# UPEC-PN: Exhaustive constant time verification of low-level software using property checking

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# Motivation

## Security of low-level software

- Prevalence of timing-based side-channel attacks
- Constant time programming as countermeasure
  - How do we know whether the code is constant time?

    → Wanted: Formal method to provide guarantees
  - Is looking at the software enough?

    → Take necessary hardware detail into account

## Goals:

- A scalable formal verification method to provide security guarantees for low-level constant time software
- A modular computational model that
  - provides the necessary detail and
  - is abstract enough to scale well.

# Constant time

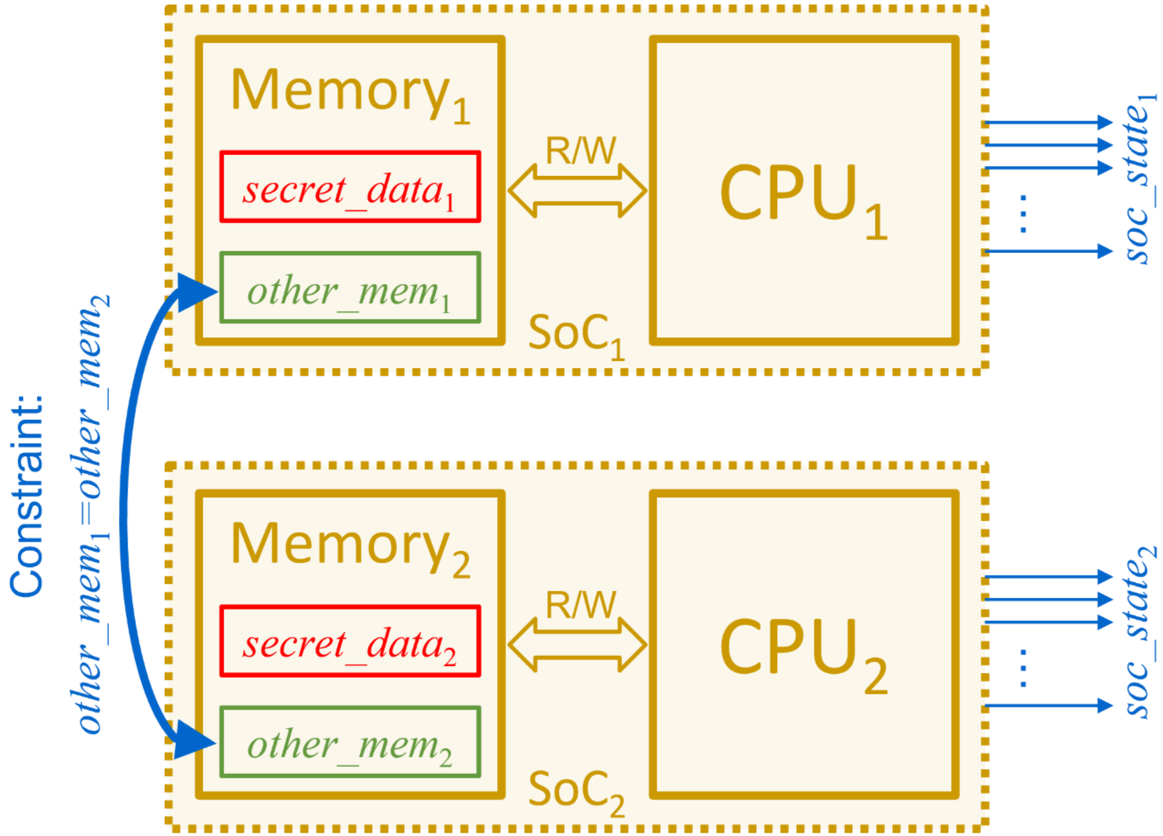
## Our notion:

- Secret-independence of:
  - Control flow
  - Memory access targets
  - Execution time of individual instructions
- Conservative view → not all violations lead to exploits
- Exhaustive view → detects all possible vulnerabilities

## Unique Program Execution Checking (UPEC) – DATE’19

- Originally: Formal approach for detecting Transient Execution Attacks
- Uses property checking on a bounded model with a symbolic initial state
  - Exhaustive and scalable
- 2-safety miter model
- Checks whether some protected secret data can influence the architectural state of the system

