Systematic comparison of symbolic execution systems

Intermediate representation and its generation

Sebastian Poeplau, Aurélien Francillon
EURECOM, Sophia Antipolis, France
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Agenda

1. Background
2. Our study
   a. Systems under analysis
   b. Experimental setup
   c. Results
3. Discussion
4. Conclusion
Background
Symbolic execution

- Trace computations in a program, building up symbolic formulas
- At points of interest (e.g., branches), generate new inputs:
  - Substitute desired value into symbolic expression
  - Solve for the program input
- Many different implementations
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

- 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

```c
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
Our study

Intermediate representations are commonplace in symbolic execution.

But which one is best?

What is their impact in the first place?

We conducted a systematic study; work to be published at ACSAC 2019.
SMT solving

- “Satisfiability modulo theories”
  - SAT solver unites several theory solvers
  - Most interesting theory for us: bit vectors
  - Popular implementation: Z3 (MS Research)

- SAT: Boolean satisfiability problem
  - Known to be NP-complete
  - Good heuristics make many instances tractable

- Used for test case generation in symbolic execution

Example SMT query for Z3

```plaintext
;; Integers x, k1 and k2
(declare-const x (_ BitVec 32))
(declare-const k1 (_ BitVec 32))
(declare-const k2 (_ BitVec 32))

;; ...all smaller than 50...
(assert (bvule x #x00000032))
(assert (bvule k1 #x00000032))
(assert (bvule k2 #x00000032))

;; ...and x is divisible by 6 and 7.
(assert (not (= x #x00000000)))
(assert (= x (bvmul k1 #x00000006)))
(assert (= x (bvmul k2 #x00000007)))

;; Solve!
(check-sat)
(get-model)
```
Our study
Research questions

- Does it matter whether we generate IR from source code or binaries? How?
- Is one IR more suitable than another? What about no IR?
## Implementations under analysis

<table>
<thead>
<tr>
<th>KLEE</th>
<th>S2E</th>
<th>angr</th>
<th>Qsym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source code to LLVM bitcode</td>
<td>Binary to LLVM bitcode via QEMU</td>
<td>Binary to VEX IR (Valgrind project)</td>
<td>No IR; execution of x86 machine code</td>
</tr>
<tr>
<td>Implemented in C++</td>
<td>Implemented in C/C++</td>
<td>Implemented in Python</td>
<td>Implemented in C++</td>
</tr>
<tr>
<td>No native execution</td>
<td>Binary translation through QEMU</td>
<td>Binary translation through Unicorn</td>
<td>Native execution via Intel Pin</td>
</tr>
</tbody>
</table>
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
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.
- Is there still value in our study?
  - Results are not representative for the set of all possible programs under 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 $\rightarrow$ QEMU $\rightarrow$ 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

- 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

Execution speed of symbolically executed instructions across 24 CGC programs
Example: Query complexity

Queries generated for the C expression

\[
\text{stdin}[3] == 55
\]

by KLEE (below) and S2E (right)

\[
(= (_ \text{bv0} 64)
  (\text{bvand}
   (\text{bvadd}
    ;; 0xFFFFFFFFFFFFFFFFC9
    (_ \text{bv18446744073709551561} 64)
    ((_ \text{zero\_extend} 56)
     ((_ \text{extract} 7 0)
      (\text{bvor}
       (\text{bvand}
        ((_ \text{zero\_extend} 56)
         (\text{select\ stdin} (_ \text{bv3} 32)))
        ;; 0x00000000000000FF
        (_ \text{bv255} 64)))
     ;; 0xFFFF88000AFDC000
     (_ \text{bv18446612132498620416} 64)))
   (_ \text{bv255} 64)))
\]
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 23 CGC programs
Discussion
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
Remark: Implementation language

- Independent of the choice of IR, but with a large impact on the overall result
- Implementation language influences the possible use cases
  - Python makes angr flexible for scripting and interactive exploration but is too slow for batch processing
  - C++ enables Qsym, KLEE and S2E to execute fast but limits extensibility
- Other factors, e.g., development speed, maintainability
Conclusion
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.
What’s next?

- Assess the **quality** of generated test cases, not just the speed of generation
  - Interesting properties: effect on code coverage, similarity to existing test cases, directedness

- Find out what makes queries hard for SMT solvers
  - Some operations known to be tough (e.g., division of bit vectors)
  - Effect of compiler optimizations?
  - Goal: produce “solver-friendly” queries

- End-to-end comparison of symbolic execution engines
  - Compare from input to output, i.e., from program under test to discovered bugs
  - Many sources of bias
  - Large differences in implementation
Thank you!

{sebastian.poeplau, aurelien.francillon}@eurecom.fr

http://www.s3.eurecom.fr/tools/symbolic_execution/