
i = 0

iter 2
i = 1

iter 3
i = 2

- Track jumps to higher buckets via range check on induction variable

```
for(i=0; i<100; i++){
    if (i > 1)
            2)    15)
            3)    31)
            7)    127)
                  128)
}
```

Intuition: use *interrupt* to detect crossing buckets!

[1]	[2]	[3]	[4,7]
[8,15]	[16,31]	[32,127]	[128+]

To signal a loop's change in a hit count buckets, we can **use a range check** guarded by **CGT-style interrupts**

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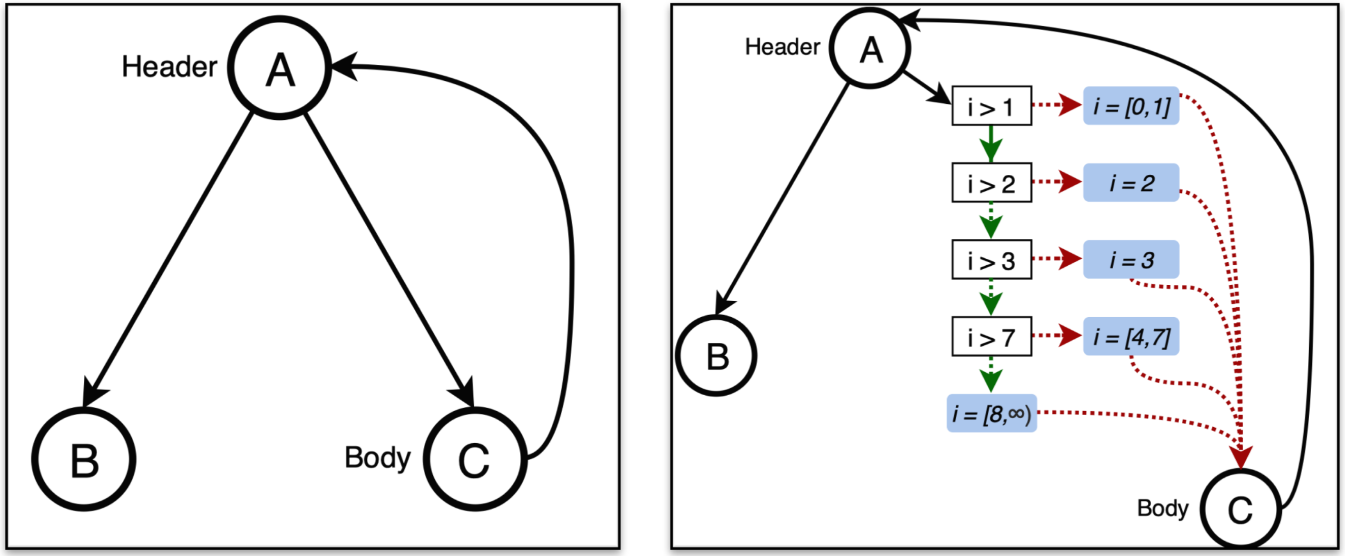
Our Solution: Bucketed Unrolling

- Inject discrete interval checks (with **interrupts** on all ***false*** edges)



- If crash, entered a ***higher*** bucket; then ***clear*** interrupt and move on

Outcome: CGT-style hit counts **without relying on always-on tracing**

Implementation: HeXcite

- **H**igh-**E**fficiency e**X**panded **C**overage for **I**mproved **T**esting of **E**xecutables
- **Binary-only** fuzzer built atop **AFL** 2.52b and **ZAFL** fuzzing rewriter
- Jump mistargeting:
  - Implementation based on *zero-address* mistargeting
  - Critical edge identification performed after control-flow parsing
  - Jumps converted to 32-bit displacements (e.g., all are mistargetable)
- Bucketed unrolling:
  - Implementation based on conventional AFL-style eight ranges
  - Loop identification performed via standard back edge analysis
  - For simplicity, we insert a fake induction variable and incrementor

