[1] list université PARIS-SACLAY
USC University of Southern California [2]

Fine-Grained Coverage-Based Fuzzing

Wei-Cheng Wu [1,2] *Bernard Nongpoh* [1] *Marwan Nour* [1]
Michaël Marcozzi [1] *Sébastien Bardin* [1] *Christophe Hauser* [2]

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This work has been mainly carried out by...

Wei-Cheng Wu

Ph.D. student

(also @ USC in Los Angeles)

Dr. Benard Nongpoh

Postdoc

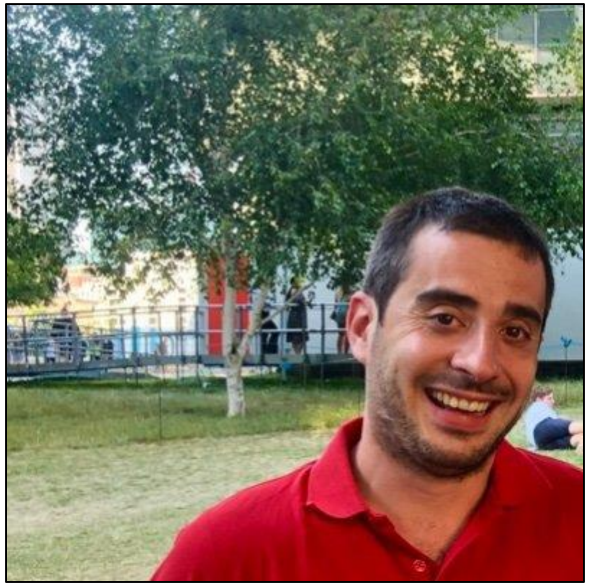
(now @ Qualcomm)

Marwan Nour

M.Sc. Intern

(from Ecole Polytechnique)

About me // Dr. Michaël Marcozzi



- **Permanent researcher** @ CEA LIST, Université Paris-Saclay
- My research group focus on **software analysis for security**
- **Invited lecturer** @ ENSTA, Institut Polytechnique de Paris

Outline

1. **Context**: coverage-based fuzzing
2. **Problem**: branch coverage is shallow
3. **Goal:** enable and evaluate fuzzer guidance with fine-grained metrics
4. **Proposal**: finer-grained objectives as new branches in fuzzed code
5. **Experimental evaluation of impact**
6. **Conclusions**

Fuzzing [1/2]

Fuzzing a program (for security) is…

1. Feed program with massive number of <u>automatically generated inputs</u>
2. <u>Trigger</u> so observable <u>failures</u> (e.g. crashes)
3. Analyse failures to <u>reveal</u> program <u>vulnerabilities</u> to fix or exploit

buffer-overflow.c

```c
int check_authentication(char *password) {
    int auth_flag = 0;
    char password_buffer[10];
    strcpy(password_buffer, password);
    if (strcmp(password_buffer, "dumbledore") == 0)
        auth_flag = 1;
    if (strcmp(password_buffer, "gandalf") == 0)
        auth_flag = 1;
    return auth_flag;
}

int main(int argc, char *argv[]) {
    AFL_INIT_ARGV();
    if (argc < 2) {
        printf("Usage: %s <password>\n", argv[0]);
        exit(0);
    } else if (check_authentication(argv[1]))
    {
        /* Code doing sensitive actions here */
        printf("\nSensitive actions done.\n");
    }
    else printf("\nAccess Denied.\n");
}
```

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```
./buffer-overflow.exe 11111111111111111111111111111111111111111
Segmentation fault
```

buffer-overflow.c

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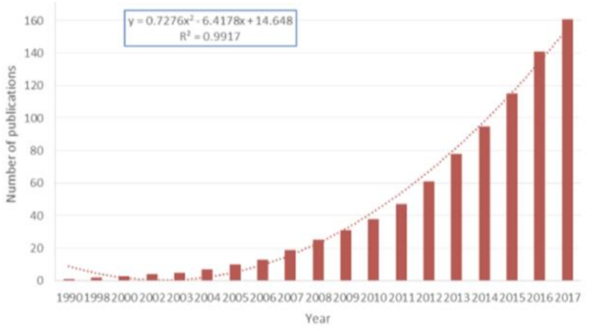
```

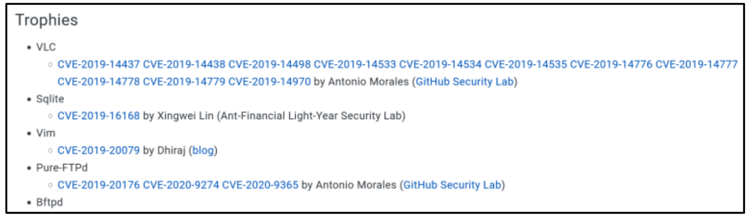
Fuzzing [2/2]

Fuzzing is **popular** (**why?** easy to understand/use, scalable, effective?)…

- Many recent research papers on improving fuzzers
- “At Google, fuzzing has uncovered tens of thousands of bugs” [Metzman et al., 2021]
- Fuzzers have found many CVE vulnerabilities in real programs



Number of fuzzing papers/year [Liang et al., 2018]



Some 2019 CVEs found by AFL++ fuzzer [AFL++ website]

Coverage-based fuzzing [1/3]