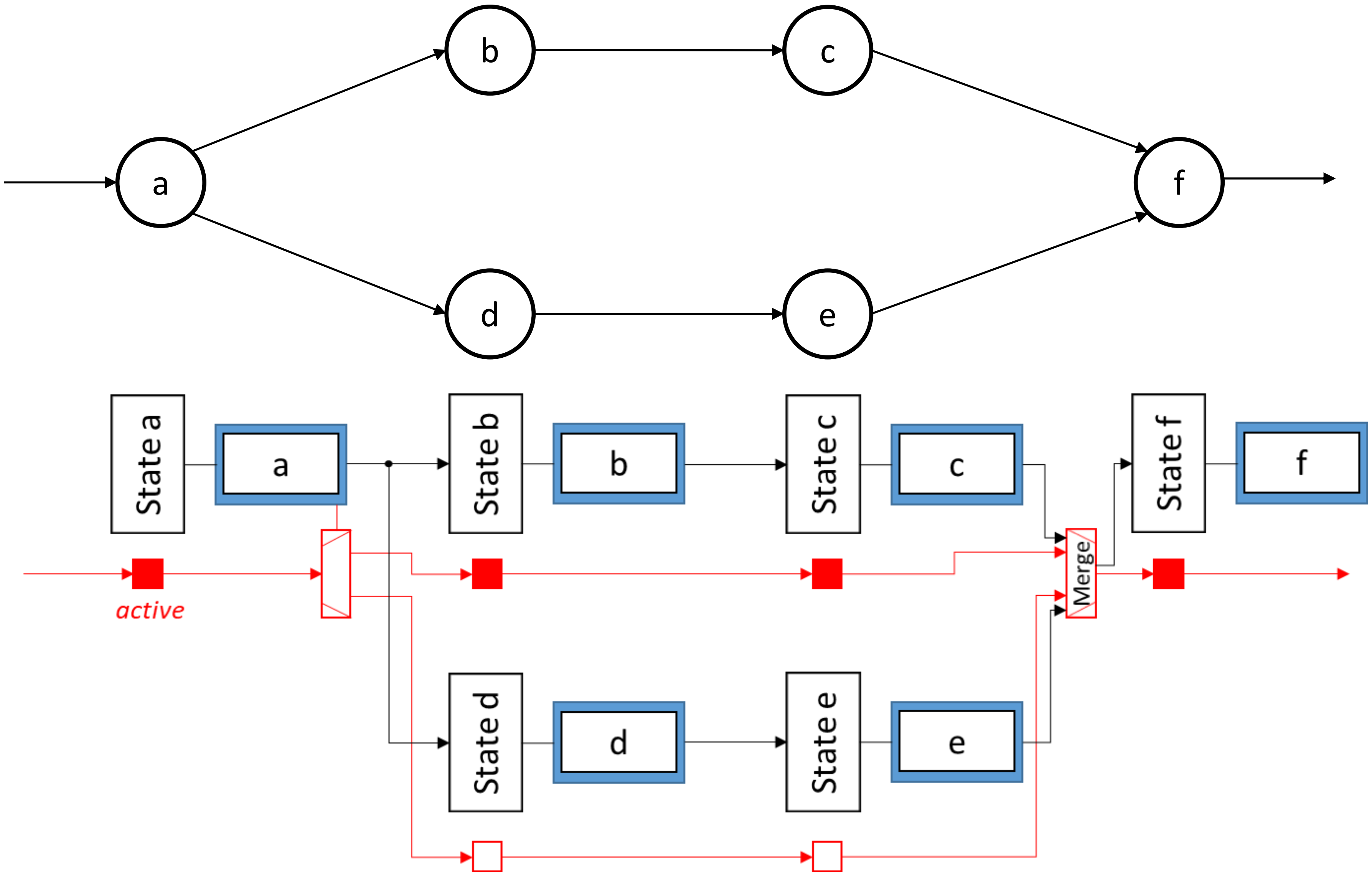
# Computational model



## Program Netlist (PN) – ASPDAC'13

- Formal representation of the ISA behavior for specific software
- Abstract sequential processor
- Compact computational model
  - Merge execution paths
  - Prune unreachable paths
- Result: Combinational circuit representing all possible executions

