Formal Verification of Binary Code

Roberto Guanciale

$$\frac{\pi : \{P\}\ \alpha \rightsquigarrow \beta \cup \beta'\{Q\} \qquad \forall \alpha' \in \beta\ .\pi : \{Q\}\ \alpha' \rightsquigarrow \beta'\ \{Q\}}{\pi : \{P\}\ \alpha \rightsquigarrow \beta'\{Q\}}$$

PROSPER

seL4

Security. Performance. Proof.

P R O S P E R

seL4

Security. Performance. Proof.

PROSPER

seL4

Security. Performance. Proof.

GCC

PROSPER

seL4
Security. Performance. Proof.

```
// a0=GETBYTE(s0, 3);
ldr     r3, [r7, #84]
lsrs    r3, r3, #24
uxtb    r3, r3
str     r3, [r7, #48]
...
// v0=*(Te[0] + a0);
ldr     r3, [r7, #48]
lsls    r2, r3, #2
ldr     r3, [pc, #928] ; AesEncrypt+0x428
adds    r3, r2, r3
ldr     r3, [r3, #0]
str     r3, [r7, #32]
...
// t0 = v0  ^ v1 ^ v2 ^ v3 ^ rk[0]
```

GCC

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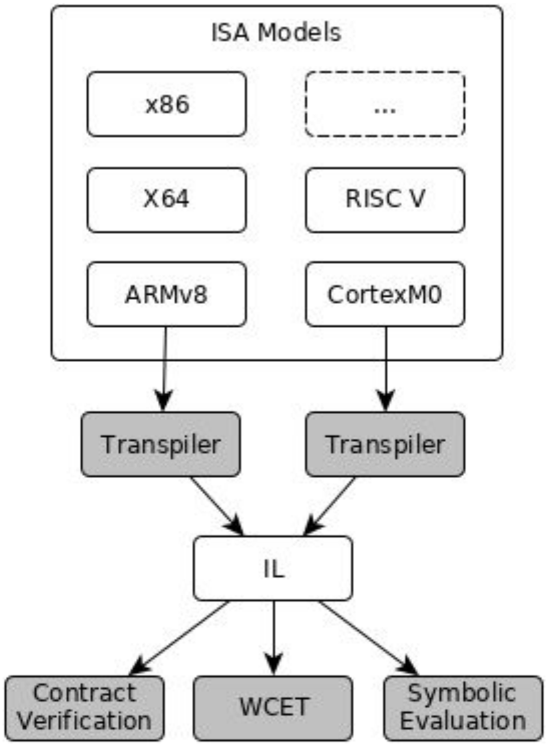
GCC

Binary Analysis Frameworks

- Valgrind
- BAP
- Angr



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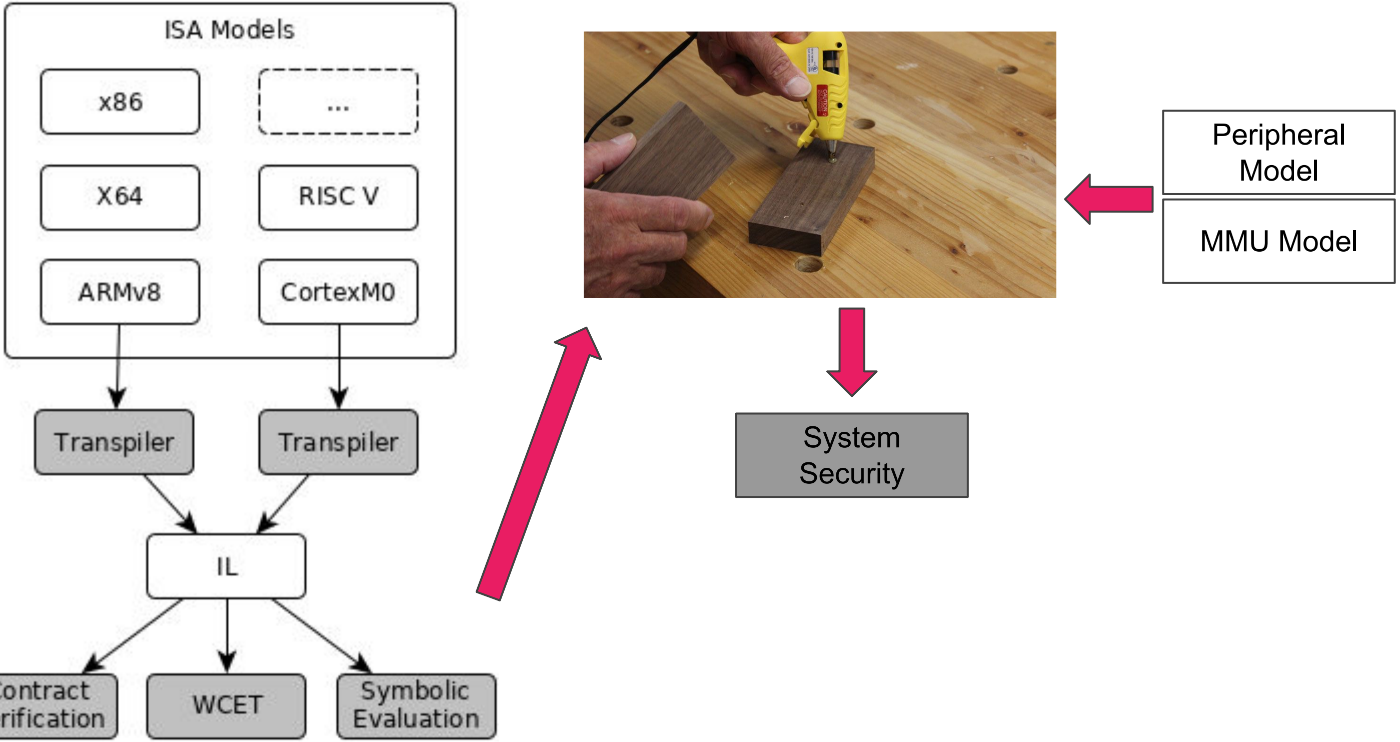