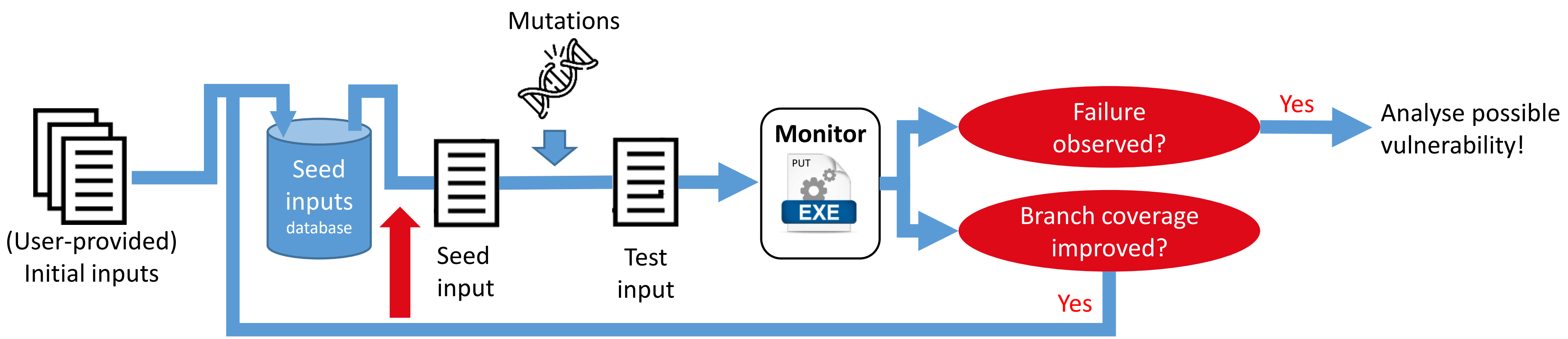
Many fuzzers use **branch coverage to guide** input generation…

- New inputs are generated by mutating the former inputs that improved branch coverage
- The rationale of this heuristic is…
  - The inputs that improved branch coverage uncovered *new interesting program behaviours*
  - Mutating these inputs should *explore these new behaviours even more*

```
if (input > 5) { // Decision point
    // THEN branch
} else {
    // ELSE branch
}
```

Coverage-based fuzzing [2/3]

More precisely, coverage-based **fuzzers** implement the following **loop**…



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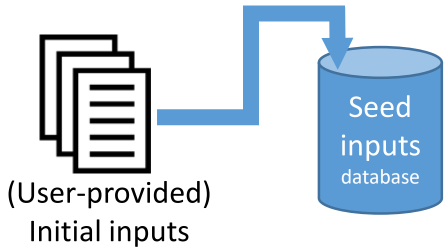

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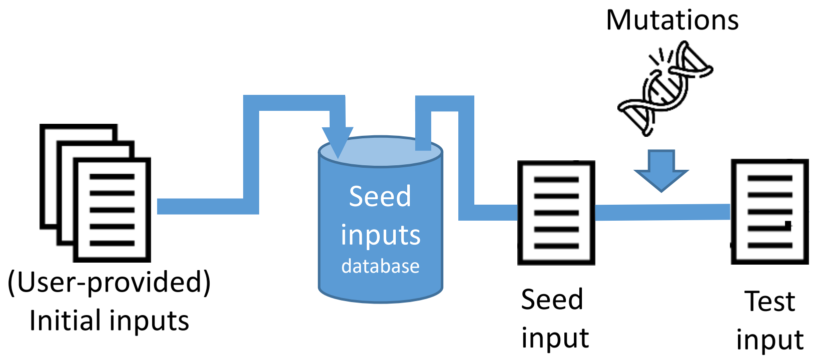

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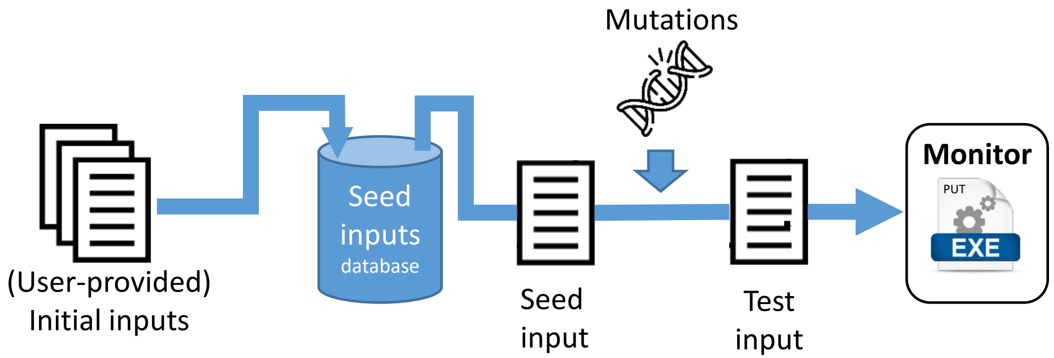

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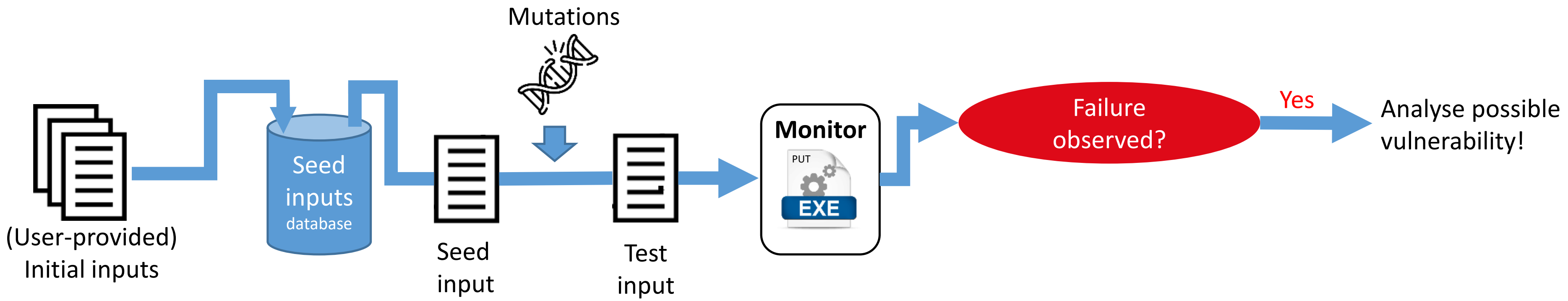