# Background

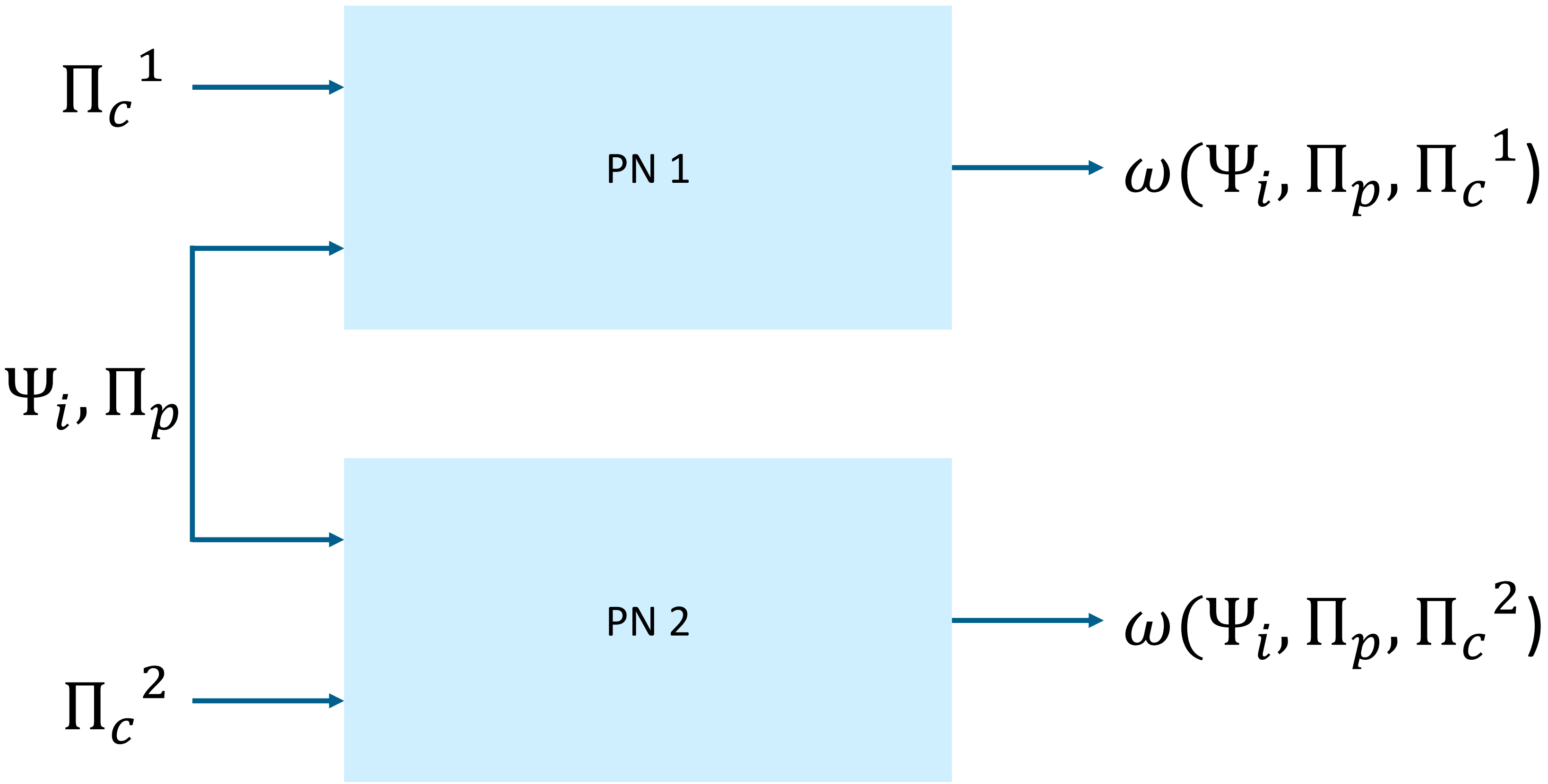

b
c
a
f
d
e
State a
a
State b
b
State c
c
State f
f
Merge
active
State d
d
State e
e

## UPEC-PN

- Verification method for constant time programming
- Apply UPEC approach to PNs
  - Divide PN inputs:
    - $\Psi_i$: initial program state
    - $\Pi_p$: public program inputs
    - $\Pi_c$: confidential program inputs
  - Abstract security function $\omega(\Psi_i, \Pi_p, \Pi_c)$ models security targets

$$\forall {\Pi_c}^1, {\Pi_c}^2 : \omega(\Psi_i, \Pi_p, {\Pi_c}^1) = \omega(\Psi_i, \Pi_p, {\Pi_c}^2)$$

# Methodology



# Constant time security targets

- Refine abstract security function $\omega$ to formalize security target
  - Control flow
  - Memory access
  - Individual instruction execution time
- Remember:

| | |
|---|---|
| Conservative view | → not all violations lead to exploits |
| Exhaustive view | → detects all possible vulnerabilities |