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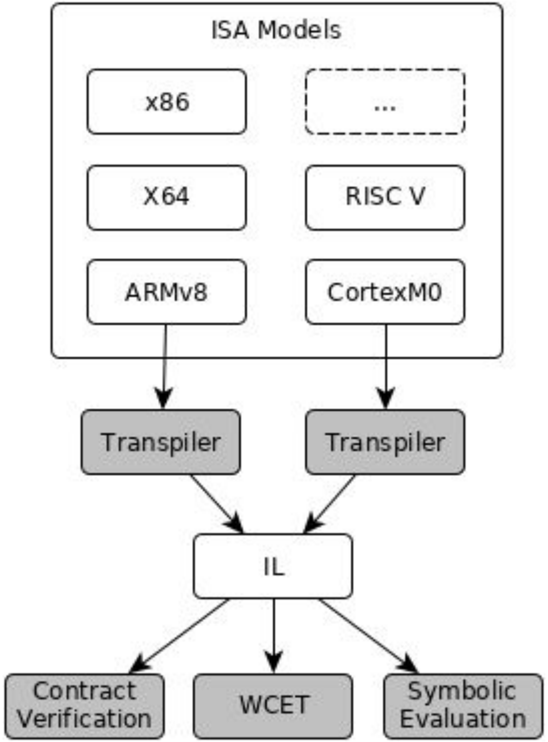

