An evaluation of Symbolic Execution Systems and the benefits of compilation with SymCC

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- System security
- Embedded devices security
- Wireless security

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- Loves software engineering and building tools for developers!
- Worked at Lastline and Zalendo before PhD
- About to complete PhD, joining startup “Code Intelligence”

Why looking at Symbolic execution (performance)?

Symbolic execution is a middle ground between formal methods and traditional testing

- Can, in theory, provide complete coverage
- And therefore prove absence of (some) bugs (categories)?

Symbolic execution was proposed in:

- “Symbolic Execution and Program Testing“, J. King, CACM, 1976

Many tools exist KLEE, S2E, Angr, Triton, BinSec... with different goals and properties

Performance improved a lot with constraint solvers improvements in recent years

Combining Fuzzing with Symbolic Execution

This was first propose in the “Driller” paper

“Driller: Augmenting Fuzzing Through Selective Symbolic Execution”, NDSS 2016

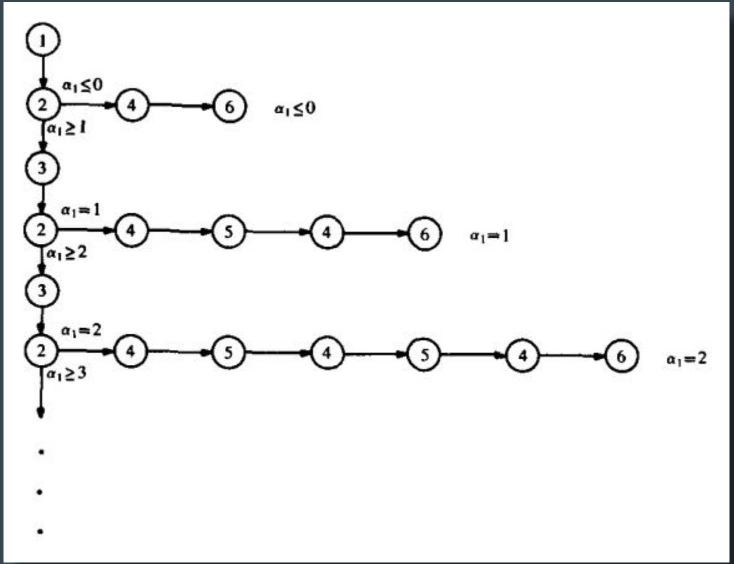
- Fuzzers are very fast but may miss some paths “if(X==0xDEADBEEF)”
- Symbolic execution alone is slow and gets stuck (state explosion, loops)

Combining Fuzzing and concolic execution: best of both worlds?

- Top 3 teams of the Cyber Grand Challenge used a combination of fuzzing and Symbolic Execution
- But performance problem with Symbolic execution engines...

Symbolic execution

- Trace computations in a program, building up symbolic formulas
- Solving symbolic expressions:
    - At branches to check if a branch is feasible
    - If a corruption (or fault) is detected, solve constraints and generate a test input



King: Symbolic Execution and Program Testing

Symbolic Execution

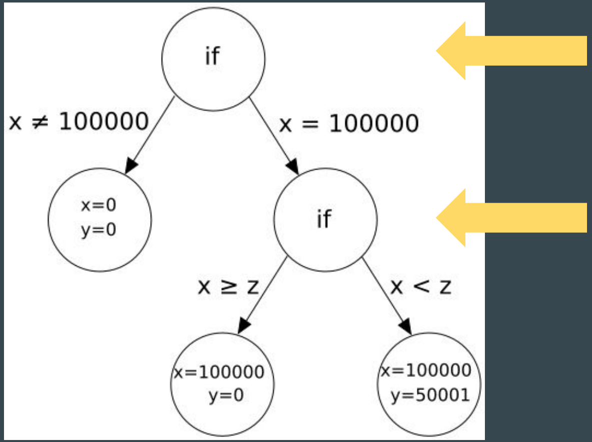
Explore programs by keeping track of computations in terms of inputs

When on one path only: “Concolic mode”

