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Symbolic Execution of Binary Code based on Formal ISA Semantics

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Motivation

Goal: Employ symbolic execution for testing embedded software

Challenges

- Tight integration between software and hardware components
- Software interacts on a low abstraction level with the hardware
- Example: Low-level instruction for configuring interrupt handlers

$\Rightarrow$ KLEE and tools build on it (e.g. FIE) do not support these

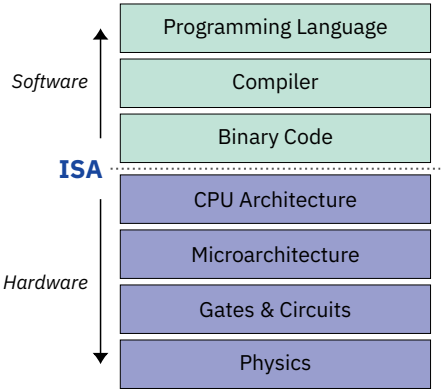
Background: Instruction Set Architectures (ISAs)

ISA: Central interface between hard- and software

- Specifies the instructions supported by the CPU
- Instructions are used in binaries $\rightarrow$ binary analysis

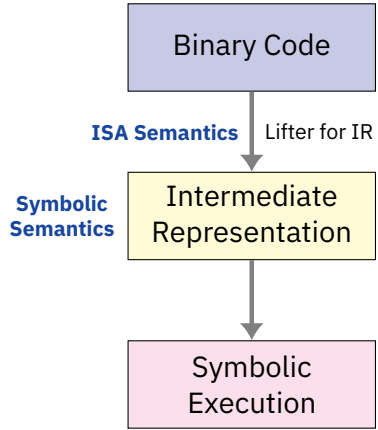
Observation: ISA specifications are very complex

- Thousands of pages of (mostly) natural language
- Problem: Need symbolic instruction semantics



Prior Work: IR-based Execution of Binary Code

Idea: Lift binaries to an intermediate representation (IR)
⇒ Symbolically execute the resulting, simpler IR



Limitations:

1. Lifting is complex and may induce inaccuracies
2. No symbolic execution of ISA-specific instructions

Formal Specifications of ISA Semantics

Idea: Describe ISA in a formal machine-readable language

- Eases supporting code generation and similar use-cases
- Newer ISAs (e.g. RISC-V) provide an official formal spec

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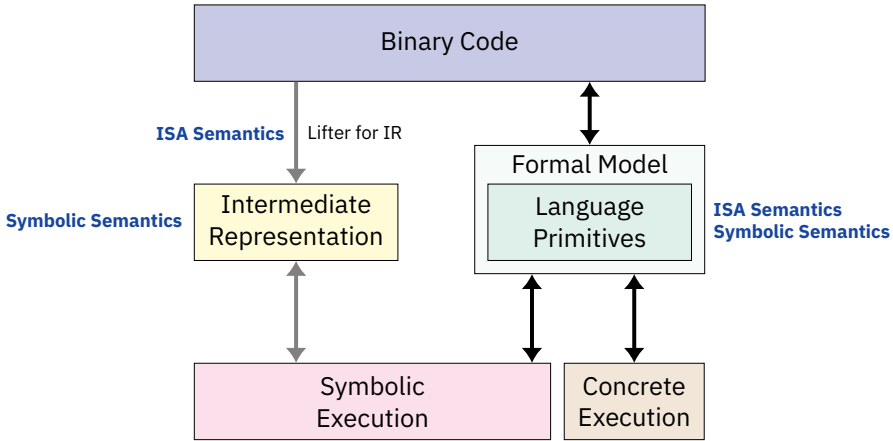
Example

```
instrSemantics LB{..} = do
    base <- readRegister rs1
    byte <- loadByte (base `Add` imm)
    writeRegister rd (SExtByte $ FromImm byte)
```