# Microarchitectural detail

- Observation: Conservative view may lead to a lot of false alerts
  - ISA-level model does not contain enough detail to judge if it is a real vulnerability
- Solution: add microarchitectural detail to the PN
  - Cache model
  - Architecture-specific instruction times

# Trade-off

Conservative proofs

Enhanced proofs

Globally valid

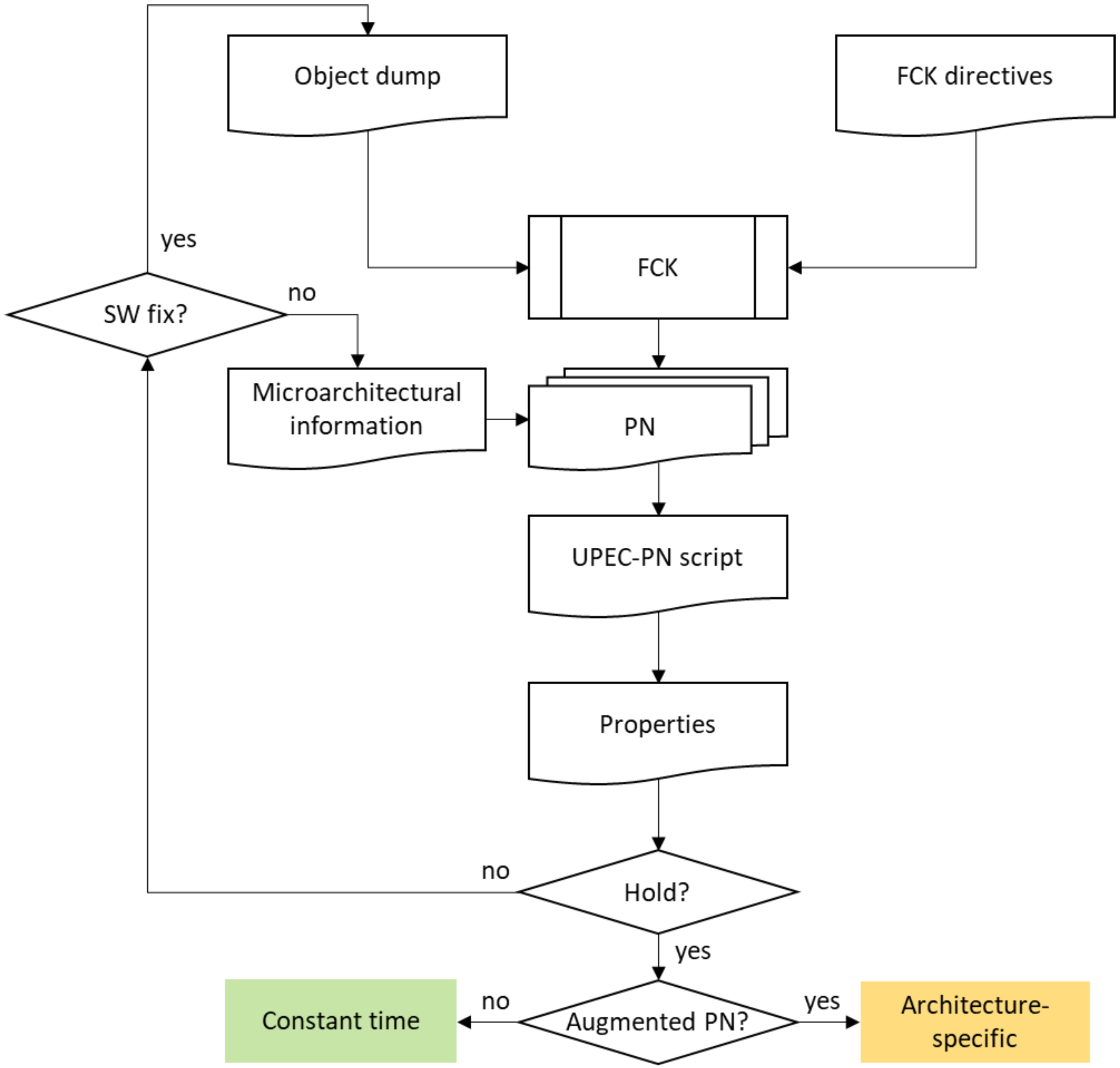
Fast

Architecture-specific

More complex

→ Find the sweet spot for least complexity and conservatism

# Verification Flow



# RSA

- Loop-based implementation using fast exponentiation
- UPEC-PN detects secret-dependent control flow

```
int powMod(int date,unsigned exp,int mod) {
  int result = 1;
  if (mod ==  0) return 0;
  if (mod == -1) return 0;
  if (mod < -30000) return 0;
  if (mod >  30000) return 0;

  while (exp > 0) {
    if ((exp & 1) == 1) {
      result = (result * date) % mod;
    }
    date = (date * date) % mod;
    exp = exp >> 1;
  }
  return result % mod;
}
```