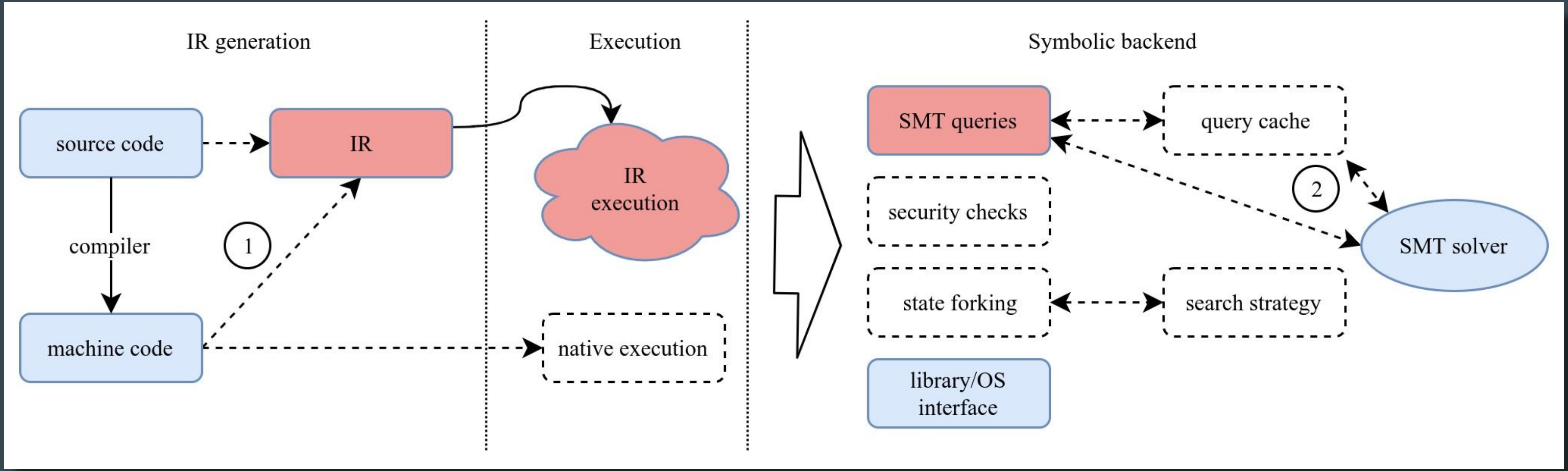
Target program

```
void f(int x, int y) {
  int z = 2*y;
  if (x == 100000) {
     if (x < z) {
        assert(0); /* error */
     }
  }
}
```

symbolic execution



Design space

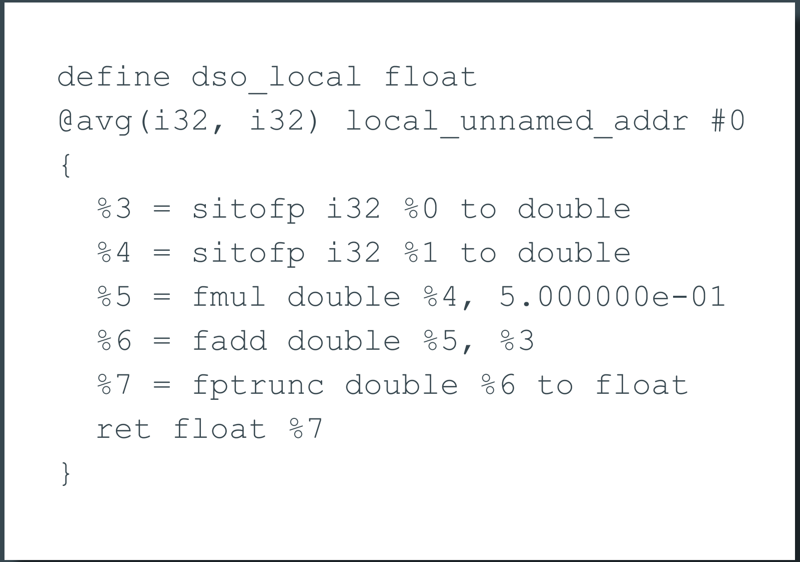


Previous work marked in the diagram:

① Kim et al.: Testing intermediate representations for binary analysis

② Palikareva and Cadar: Multi-solver support in symbolic execution
and Liu et al.: A comparative study of incremental constraint solving approaches in symbolic execution