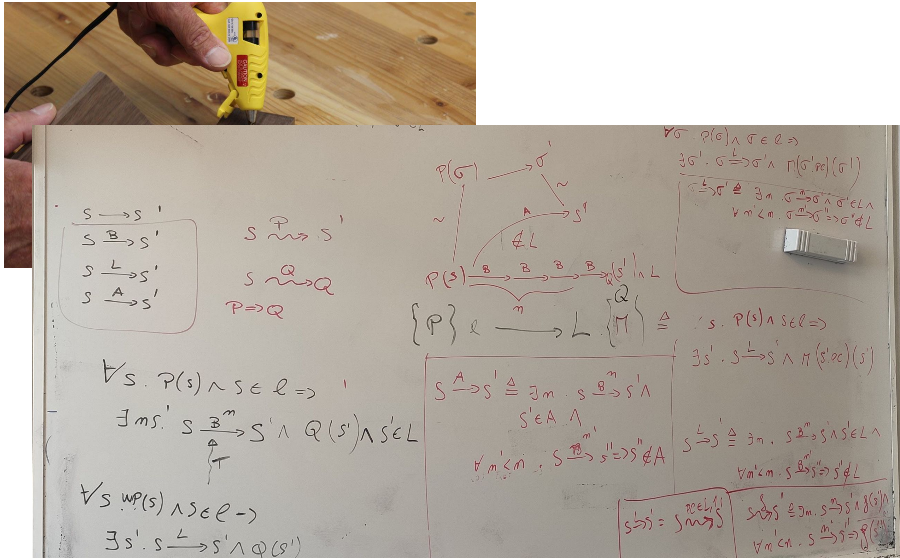

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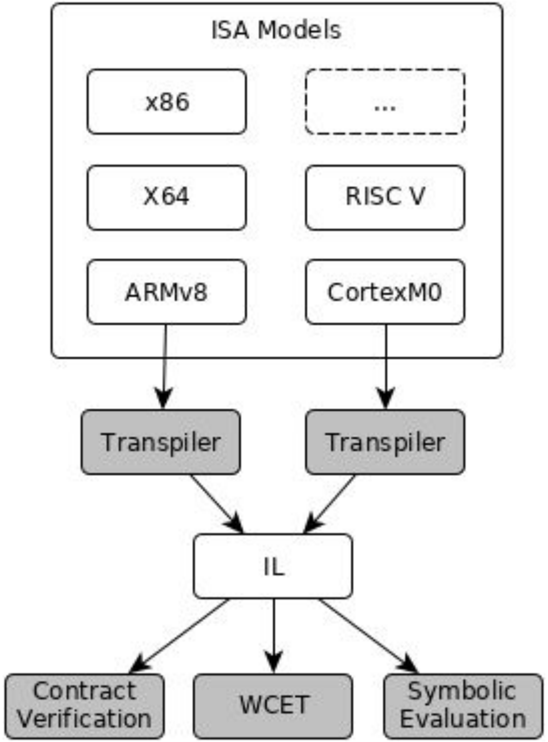
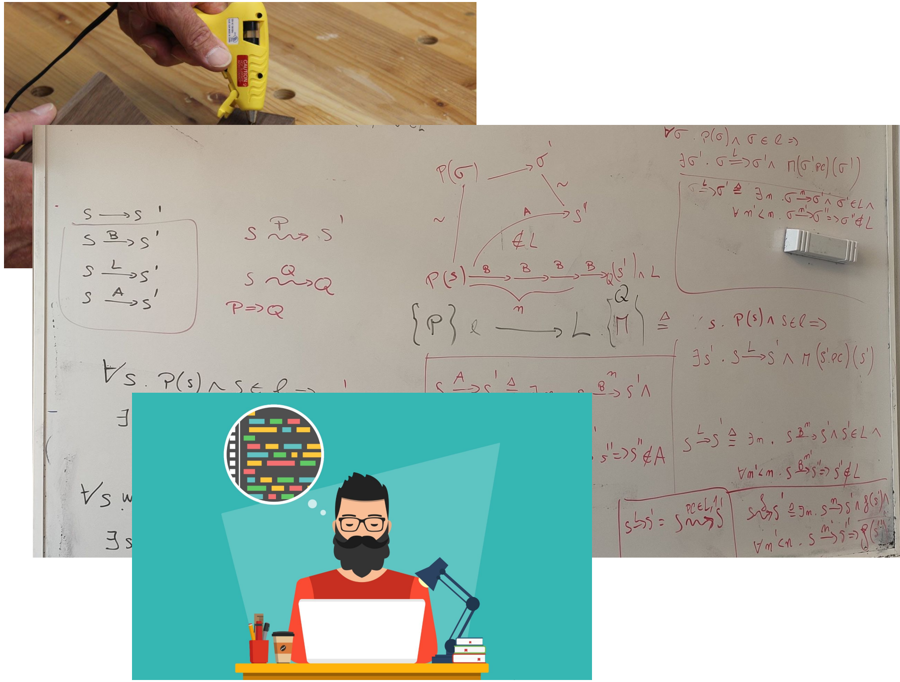




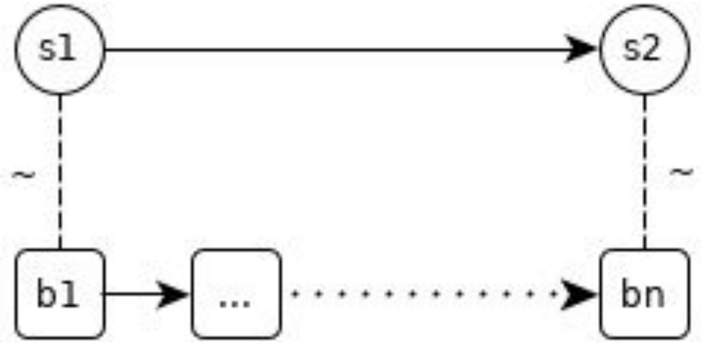
Certifying (Proof-producing) Analysis of Binaries

- Implemented using Interactive Theorem Prover (HOL4)
  - => Machine checkable proofs
- Formal semantics if ISAs (ARM/Risc-V/etc)
- Formal semantics of BinaryIntermediateRepresentation
  - Similar to LLVM IR
  - Language designed to automate analysis
    - Program not in memory / Assertions
- Verified theories and proof producing analyses
  - Transpilation
  - Contract based verification
  - ...