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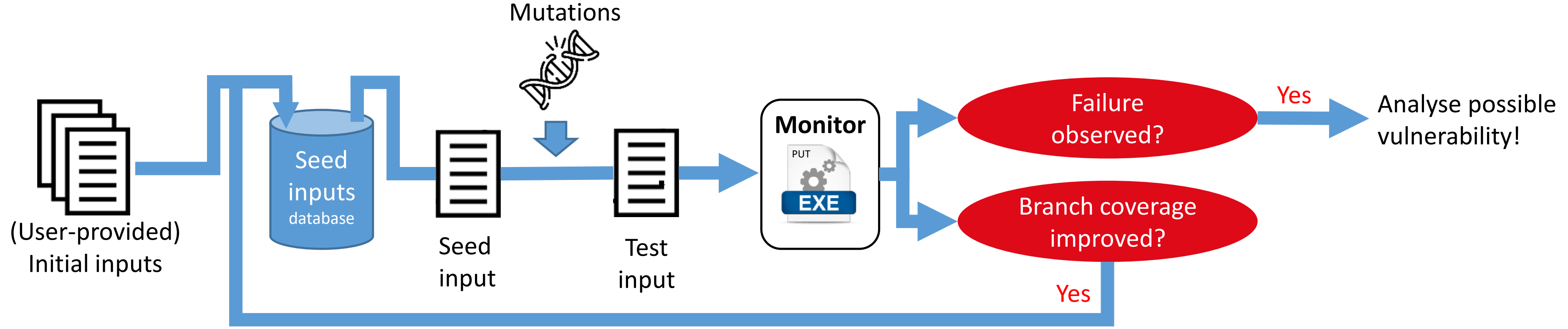

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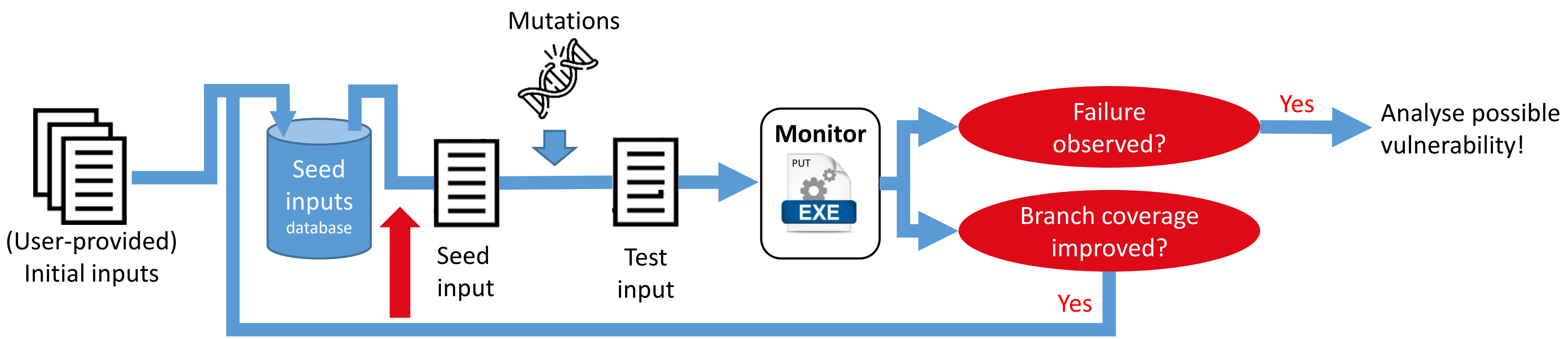

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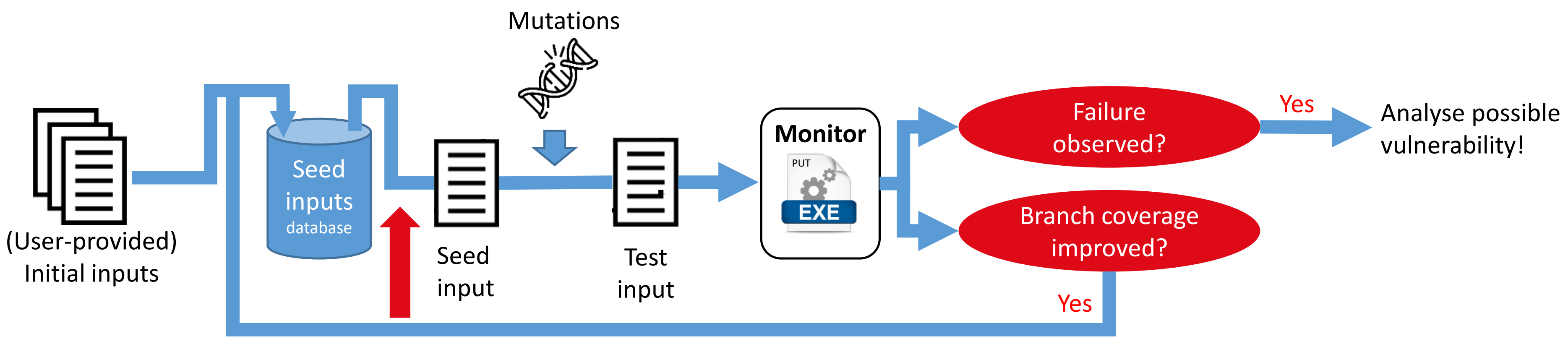

The loop terminates when the fuzzing budget is over!