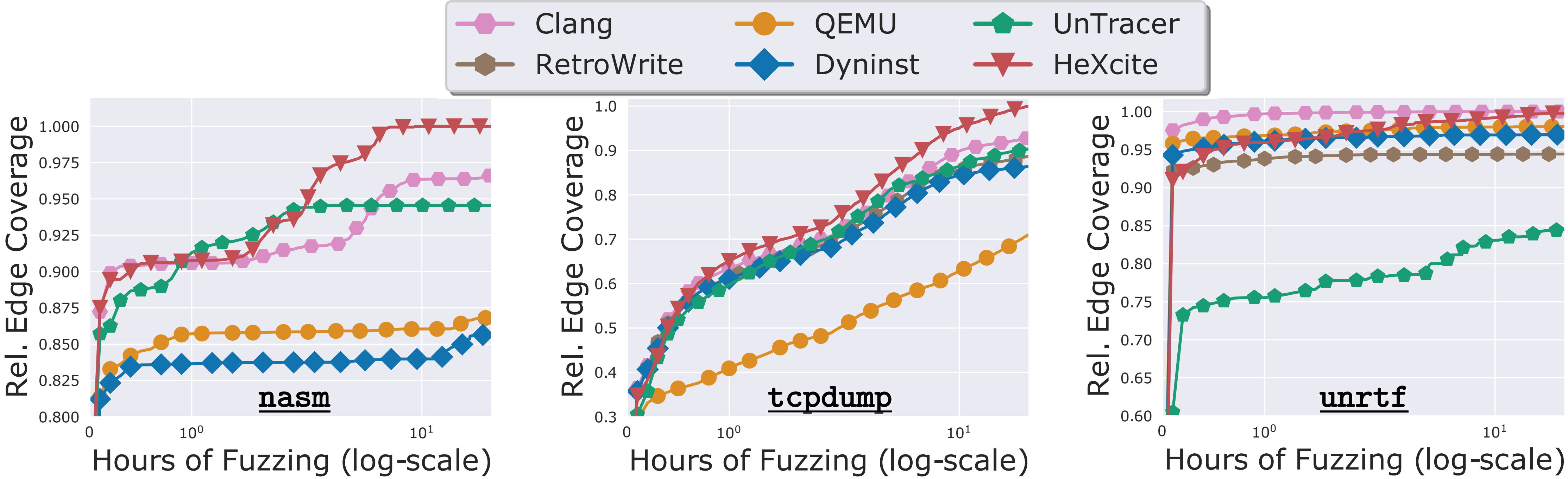
Evaluation

Evaluation Setup

Approach	Tracing Type	Level	Coverage
HeXcite	coverage-guided	binary	edge + counts
UnTracer	coverage-guided	binary	block
QEMU	always-on	binary	edge + counts
Dyninst	always-on	binary	edge + counts
RetroWrite	always-on	binary	edge + counts
Clang	always-on	source	edge + counts

- **Benchmarks:** 8 diverse open-source + 4 closed-source binaries
- **Evaluations:** perform 16x24-hr trials per benchmark on Azure cloud
- **Edge coverage:** collect with LLVM instrumentation and AFL tools
- **Loop coverage:** compute max consecutive iterations capped at 128
- **Performance:** scale throughput relative to worst-performing competitor
- **Bug-finding:** crash triage performed via AddressSanitizer

Does HeXcite improve edge coverage?



6.2% more edges than block-only UnTracer
23.1%, 18.1%, and 6.3% more edges than binary-level QEMU, Dyninst, and RetroWrite
1.1% more edges than source-level AFL-Clang