Certifying Transpilation

```
0: pop R1
4: push R1
```

```
[0 { R1 := MEM[SP];
     SP := SP-4;
     PC := PC+4;
     JMP 4}]
[4 { MEM := MEM with [SP<-R1];
     SP := SP+4;
     PC := PC+4;
     JMP 8}]
```



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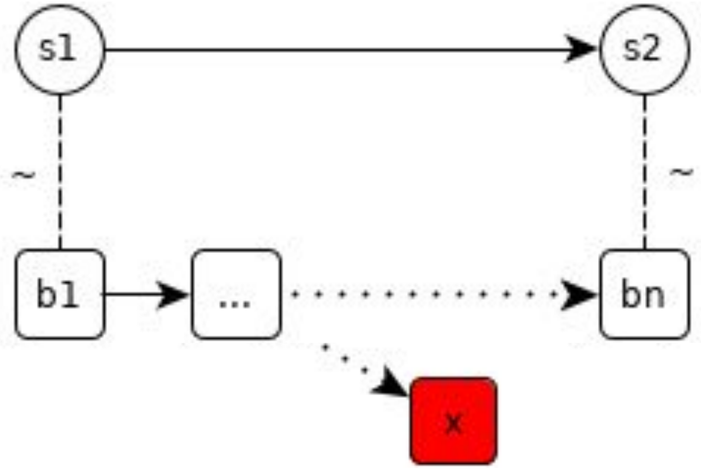
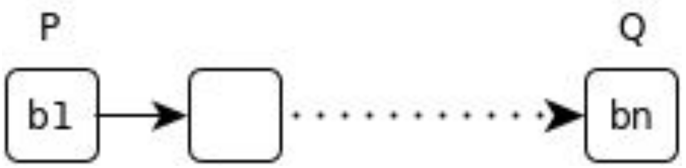



```
[0 { R1 := MEM[SP];
     SP := SP-4;
     PC := PC+4;
     JMP 4}]
[4 { ASSERT(SP not in CODE SECTION);
     MEM := MEM with [SP<-R1];
     SP := SP+4;
     PC := PC+4;
     JMP 8}]
```

Contract Based Verification:

- For structured program
  - {P} statements {Q}
- For unstructured program?



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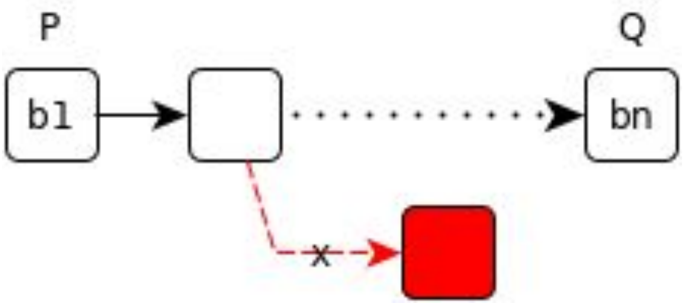

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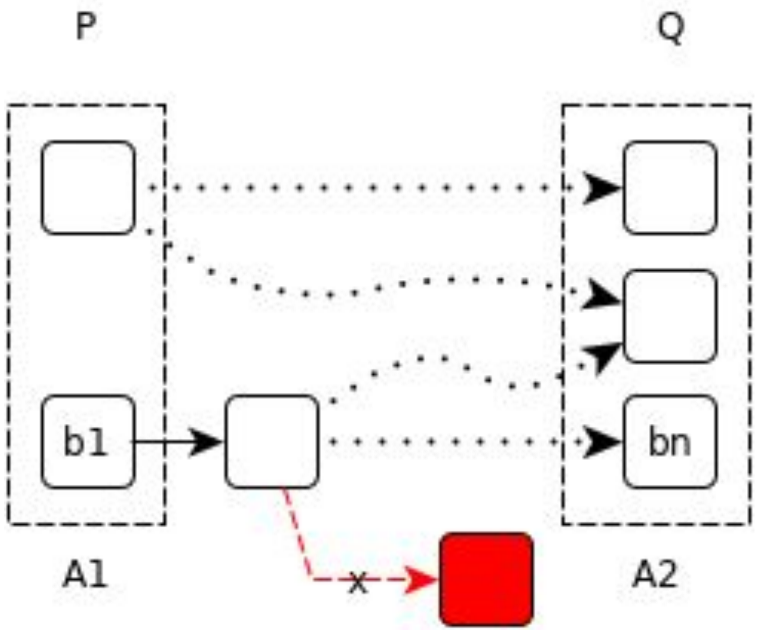
  - {P} program: A1 -> A2 {Q}