Intermediate representation



```
define dso_local float
@avg(i32, i32) local_unnamed_addr #0
{
  %3 = sitofp i32 %0 to double
  %4 = sitofp i32 %1 to double
  %5 = fmul double %4, 5.000000e-01
  %6 = fadd double %5, %3
  %7 = fptrunc double %6 to float
  ret float %7
}
```

LLVM bitcode generated by Clang

- Abstract representation of a program
  - Often in static single assignment form (SSA)
  - Small instruction set
- Designed for different purposes
  - Compilers: LLVM bitcode
  - Dynamic instrumentation: VEX
  - Binary analysis: BIL, REIL
  - Many more; see Kim et al.: Testing Intermediate Representations for Binary Analysis

Research questions

- What is the impact of generating IR from source code or binaries?
- Is one IR more suitable than another? What about no IR?

Experiments

Code size

- How does IR generation impact code size?
- Estimate “information content” of IR

Execution speed

- How fast can we execute the IR?
- Crucial property according to Yun et al.

Query complexity

- How complex are the resulting SMT queries?
- Difficult queries slow down the analysis a lot

Implementations under analysis

KLEE	S2E	angr	Qsym
Source code to LLVM bitcode	Binary to LLVM bitcode via QEMU	Binary to VEX IR (Valgrind project)	No IR; execution of x86 machine code
Implemented in C++	Implemented in C/C++	Implemented in Python	Implemented in C++
No native execution	Binary translation through QEMU	Binary translation through Unicorn	Native execution via Intel Pin
	Based on KLEE		

Setup

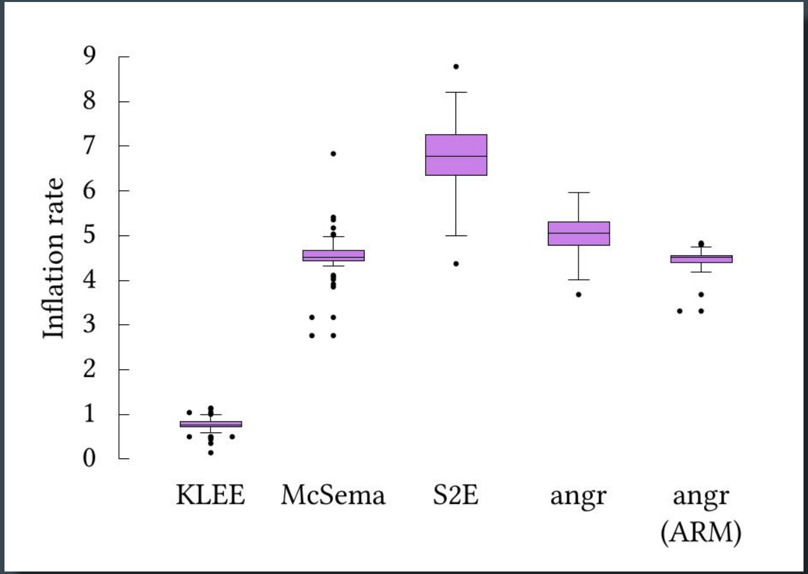
- Programs from DARPA Cyber Grand Challenge
  - Designed around a simple architecture (“DECREE”)
  - Source code available
  - Meant to be used as a test set for vulnerability detection (and exploit generation)
- Concolic execution
  - Follow the same fixed path in all engines
  - No bias from different exploration strategies
  - Path based on provided crashing inputs (“proofs of vulnerability”)
- Environment
  - Ubuntu 16.04, 24 GB of memory
  - 30 minutes per execution or solver run (whichever applies to the experiment)

Challenges

- We had to patch all engines
  - Add support for program particularities (e.g., support mmap in KLEE)
  - Insert measurement probes
- Still, only 24 out of 131 programs work in all four engines 😞
  - Unsupported instructions (e.g., floating-point arithmetic)
  - Excessive memory or CPU time consumption
  - Others concur: e.g., see Qu and Robinson, as well as Xu et al.
- Results are not fully representative of any possible program to test
  - But: scientific progress requires evaluation and comparison!
  - Need a methodology for comparing symbolic execution engines
  - We can still identify trends