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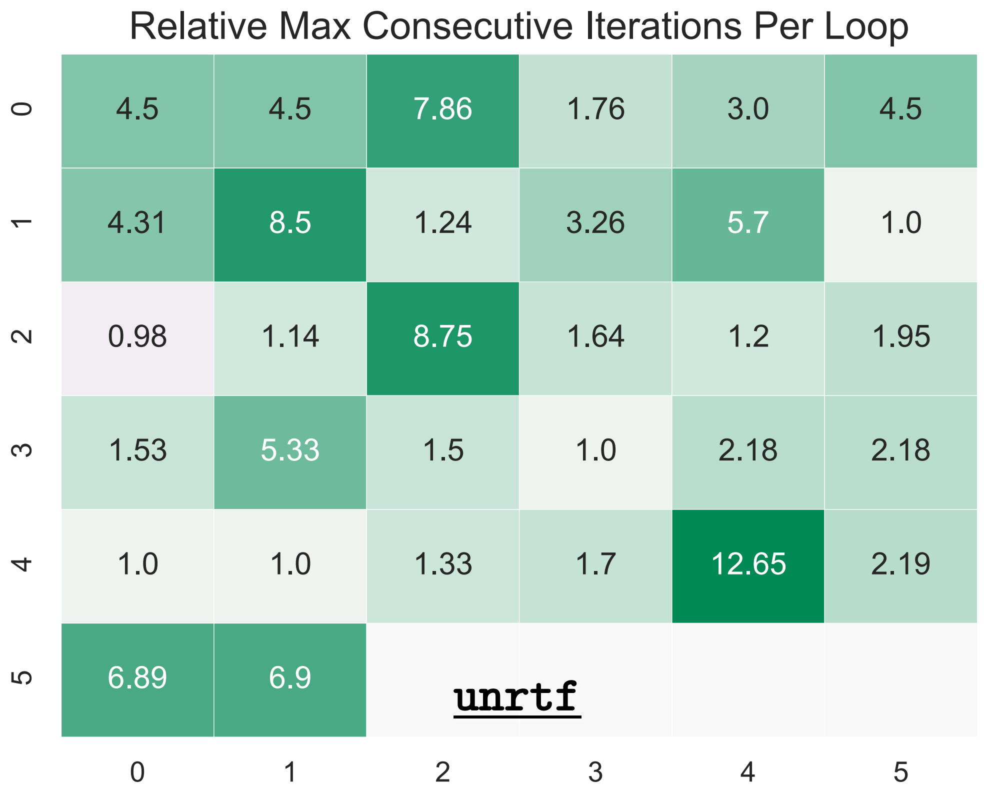
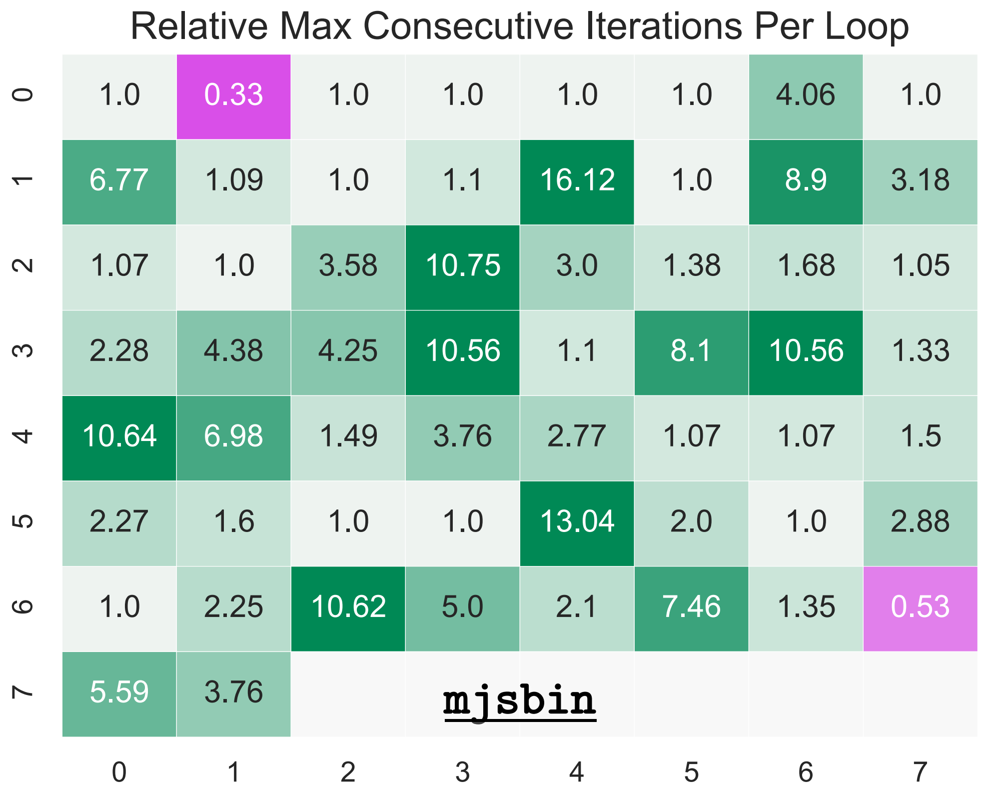
Does HeXcite improve loop exploration?