Coverage-based fuzzing [3/3]

Yet, the fuzzing loop alone requires **a high budget to find bugs** in “**difficult**” **branches**…

- A branch in fuzzed code is “difficult” when only activated by tiny fraction of inputs

```
int main (long long input) {
...
if (input == 666) {
    // Difficult branch
}
```

- Code analyses enable fuzzers to be faster at finding inputs entering difficult branches…
    - (Taint tracking) *Track comparisons* between inputs and constants in fuzzed code (e.g. AFL++ fuzzer)
    - (Symbolic execution) *Derive and solve path constraints* to enter barely covered branches (e.g. Qsym fuzzer)

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Fine-grained coverage metrics [1/2]

- Branch coverage is a **shallow metric** of interesting program behaviours
- Fuzzers may thus **ignore inputs** that were interesting to find and mutate
- Software testing researchers have for long proposed **finer-grained metrics**
- **Idea**: guide fuzzers using these **control-flow**, **data-flow** or **mutation metrics**

Fine-grained coverage metrics [2/2]

For example, MCC metric considers subtler variations of program logic…

```
if (engine_speed  > 0 || wheels_speed > 0) {
   // Lock door
} else { … }
```

program

Branch Coverage
cover both branches

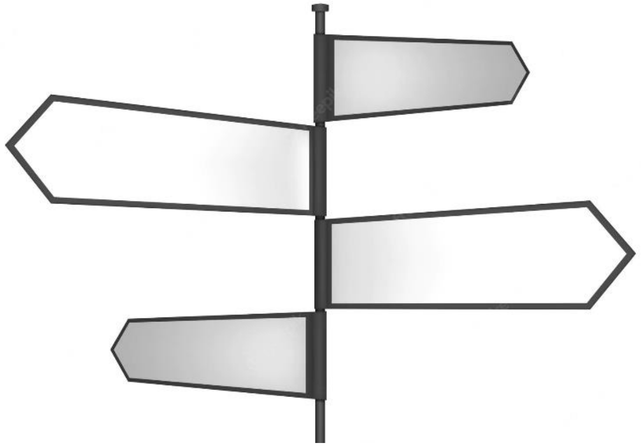
Coverage objective	Satisfying input
Take THEN branch	engine_speed = 5 wheels_speed = 0
Take ELSE branch	engine_speed = 0 wheels_speed = 0

Multiple Condition Coverage (MCC)
cover whole truth table

Coverage objective	Satisfying input
true || true	engine_speed = 5 wheels_speed = 5
true || false	engine_speed = 5 wheels_speed = 0
false || true	engine_speed = 0 wheels_speed = 5
false || false	engine_speed = 0 wheels_speed = 0

State of the art

- **Early research exists** for a **specific** fine-grained metric in a **specific** fuzzer
- Yet, **no clear and general idea of** what practical **impact** is
- **Huge effort needed** to support all fine-grained metrics in all legacy fuzzers



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Challenges of guiding fuzzers with finer-grained metrics

1. **Harness the wild variety** of legacy fuzzers and fine-grained metrics…

   Provide a <u>runtime guidance mechanism</u> that works without modifying legacy fuzzers:

   - *Activate* coverage objectives from most fine-grained metrics *for seed selection*
   - *Trigger* search for inputs that satisfy *difficult fine-grained coverage objectives*

2. **Evaluate impact** of fine-grained metrics **over legacy fuzzers performance**

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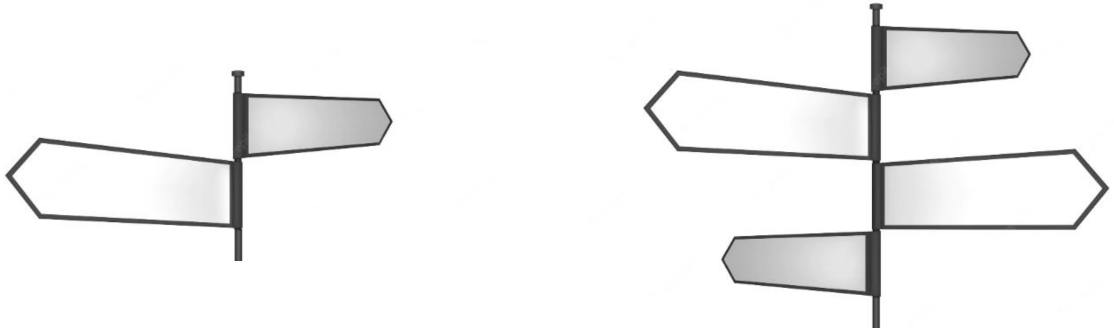
Principle [1/3]

We guide legacy (branch) fuzzers by **transforming the fuzzed program**…

- Objectives from most metrics can be made explicit as assertions in the fuzzed code

  [Bardin et al., 2021]

- Thus, we add a no-op branch (**if** guarded by the assertion predicate) for each assertion



Principle [2/3]

```
if (engine_speed  > 0 || wheels_speed > 0) {
   // Lock door
} else { … }
```

program

+

Multiple Condition Coverage (MCC)