Contract Based Verification:

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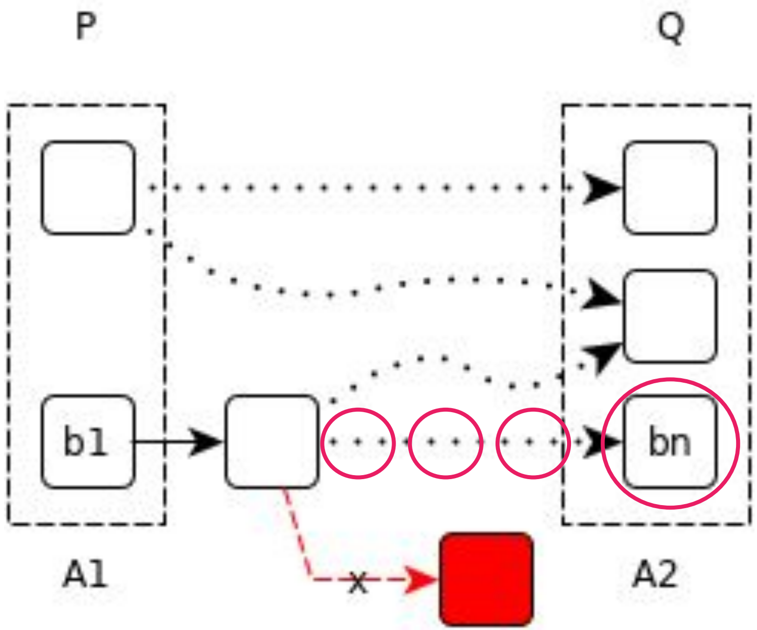
- Semi-automatic verification
  - Weakest precondition: WP
  - SMT solver P ⇒ WP



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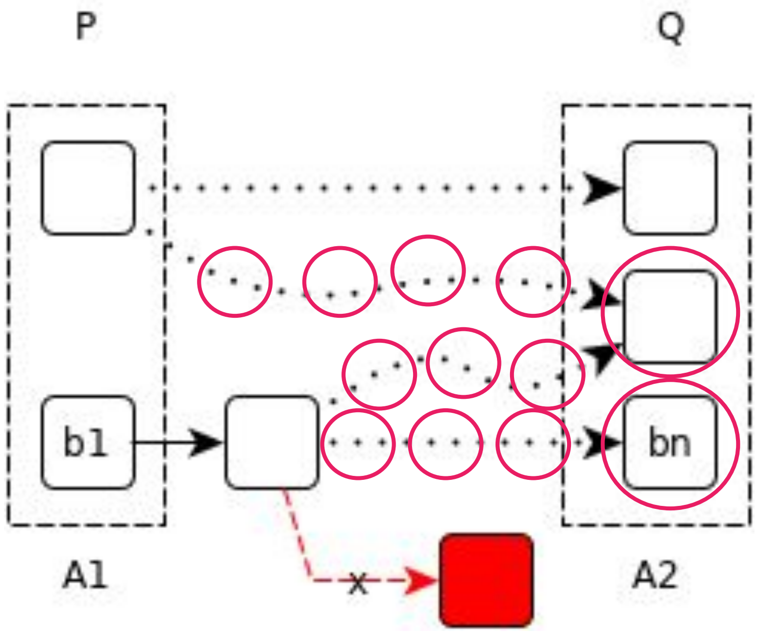

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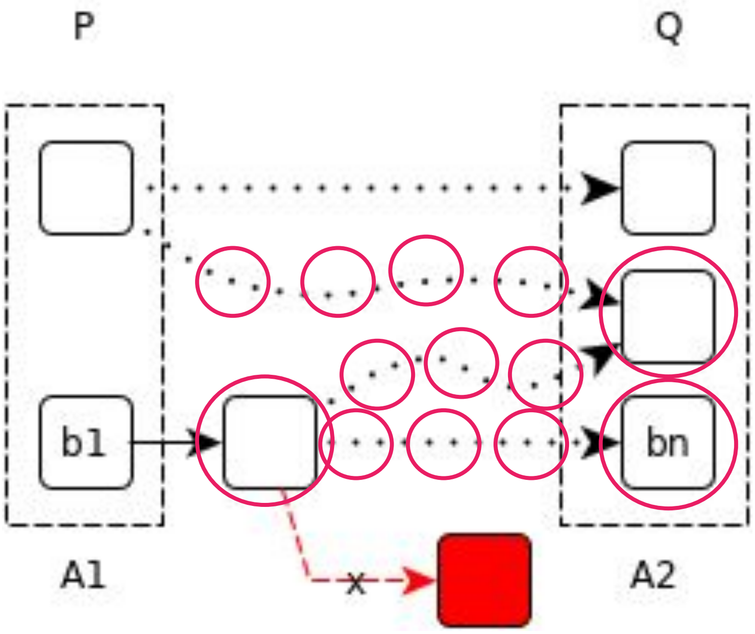