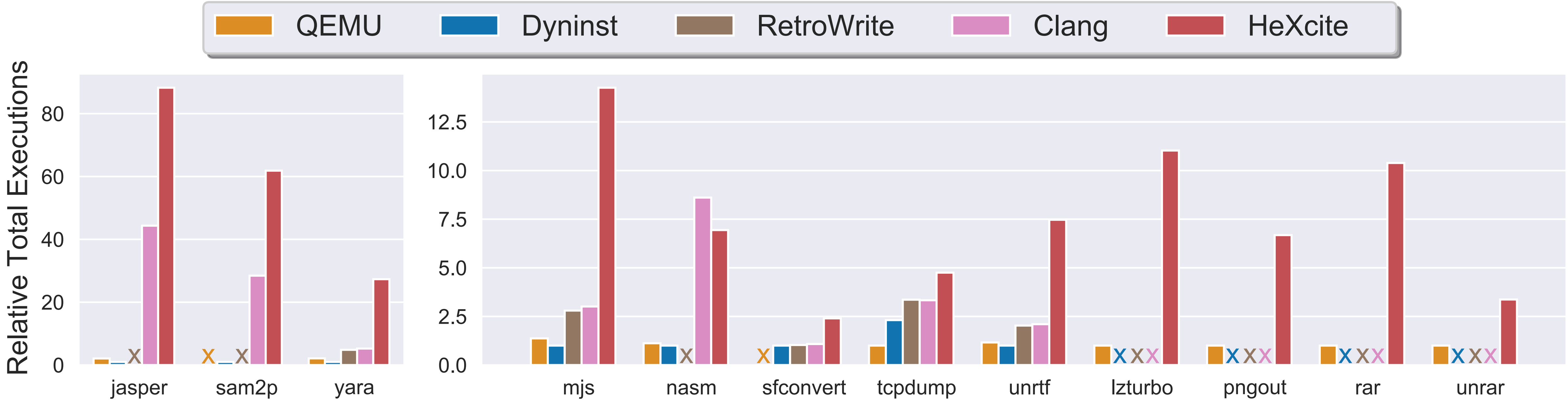




130% more iterations than block-only UnTracer

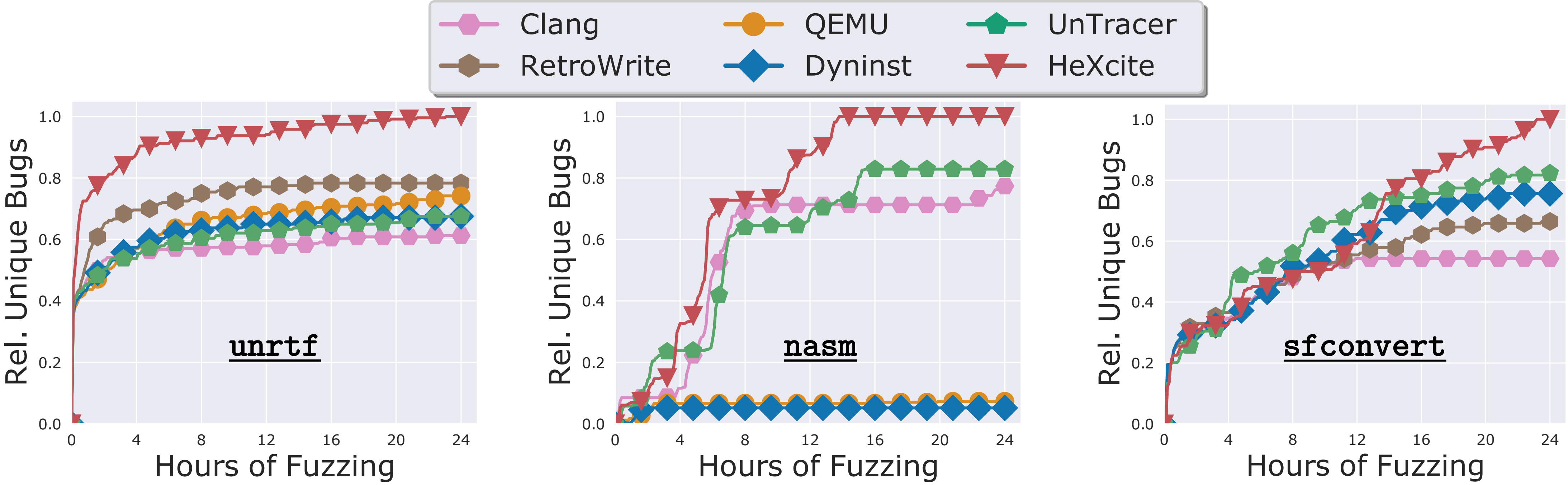
36% more iterations than source-level AFL-Clang