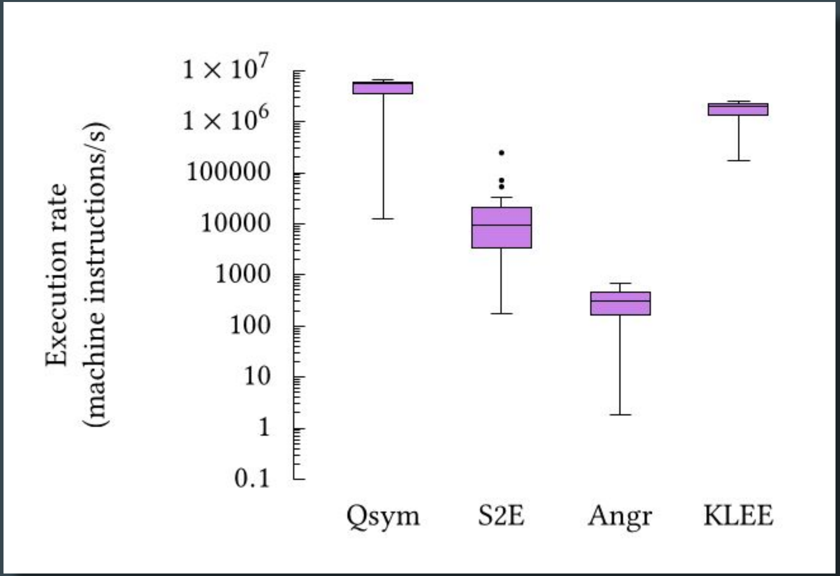
Results: Code size

- Measured *IR inflation rate*
  - Ratio between number of machine-code instructions and number of IR instructions
- Added two extra data points
  - McSema: lifter from binaries to LLVM bitcode
  - angr on ARM: apply angr's VEX translation to ARM machine code
- IR from source code is more concise
- S2E: problem with double translation?
  - Machine code → QEMU → LLVM bitcode



Inflation rate per IR generation mechanism
across 123 CGC programs and 106 coreutils binaries;
boxes contain 50% of the data points with the line marking the median, whiskers extend to 1.5 times the interquartile range, dots are outliers

Results: Execution speed



Execution speed of symbolically executed instructions across 24 CGC programs

- Measured *IR execution rate*
    - Symbolically executed instructions per unit of time
    - Normalized by average inflation rate
- Qsym unsurprisingly fastest
- angr: slow because of Python
- KLEE and S2E: same basis, but S2E executes less expressive IR
- Absence of IR seems beneficial

Example: Query complexity

Queries generated for the C expression

data[3] == 55

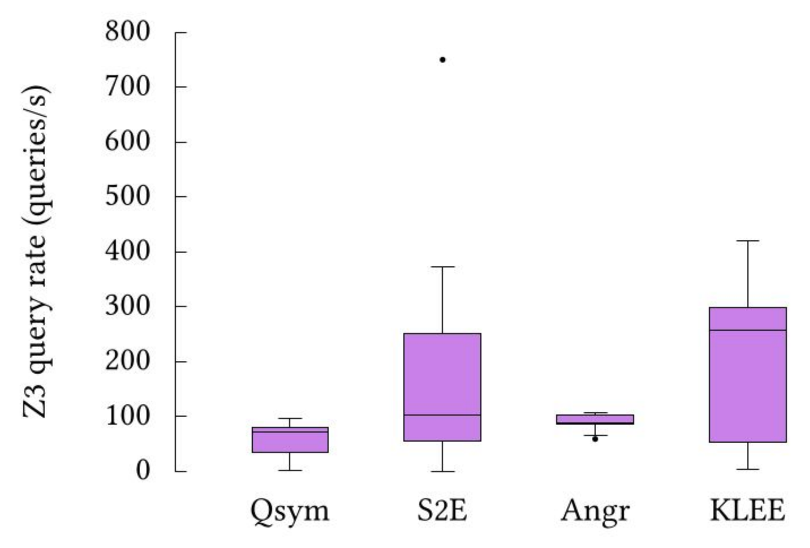
by KLEE (below) and S2E (right)

```
(= (_ bv55 8)
   ((_ extract 7 0)
    ((_ zero_extend 24)
     (select data (_ bv3 32)))))
```

```
(= (_ bv0 64)
   (bvand
    (bvadd
     ;; 0xFFFFFFFFFFFFFFC9
     (_ bv18446744073709551561 64)
     ((_ zero_extend 56)
      ((_ extract 7 0)
       (bvor
        (bvand
         ((_ zero_extend 56)
          (select data (_ bv3 32)))
         ;; 0x00000000000000FF
         (_ bv255 64))
        ;; 0xFFFF88000AFDC000
        (_ bv18446612132498620416 64))))))
    (_ bv255 64)))
```