cover whole truth table

Coverage objective	Satisfying input
true || true	engine_speed = 5 wheels_speed = 5
true || false	engine_speed = 5 wheels_speed = 0
false || true	engine_speed = 0 wheels_speed = 5
false || false	engine_speed = 0 wheels_speed = 0

```
if (engine_speed  > 0 && wheels_speed > 0) {}
if (engine_speed  > 0 && wheels_speed <= 0) {}
if (engine_speed  <= 0 && wheels_speed > 0) {}
if (engine_speed  <= 0 && wheels_speed <= 0) {}

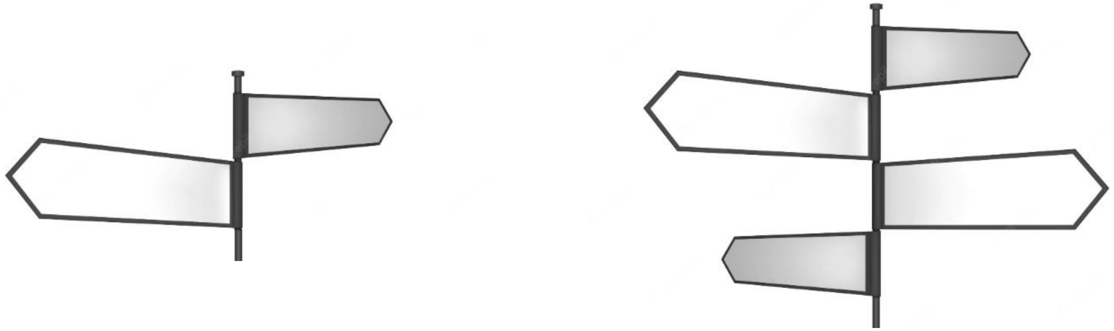
if (engine_speed  > 0 || wheels_speed > 0) {
   // Lock door
} else { … }
```

transformed program

Principle [3/3]

When **fuzzing the transformed program** with a legacy (branch) fuzzer…

- …inputs covering the fine-grained objectives will effortlessly <u>be saved as seeds</u>
- …code analyses for difficult branches will help with <u>difficult fine-grained objectives</u>



Practical contributions

We propose a **careful no-op branch insertion tool** for fine-grained metrics…

- …which avoids corrupting the program semantics (side-effects, spurious crashes)
- …which avoids branches being tampered by compiler or fuzzing harness

Simple example of corruption avoidance

```
if (print("a") || graph_ok) {
   // Proceed
} else { /* Error */ }
```

program

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if (print("a") || graph_ok) {
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```
if (print("a") && graph_ok) {}
if (print("a") && !graph_ok) {}
if (!print("a") && graph_ok) {}
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transformed program for MCC

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transformed program for MCC

Prints "a" 4x more!
(semantic change)

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if (print(“a”) || graph_ok) {
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   // Proceed
} else { /* Error */ }
```

transformed program for MCC

Prints “a” 4x more!
(semantic change)

```
int temp = print(“a”);
if (temp || graph_ok) {
   // Proceed
} else { /* Error */ }
```

pre-processed program

Simple example of corruption avoidance

```
if (print("a") || graph_ok) {
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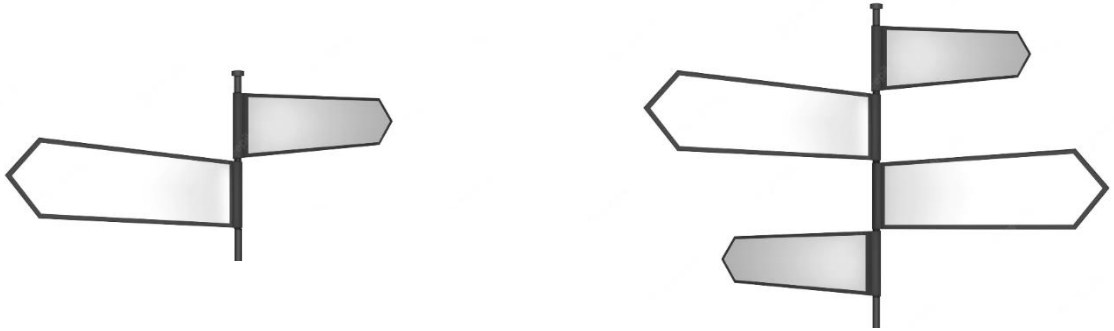
transformed pre-processed program for MCC

Possible extensions

No-op branches could be **used as a more general guidance mechanism**...

- They could also be guarded by predicates written by human developers…
- …or by predicates computed by static analysers (like fault preconditions)



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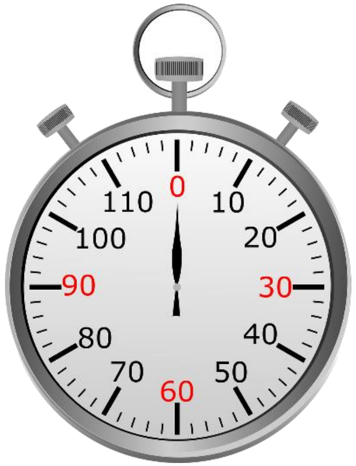
Main evaluation plan

We **evaluate the impact of fine-grained metrics** over fuzzing…

- …by running legacy fuzzers over original programs and transformed versions
- …and comparing throughput, seeds number, covered branches and found bugs