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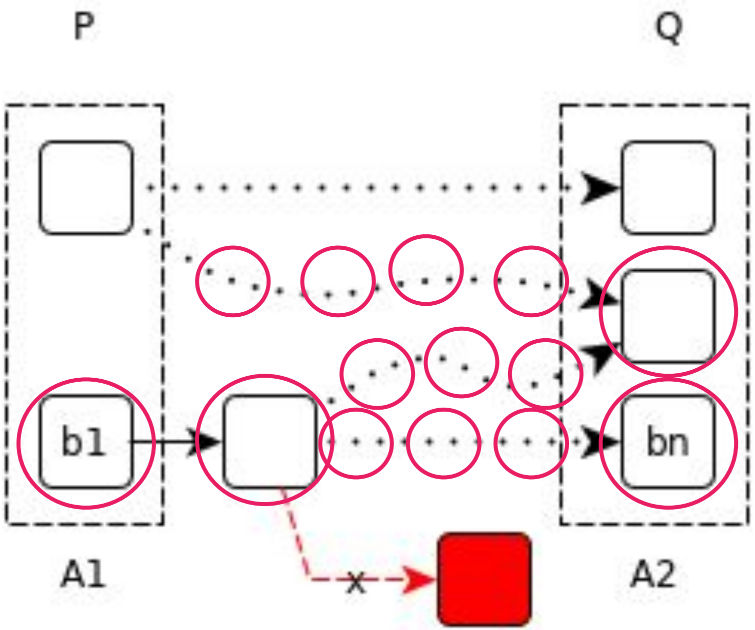
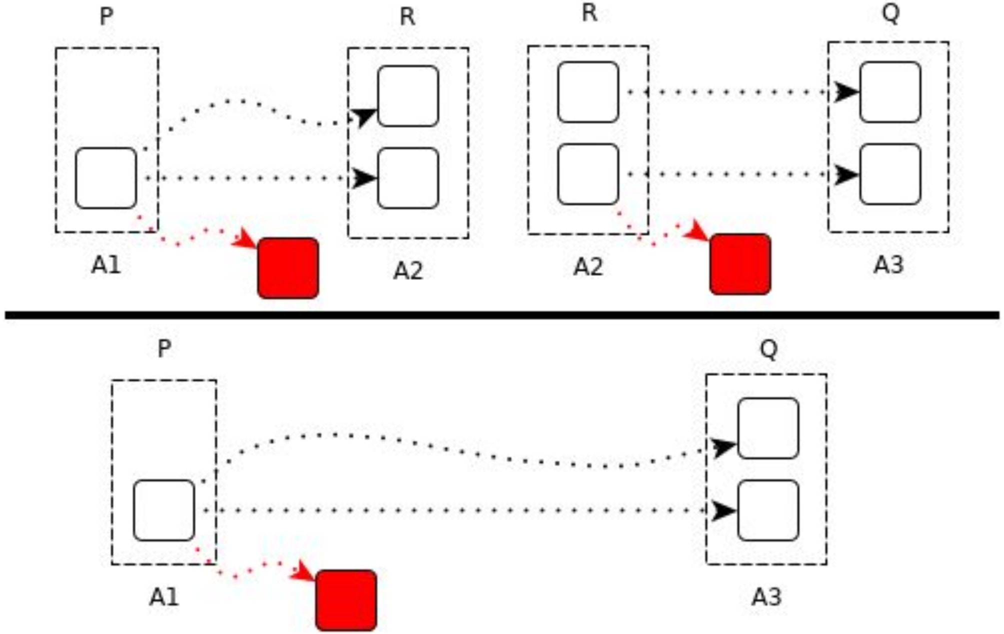


Compositional Logic For Binary Code



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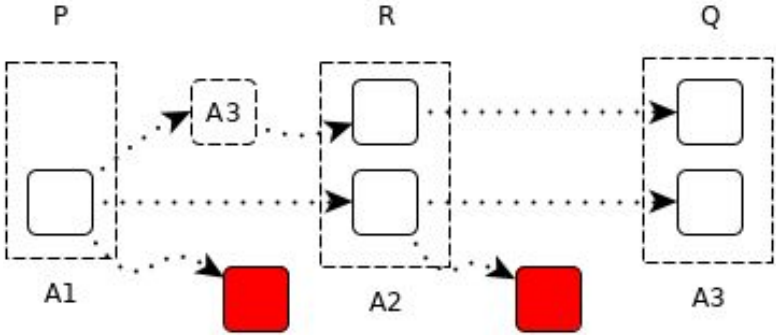