Is HeXcite as fast as block-only CGT?



10% higher best-case than block-only UnTracer
11.4x, 24.1x, and 3.6x the fuzzing throughput of binary-level QEMU, Dyninst, and RetroWrite
2.8x the throughput of source-level AFL-Clang

Can HeXcite improve binary bug-finding?



12% more bugs than block-only UnTracer
521%, 749%, and 56% more bugs than binary-level QEMU, Dyninst, and RetroWrite
46% more bugs than source-level AFL-Clang

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Does HeXcite accelerate bug-finding?

Identifier	Category	Binary	*Coverage-guided Tracing* HeXcite	*Coverage-guided Tracing* UnTracer
CVE-2011-4517	heap overflow	jasper	13.1 hrs	18.2 hrs
GitHub issue #58-1	stack overflow	mjs	13.3 hrs	19.0 hrs
GitHub issue #58-2	stack overflow	mjs	13.6 hrs	16.4 hrs
GitHub issue #58-3	stack overflow	mjs	5.88 hrs	6.80 hrs
GitHub issue #58-4	stack overflow	mjs	8.60 hrs	10.7 hrs
GitHub issue #136	stack overflow	mjs	1.30 hrs	7.50 hrs
Bugzilla #3392519	null pointer deref	nasm	12.1 hrs	13.5 hrs
CVE-2018-8881	heap overflow	nasm	5.06 hrs	14.6 hrs
CVE-2017-17814	use-after-free	nasm	3.54 hrs	6.31 hrs
CVE-2017-10686	use-after-free	nasm	3.84 hrs	5.40 hrs
Bugzilla #3392423	illegal address	nasm	8.17 hrs	14.2 hrs
CVE-2008-5824	heap overflow	sfconvert	13.1 hrs	14.8 hrs
CVE-2017-13002	stack over-read	tcpdump	8.34 hrs	12.5 hrs
CVE-2017-5923	heap over-read	yara	3.24 hrs	5.67 hrs
CVE-2020-29384	integer overflow	pngout	5.40 min	34.5 min
CVE-2007-0855	stack overflow	unrar	10.7 hrs	17.6 hrs

52.4% exposure speedup over block-only UnTracer

Conclusion: Why Coverage-preserving CGT?

- Maximizing fuzzing performance is critical for effective bug-finding.
- Yet, the coverage shortcomings of **Coverage-guided Tracing**—fuzzing's ***fastest*** tracing strategy—restrict fuzzers to far slower, ***always-on* tracing**.

Making CGT's **orders-of-magnitude** faster tracing available **to *all* fuzzers** demands extending it to the finer-grained coverage metrics used today: **edges** and **hit counts**.

By forcing finer-grained control-flow to **self-report** its coverage, we expand CGT to ***binary-level*** **edge** and **hit count coverage** at virtually **no performance loss**.

- **Fuzzing speed:** **2.8—24.1x** higher than binary- *and* source-level tracing
- **Code coverage:** **6.2%** more edges and **130%** deeper loops than *block-only* CGT
- **Bug-finding:** **12—749%** more bugs than block-only CGT *and* always-on tracing

Thank you!

Find HeXcite and our evaluation benchmarks at:

https://github.com/FoRTE-Research/hexcite

Happy (*binary*) fuzzing!

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