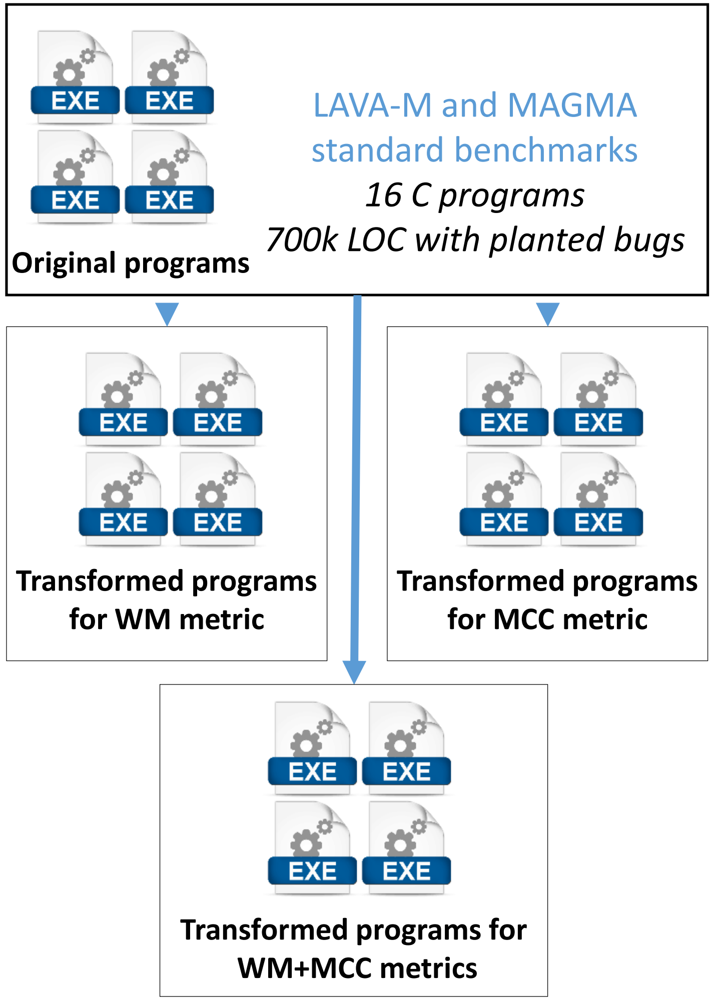


Main experimental setup

Original programs

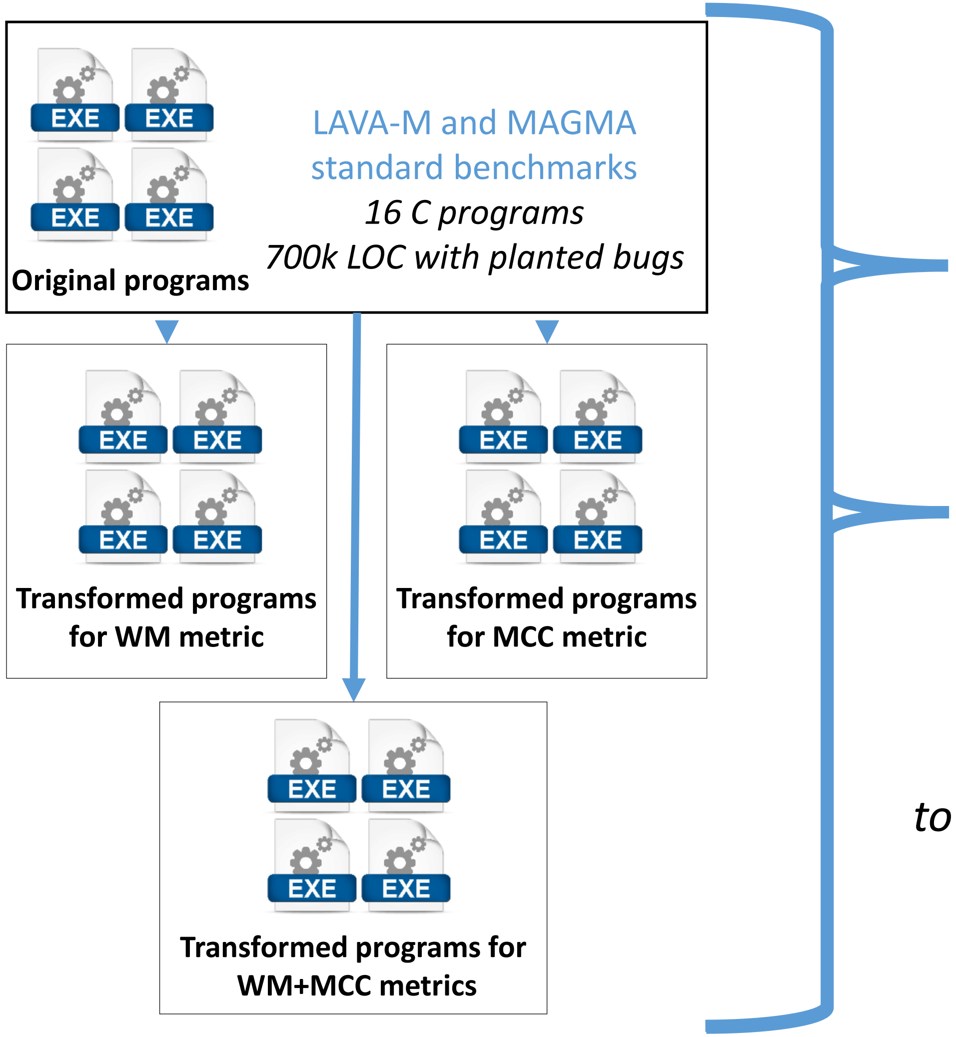
LAVA-M and MAGMA standard benchmarks
16 C programs
700k LOC with planted bugs

Main experimental setup



We use **Multiple Condition Coverage** (MCC) and **Weak Mutations** coverage (WM) two **common** fine-grained metrics, notoriously **denser** than branch coverage