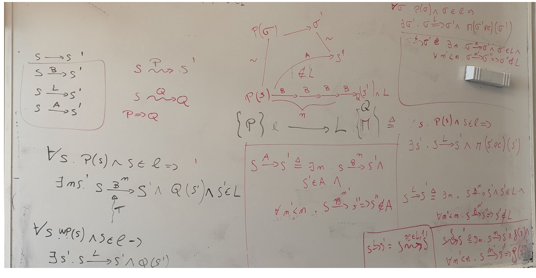

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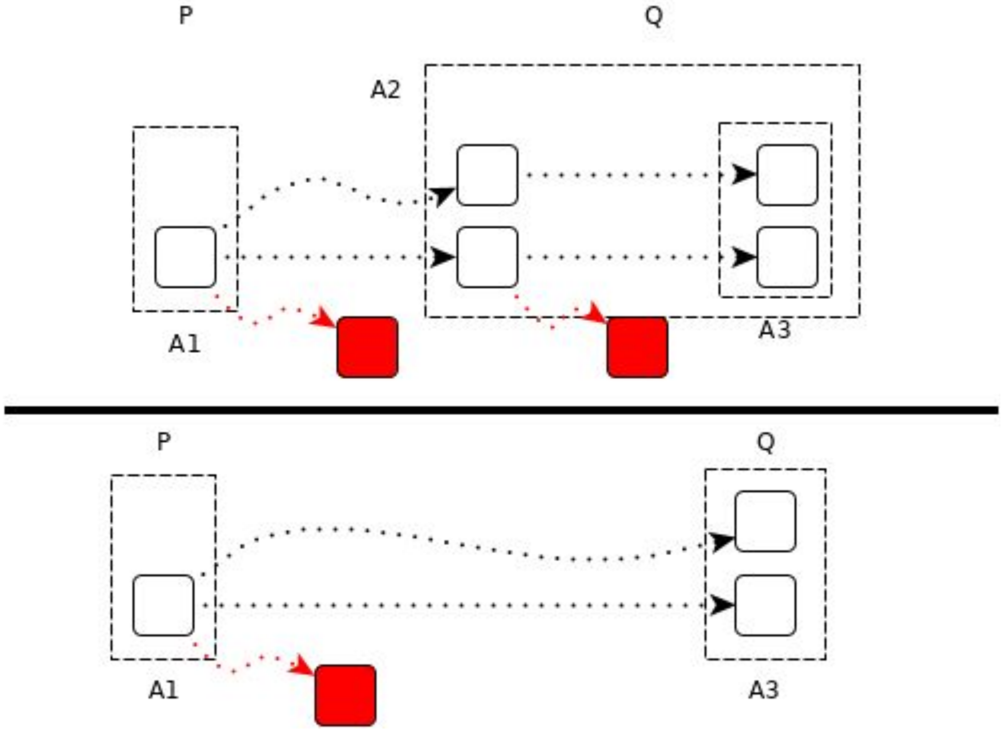
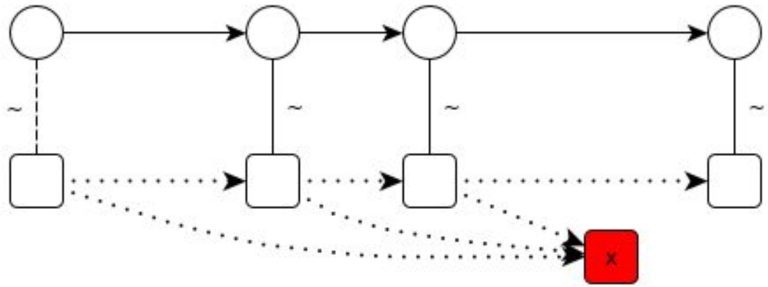


Putting things together



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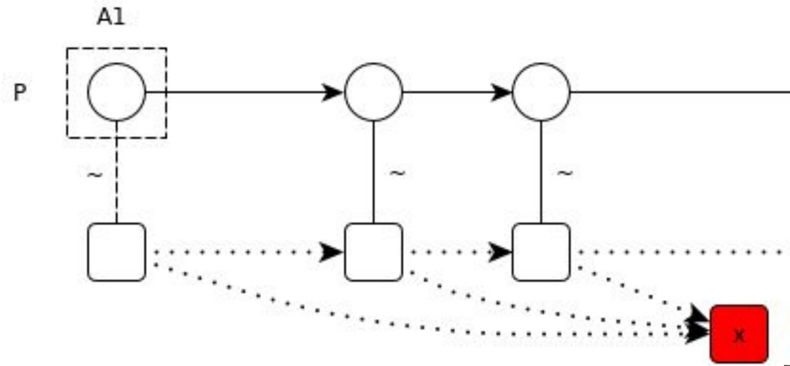