Results: Query complexity

- Measured *query rate*
  - Number of solved queries per unit of time
- KLEE’s queries are simplest
  - Potentially because they are derived from high-level IR
- S2E gets close to KLEE
  - Internally based on KLEE
  - But different IR generation mechanism
- Is LLVM bitcode beneficial?



Query rates as a proxy for query complexity across across 23 CGC programs

Source vs binary

Research question 1

- Large impact on IR size, thus possibly on execution speed
- SMT queries derived from source are easier

Difference between IRs

Research question 2

- No observable difference between LLVM bitcode and VEX
- Fastest execution is achieved by using machine code directly

What did we find?

For easy queries, generate IR from source code.

For fast execution, work on machine code directly.

Limitations: small data set, effects of IR and IR generation are hard to isolate.

Symbolic execution with SymCC: Don’t interpret, compile!

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Sebastian Poeplau, Aurélien Francillon

Distinguished paper award, Usenix Security 2020

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Compiling symbolic-execution capabilities into executables

Current approaches
(e.g., KLEE, S2E, angr)

Interpreter approach

Target program (bitcode)

```
define i32 @is_double(i32, i32) {
  %3 = shl nsw i32 %1, 1
  %4 = icmp eq i32 %3, %0
  %5 = zext i1 %4 to i32
  ret i32 %5
}
```

N times

Interpreter (e.g., KLEE, S2E, angr)

```
while (true) {
    auto instruction = getNextInstruction();
    switch (instruction.type) {
        // ...
        case SHL: {
            auto result = instruction.operand(0) <<
                          instruction.operand(1);
            auto resultExpr =
                buildLeftShift(instruction.operandExpr(0),
                               instruction.operandExpr(1));
            setResult(result, resultExpr);
            break;
        }
    }
}
```

SymCC

Compilation instead of interpretation

SymCC: Overview

Target program (bitcode)

```
define i32 @is_double(i32, i32) {
  %3 = shl nsw i32 %1, 1
  %4 = icmp eq i32 %3, %0
  %5 = zext i1 %4 to i32
  ret i32 %5
}
```

once

Instrumented target (bitcode)

```
define i32 @is_double(i32, i32) {
  %3 = call i8* @_sym_get_parameter_expression(i8 0)
  %4 = call i8* @_sym_get_parameter_expression(i8 1)
  %5 = call i8* @_sym_build_integer(i64 1)
  %6 = call i8* @_sym_build_shift_left(i8* %4, i8* %5)
  %7 = call i8* @_sym_build_equal(i8* %6, i8* %3)
  %8 = call i8* @_sym_build_bool_to_bits(i8* %7)

  %9 = shl nsw i32 %1, 1
  %10 = icmp eq i32 %9, %0
  %11 = zext i1 %10 to i32
  call void @_sym_set_return_expression(i8* %8)
  ret i32 %11
}
```

SymCC: Implementation

- Compiler pass and run-time library
- Pass inserts calls to the run-time library at compile time
  - → Built on top of LLVM
  - → Easily integrate with all LLVM-based compilers
  - → Independent of CPU architecture and source language
- Run-time library builds up symbolic expressions and calls the solver
  - → Two options for run-time library
  - → “Simple backend”: wrapper around Z3, little optimization, good for debugging
  - → “QSYM backend”: reuse expressions and solver infrastructure from QSYM (but NOT the instrumentation!)

QSYM is different

- Yun et al., USENIX Security 2018
- Based on dynamic binary instrumentation
  - → Rewrites binaries at run time using Intel Pin
  - → Inserts calls to functions that build symbolic expressions and interacts with a solver
- Strengths
  - → No interpreter: higher performance than interpreted systems
  - → Support for binaries
- But...
  - → Rewritten program is less efficient than compiled programs
  - → Binary level, i.e., need to implement symbolic handling for *each x86 instruction*

Analysis process (QSYM)

attach via ptrace

Target process

Recap

We compile symbolic-execution capabilities right into the binary.