Main experimental setup



AFL++

qsym

5 x (24h fuzzing campaign)
per program
to improve statistical significance

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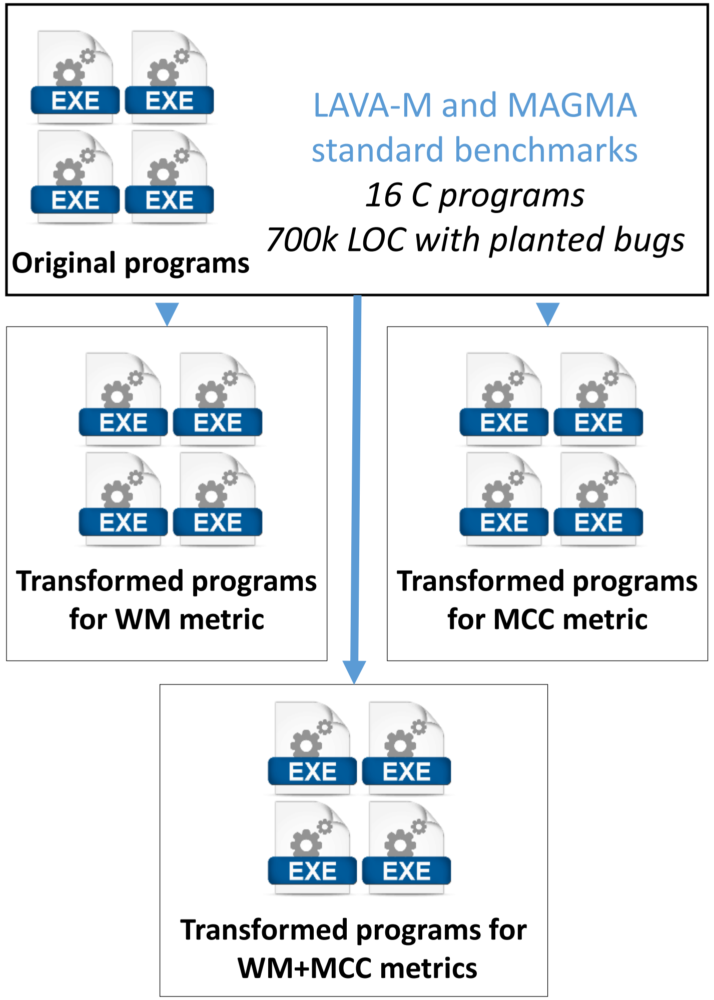

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Averaged…

- fuzzer’s throughput
- # saved seeds
- # covered branches
- # planted bugs that were detected

2.5 years of CPU computation happen here

Consolidated results for AFL++

(detailed results for AFL++ and QSYM are available in the paper, observations are similar)

Executable	AFL++ with MCC				AFL++ with WM				AFL++ with MCC + WM			
	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs
base64	+29%	+2%	+2	—	+40%	+1%	—	—	-5%	+2%	+2	—
uniq	+16%	-5%	+7	—	-1%	+12%	+10	—	-21%	+13%	+6	—
md5sum	+18%	-34%	-41	—	+3%	-31%	-41	—	+25%	-24%	-12	—
who	-6%	+19%	+133	+165	-9%	+28%	+6	+98	-19%	+22%	-4	-56
lua	-8%	+6%	-65	—	-33%	+7%	-159	—	-36%	+6%	-99	—
exif	-21%	-19%	-41	+1	-12%	-5%	-13	+1	-27%	-25%	-98	+1
sndfile	-48%	+2%	-239	—	-72%	+39%	-578	—	-64%	+48%	-373	—
libpng_read	-7%	+64%	-33	-1	-3%	+45%	-12	—	-13%	+95%	-16	—
tiff_read_rgba	-49%	-2%	-268	-2	-48%	+11%	-354	-1	-45%	+15%	-158	-1
tiffcp	-49%	-9%	-653	-2	-52%	+18%	-512	-2	-44%	+18%	-543	-2
read_memory	-84%	+35%	-1447	—	-63%	+8%	-556	—	-86%	+53%	-1333	—
xmllint	-72%	+46%	-850	-1	-49%	+12%	+401	-1	-77%	+54%	-1059	-1
sqlite3	-19%	-7%	-2489	—	-25%	-10%	-5297	—	-45%	-19%	-6062	—
server	-17%	-3%	+3	-1	-18%	-5%	-26	-1	-33%	-5%	-47	-1
client	-17%	+2%	+16	—	-27%	—	-20	—	-42%	-1%	-27	—
x509	-18%	+1%	-9	-1	-21%	+1%	-11	—	-24%	+1%	-13	-1

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[redacted]												
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lua	-8%	+6%	-65	—	-33%	+7%	-159	—	-36%	+6%	-99	—
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sndfile	-48%	+2%	-239	—	-72%	+39%	-578	—	-64%	+48%	-373	—
libpng_read	-7%	+64%	-33	-1	-3%	+45%	-12	—	-13%	+95%	-16	—
tiff_read_rgba	-49%	-2%	-268	-2	-48%	+11%	-354	-1	-45%	+15%	-158	-1
tiffcp	-49%	-9%	-653	-2	-52%	+18%	-512	-2	-44%	+18%	-543	-2
read_memory	-84%	+35%	-1447	—	-63%	+8%	-556	—	-86%	+53%	-1333	—
xmllint	-72%	+46%	-850	-1	-49%	+12%	+401	-1	-77%	+54%	-1059	-1
sqlite3	-19%	-7%	-2489	—	-25%	-10%	-5297	—	-45%	-19%	-6062	—
server	-17%	-3%	+3	-1	-18%	-5%	-26	-1	-33%	-5%	-47	-1
client	-17%	+2%	+16	—	-27%	—	-20	—	-42%	-1%	-27	—
x509	-18%	+1%	-9	-1	-21%	+1%	-11	—	-24%	+1%	-13	-1

Fuzzer quickly saturates on smaller and simpler programs…

Consolidated results for AFL++

(detailed results for AFL++ and QSYM are available in the paper, observations are similar)