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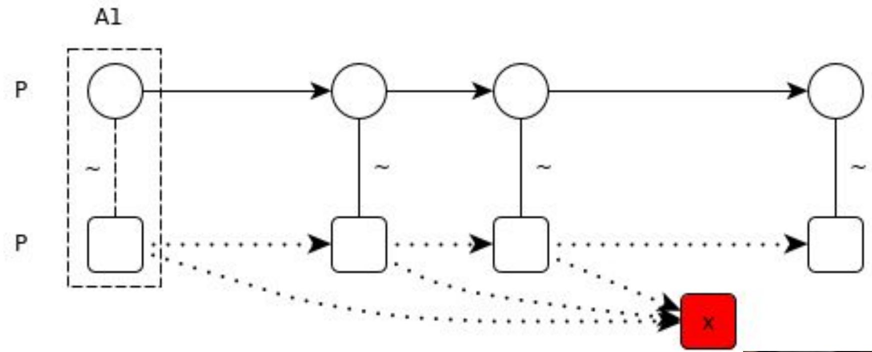

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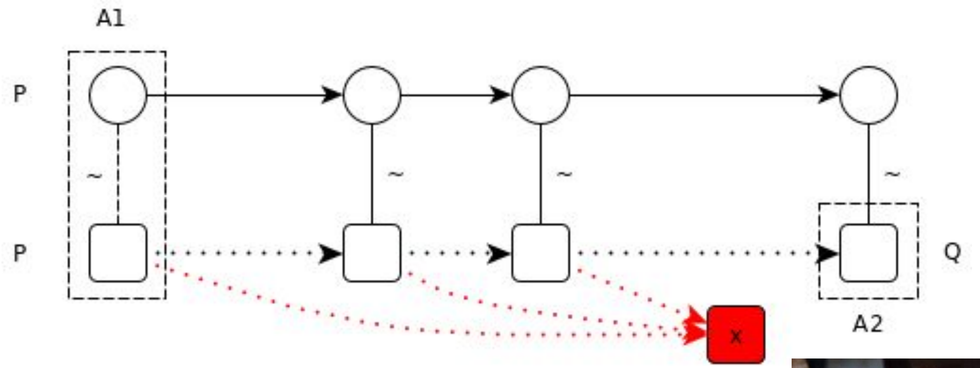

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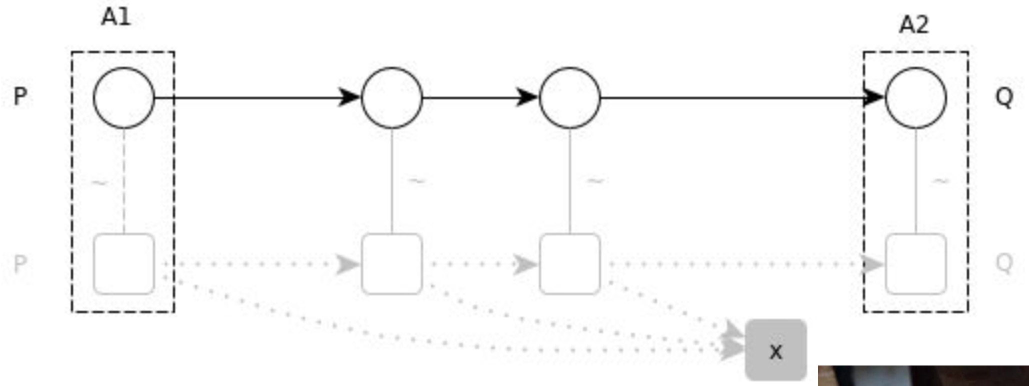

Real world usage

- Transpilation:
  - ~ 5 instructions / s
  - numlib / wolf-ssl / lua / SQLite / libc
  - ARMv8 / Cortex M0 / Ongoing Risc-V
- Weakest precondition
  - ~ 1 instruction / s
  - fragments consisting of 10/100 instructions (i.e. AES loop body)

Thank You

https://github.com/kth-step/HolBA

- Side channel analysis
- Symbolic execution
  - WCET
  - Translation validation
- Kernel verification