Symbolic Execution using Formal ISA Semantics



LibRISCV: A versatile formal model for RISC-V

Contribution: Formal model tailored to creation of ISA interpreters

$\Rightarrow$ Models instruction semantics independent of value representation

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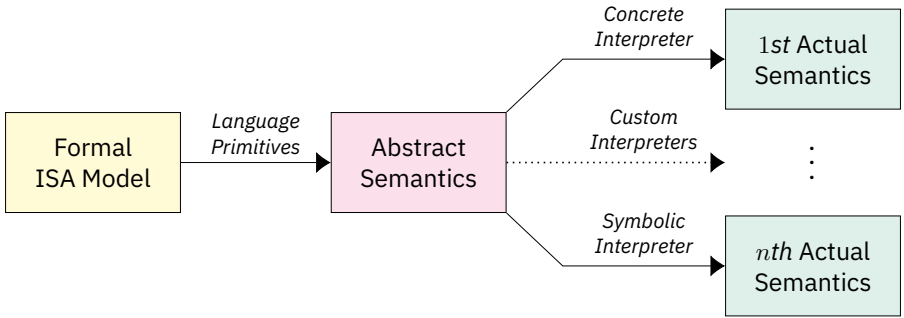

BinSym: Symbolic Semantics for LibRISCV

Contribution: Actual semantics for symbolic execution of RISC-V binaries

- Provides symbolic implementations of register file, memory, …
- Maps LibRISCV expression language to Z3 bit-vectors

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Implementation: `https://github.com/agra-uni-bremen/BinSym`
⇒ Standard DSE implementation in Haskell

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Properties

1. Operates on the binary-level without IR-lifting
2. More faithful to the (formal) ISA specification
3. Supports low-level interactions with the architectural state

Evaluation

Observation from prior work:

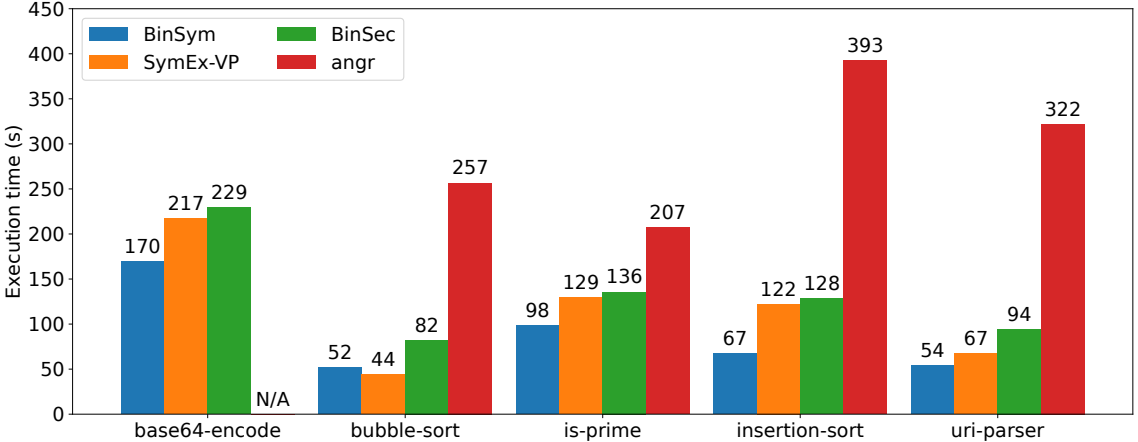
[Binary lifting] tends to inflate the code by a factor between 3 and 7.

— Poeplau et al., Systematic comparison of symbolic execution systems

RQ: What is the impact of code size inflation on *symbolic* execution speed?

$\Rightarrow$ Compare symbolic execution speed on synthetic benchmarks

Preliminary Results



Conclusion

Key Insights:

1. Formal ISA semantics are beneficial for symbolic execution
2. Ease supporting architecture-specific low-level instructions
3. Eliminating the IR abstraction might improve query complexity

More Information:

LibRISCV `https://doi.org/10.1007/978-3-031-38938-2_2`

BinSym `https://doi.org/10.48550/arXiv.2404.04132`

Source code and artifacts are referenced in the papers.