Executable	AFL++ with MCC				AFL++ with WM				AFL++ with MCC + WM			
	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs
base64	+29%	+2%	+2	—	+40%	+1%	—	—	-5%	+2%	+2	—
uniq	+16%	-5%	+7	—	-1%	+12%	+10	—	-21%	+13%	+6	—
md5sum	+18%	-34%	-41	—	+3%	-31%	-41	—	+25%	-24%	-12	—
who	-6%	+19%	+133	+165	-9%	+28%	+6	+98	-19%	+22%	-4	-56
lua	-8%	+6%	-65	—	-33%	+7%	-159	—	-36%	+6%	-99	—
exif	-21%	-19%	-41	+1	-12%	-5%	-13	+1	-27%	-25%	-98	+1
sndfile	-48%	+2%	-239	—	-72%	+39%	-578	—	-64%	+48%	-373	—
libpng_read	-7%	+64%	-33	-1	-3%	+45%	-12	—	-13%	+95%	-16	—
tiff_read_rgba	-49%	-2%	-268	-2	-48%	+11%	-354	-1	-45%	+15%	-158	-1
tiffcp	-49%	-9%	-653	-2	-52%	+18%	-512	-2	-44%	+18%	-543	-2
read_memory	-84%	+35%	-1447	—	-63%	+8%	-556	—	-86%	+53%	-1333	—
xmllint	-72%	+46%	-850	-1	-49%	+12%	+401	-1	-77%	+54%	-1059	-1
sqlite3	-19%	-7%	-2489	—	-25%	-10%	-5297	—	-45%	-19%	-6062	—
server	-17%	-3%	+3	-1	-18%	-5%	-26	-1	-33%	-5%	-47	-1
client	-17%	+2%	+16	—	-27%	—	-20	—	-42%	-1%	-27	—
x509	-18%	+1%	-9	-1	-21%	+1%	-11	—	-24%	+1%	-13	-1

Fine-grained metrics slow down the fuzzer

(instrumented program is slower and produces more coverage data)

Consolidated results for AFL++

(detailed results for AFL++ and QSYM are available in the paper, observations are similar)

Executable	AFL++ with MCC				AFL++ with WM				AFL++ with MCC + WM			
	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs	Throughput	Seeds	Branches	Bugs
base64	+29%	+2%	+2	—	+40%	+1%	—	—	-5%	+2%	+2	—
uniq	+16%	-5%	+7	—	-1%	+12%	+10	—	-21%	+13%	+6	—
md5sum	+18%	-34%	-41	—	+3%	-31%	-41	—	+25%	-24%	-12	—
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lua	-8%	+6%	-65	—	-33%	+7%	-159	—	-36%	+6%	-99	—
exif	-21%	-19%	-41	+1	-12%	-5%	-13	+1	-27%	-25%	-98	+1
sndfile	-48%	+2%	-239	—	-72%	+39%	-578	—	-64%	+48%	-373	—
libpng_read	-7%	+64%	-33	-1	-3%	+45%	-12	—	-13%	+95%	-16	—
tiff_read_rgba	-49%	-2%	-268	-2	-48%	+11%	-354	-1	-45%	+15%	-158	-1
tiffcp	-49%	-9%	-653	-2	-52%	+18%	-512	-2	-44%	+18%	-543	-2
read_memory	-84%	+35%	-1447	—	-63%	+8%	-556	—	-86%	+53%	-1333	—
xmllint	-72%	+46%	-850	-1	-49%	+12%	+401	-1	-77%	+54%	-1059	-1
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client	-17%	+2%	+16	—	-27%	—	-20	—	-42%	-1%	-27	—
x509	-18%	+1%	-9	-1	-21%	+1%	-11	—	-24%	+1%	-13	-1

Fine-grained metrics improve performance when fuzzer slowdown is low enough and bug density is high enough (favour local exploration vs. new branch discovery)

Consolidated results for AFL++

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Executable	AFL++ with MCC				AFL++ with WM				AFL++ with MCC + WM			
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uniq	+16%	-5%	+7	—	-1%	+12%	+10	—	-21%	+13%	+6	—
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read_memory	-84%	+35%	-1447	—	-63%	+8%	-556	—	-86%	+53%	-1333	—
xmllint	-72%	+46%	-850	-1	-49%	+12%	+401	-1	-77%	[illegible]	[illegible]	[illegible]
sqlite3	-19%	-7%	-2489	—	-25%	-10%	-5297	—	-45%	[illegible]	[illegible]	[illegible]
server	-17%	-3%	+3	-1	-18%	-5%	-26	-1	-33%	[illegible]	[illegible]	[illegible]
client	-17%	+2%	+16	—	-27%	—	-20	—	-42%	[illegible]	[illegible]	[illegible]
x509	-18%	+1%	-9	-1	-21%	+1%	-11	—	-24%	[illegible]	[illegible]	[illegible]

Hard to know if these conditions are met before fuzzing (most of the time, no)… :-(

Fine-grained metrics improve performance when fuzzer slowdown is low enough and bug density is high enough (favour local exploration vs. new branch discovery)

Outline

1. **Context**: coverage-based fuzzing
2. **Problem**: branch coverage is shallow
3. **Goal:** enable and evaluate fuzzer guidance with fine-grained metrics
4. **Proposal**: finer-grained objectives as new branches in fuzzed code
5. **Experimental evaluation of impact**
6. **Conclusions**

Conclusions [1/2]

Adding **no-op branches** to **fuzzed code**…

- Can provide runtime guidance to legacy (branch) fuzzers out of the box
- Can encode guidance from most fine-grained coverage metrics
- Requires careful transformation for not breaking semantics (beware of corner cases)

Future work involves…

- Study tighter integration with fuzzer harness and configuration
- Use to encode human directives or bug preconditions from static analysers

Conclusions [2/2]

Fine-grained metrics should **not replace branch coverage** to guide fuzzers…

- Impact is hard to predict before fuzzing and usually neutral or negative
- Other studies (with tight fuzzer/metric integration) tend to confirm this trend
- Yet, they might be useful in small doses, to improve local exploration where needed

Future work involves…

- Investigate favourable circumstances that could make fine-grained metrics profitable
- Notably, use them only in fragile or sensitive parts of the code…

Fine-Grained Coverage-Based Fuzzing

Key takeaways

> Carefully adding branches to fuzzed code provides guidance to fuzzers

> Fine-grained metrics slow down fuzzers but favour local exploration

Dr. Michaël Marcozzi

Permanent Researcher

@michaelmarcozzi

www.marcozzi.net

www.marcozzi.net

Postdocs, Ph.D. students and interns

Software security and program analysis