- Most others interpret
- QSYM uses dynamic binary instrumentation

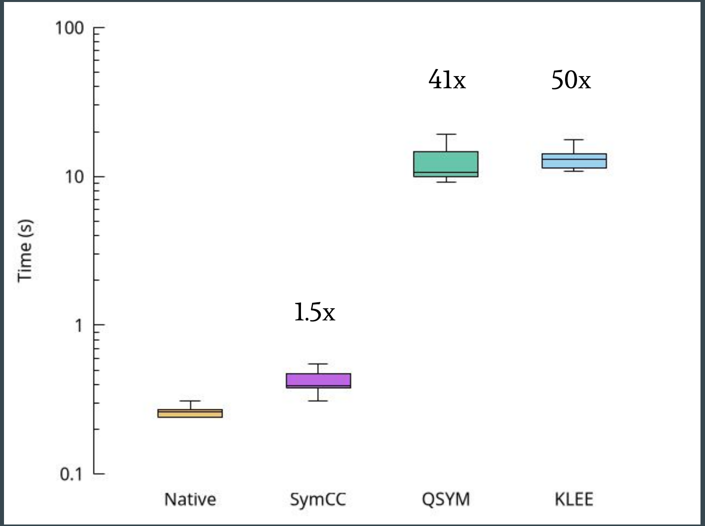
Evaluation

Benchmark and real-world targets

Benchmark: Execution Speed

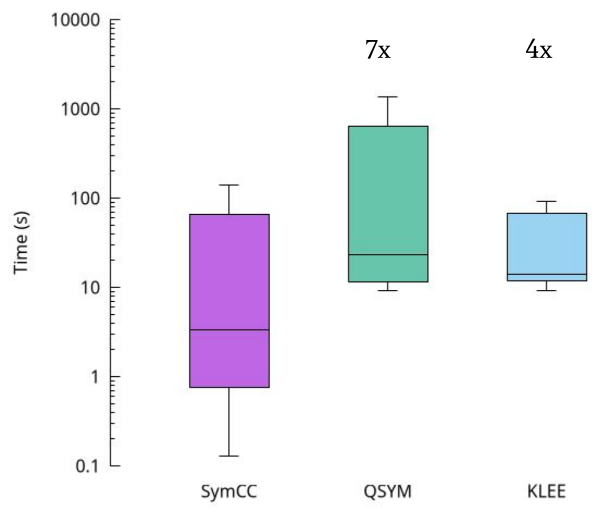
Fully concrete

No symbolic input provided



Concolic

Input data is made symbolic



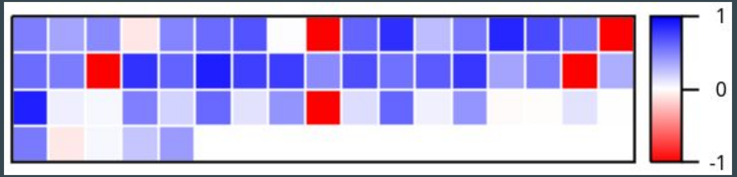
Benchmark: Coverage

Approach

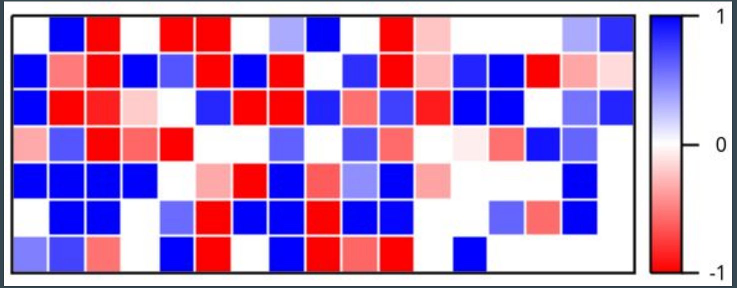
After concolic execution, measure edge coverage of newly generated inputs with afl-showmap.

