Automated Code Proofs on a Formal Model of the X86

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OUTLINE

Outline

Our Goals

1. Develop an accurate model of the x86 Instruction Set Architecture (ISA)

2. Develop automated procedures for reasoning about x86 machine code

WHY DO WE CARE?

- Analysis of high-level programs is not good enough.
- High-level programs are not always available.
- **Formal verification** of machine code!
  - Formal model of the x86 ISA
  - Reason about machine code on this model

Our Goals, revisited

1. Develop a **formal** and **executable** model of the x86 ISA
   - **Accurate** and **unsimplified** model
   - Specifications: Intel's Software Developer's Manuals
   - ~3000 pages of prose
   - **Co-simulations**
   - Need executability to do co-simulations

A **single model** for simulation and formal analysis enables us to **validate** it with co-simulations so that we can **trust** it for our proofs.

OUR GOALS, REVISITED

1. Develop an accurate, formal, and executable model of the x86 ISA
2. Develop **automated procedures** for reasoning about x86 machine code
   - **Functional correctness** of machine code
   - Minimize lemma construction

Outline

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FORMALIZING X86 ISA IN ACL2

ACL2:

- *A Computational Logic for Applicative Common Lisp*
- Descendant of the Boyer-Moore theorem prover
- Programming language
- Mathematical logic
- Mechanical theorem prover

FORMALIZING X86 ISA IN ACL2

- Our x86 ISA model has been formalized using an *interpreter approach to operational semantics.*
- Semantics of a program is given by the effect it has on the state of the machine.
- State-transition function is characterized by a recursively defined interpreter.

X86 STATE

Component	Description
registers	general-purpose, segment, debug, control, model-specific registers
rip	instruction pointer
flg	64-bit flags register
mem	physical memory

Run Function

Recursively defined interpreter that specifies the x86 model

```
run (n, x86):

if n == 0:
   return (x86)
else
   if halt instruction encountered:
      return (x86)
   else
      run (n - 1, step (x86))
```

STEP FUNCTION

```
step (x86):

pc = rip (x86)

[prefixes, opcode, ... , imm] = Fetch-and-Decode (pc, x86)

case opcode:
     #x00 -> add-semantic-fn (prefixes, ... , imm, x86)

     ...      ...

     #xFF -> inc-semantic-fn (prefixes, ... , imm, x86)
```

INSTRUCTION SEMANTIC FUNCTIONS

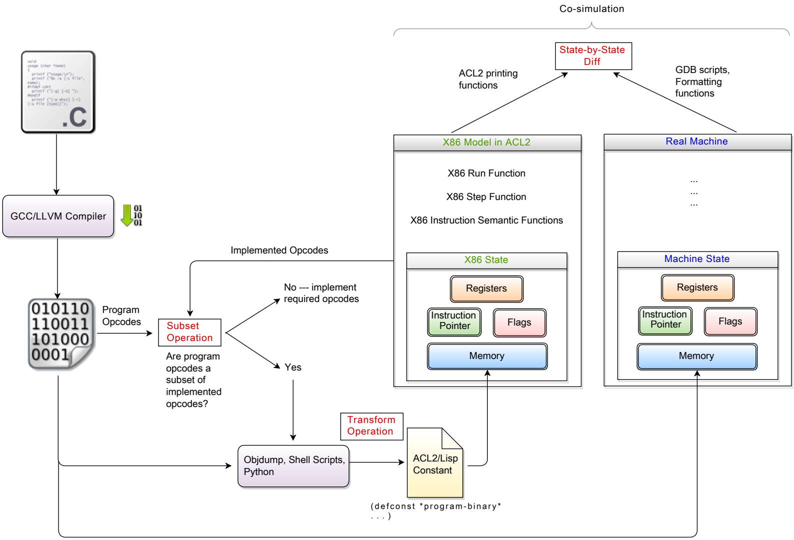
- INPUT: x86 state
  Decoded instruction
  OUTPUT: Next x86 state
- A semantic function describes the effects of executing an instruction.
- Every instruction in the model has its own semantic function.

X86 MODEL

- 64-bit mode
- Model entire 2^{52} bytes (4096 TB) of memory
- All addressing modes
- Supports IA-32e paging
- 118 user-mode instructions (219 opcodes)
- +40,000 lines of code

Outline

Executing Binary Programs on X86 model



EXECUTING PROGRAMS ON X86 MODEL

- Execute a contemporary SAT solver on our model
  - Produces exactly the ***same effects*** on model's registers and memory as those produced on the real x86 processor.
- Execution speed: [1]
  - Paging excluded: ~3.3 million instructions/second
  - Paging included: ~300,000 instructions/second
- ACL2 has features that help us **avoid trade-offs** between **efficiency** and **reasoning**.

[1] on an Intel Xeon CPU @ 3.50GHz

Outline

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SYMBOLIC EXECUTION IN ACL2

- **Symbolic Execution**: Executing functions on symbolic data
- **GL**: framework **verified in ACL2** for proving theorems involving **finite symbolic objects** via **bit-blasting**
- Symbolic object: **any** ACL2 object (like lists, numbers, etc.)

OUTLINE

DEMO

Automatic correctness proof for an x86 *popcount* binary program, for **counting** the number of **non-zero bits** in the bit-level representation of an unsigned integer input.

CODE PROOFS: SYMBOLIC EXECUTION APPROACH

- Write the program's **specification**
- Prove that the **program satisfies the specification** (fully automatic)

CODE PROOFS: SYMBOLIC EXECUTION APPROACH

- No lemma construction needed — proof done **fully automatically**
- Reason directly about semantics of programs
  - Account for the complicated x86 **decoding process**
- Proofs of correctness of larger programs to be obtained **compositionally** using traditional theorem proving techniques

Outline

CONCLUSION

- Executable, formal model of a significant subset of x86 ISA
- No simplification of the semantics of x86 instructions
- Validation of the x86 model using efficient co-simulation
- x86 model capable of running as well as reasoning about real x86 binary programs

Future Work

- Add system calls to enable reasoning about I/O (`open`, `read`, `write`, etc.)
- Extend the model with more instructions
- Infrastructure for verification of linux utilities

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Questions?