Visualization

- Compare paths found by only one system
- More intense color: more unique paths
- Blue for SymCC, red for KLEE/QSYM



Comparison with KLEE (56 programs): SymCC is better on 46 and worse on 10



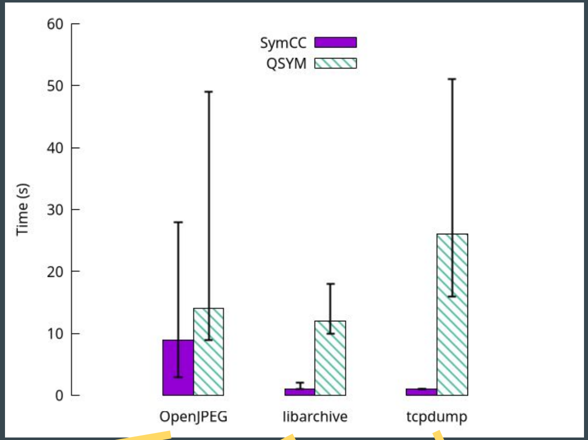
Comparison with QSYM (116 programs): SymCC is better on 47, worse on 40, and equal on 29

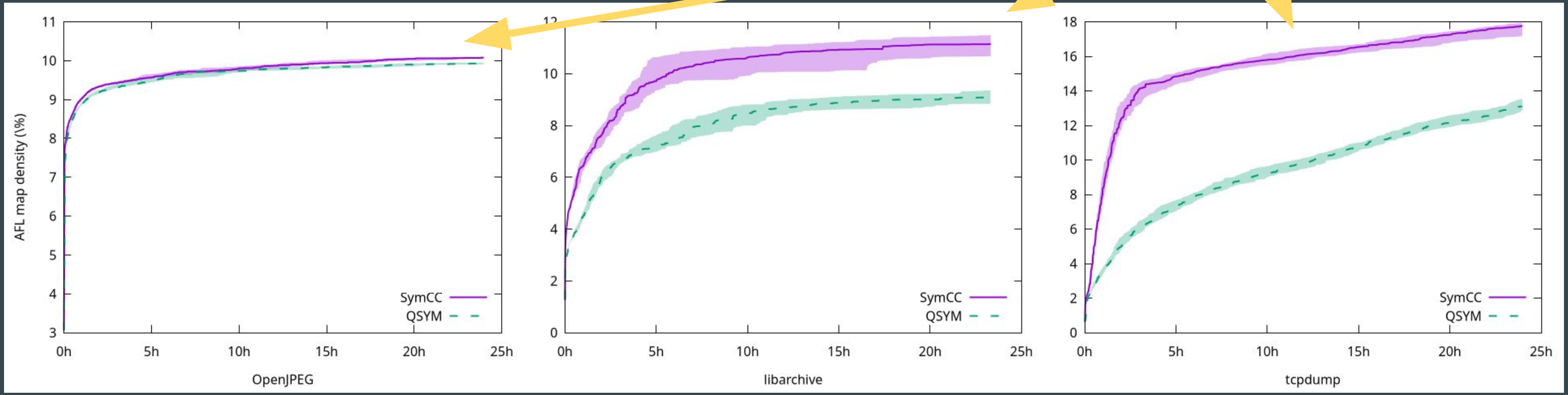
Real-world targets: Setup

- Goal: show scalability to real-world software
- Popular open-source projects: OpenJPEG, libarchive, tcpdump
- Hybrid fuzzing: AFL and concolic execution with SymCC/QSYM
    - → Same approach as Driller and QSYM
    - → 2 AFL processes, 1 SymCC/QSYM (like in QSYM's evaluation)
- Intel Xeon Platinum 8260 CPU with 2GB of RAM *per core*
- 24 hours, 30 iterations (→ roughly 17 CPU core months)
- Excluded KLEE: unsupported instructions in target programs

Real-world targets: Results

- Higher coverage than QSYM
- Statistically significant coverage difference (Mann-Whitney-U, $p < 0.0002$)
- Found 2 CVEs in OpenJPEG
- Speed advantage correlates with coverage gain





Conclusion

Compilation makes symbolic execution more efficient

- SymCC compiles symbolic-execution capabilities into binaries
- Orders of magnitude faster than state of the art
- Significantly more code coverage per time, 2 CVEs

Needs source code

- Often the case that source is available
- Binary code (libraries) just executed concretely

How to perform multipath exploration like Klee?

Thank you!

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https://github.com/eurecom-s3/symcc
(code, docs, evaluation details)