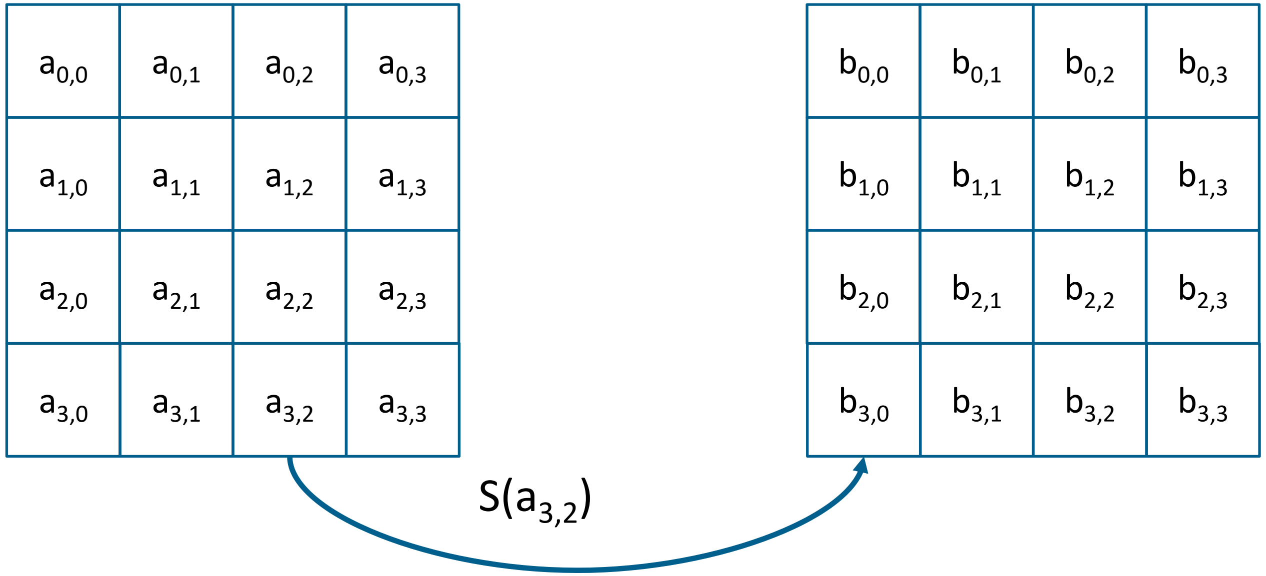
# RSA

- Software fix for control flow dependencies

```
int i = 32;
while (i-- > 0) {
    c_true = (exp & 1);
    __asm__("slti %[rd], %[rs1], 1" : [rd] "=r" (
     c_false) : [rs1] "r" (c_true));
    interm = (result * date) % mod;
    date = (date * date) % mod;
    exp = exp >> 1;
    result = c_true * interm + c_false*result;
}
```

# AES

- Substitution-box-based implementation
  - Key-dependent look-ups



# AES

- UPEC-PN detects secret-dependent memory targets
  - Counterexamples pinpoint the address range
- Exploitability depends on the system
- Possible countermeasure:
  - Load the substitution box into the cache to ensure cache hits
- Add abstract cache model to the computational model

## Summary:

| Software | Control Flow | | | Memory Access | | | #ICs |
|---|---|---|---|---|---|---|---|
| | Time (s) | Mem (MB) | SI | Time (s) | Mem (MB) | SI | |
| RSA | 43 | 8585 | ✗ | 53 | 8568 | ✓ | 964 |
| Fixed RSA | 39 | 8605 | ✓ | 53 | 8726 | ✓ | 1093 |
| AES | <1 | 700 | ✓ | 409 | 3056 | ✗ | 7444 |

Proof of concept – UPEC-PN detects the expected vulnerabilities

# Conclusion

- UPEC-PN
  - Provides architecture-independent security guarantees
  - Detects ISA-level-visible constant time violations
  - Enables the consideration of necessary microarchitectural detail
  - Is independent of a specific toolchain
- Future Work
  - Conduct experiments on more low-level programs
  - Support for other ISAs

# Thank you for your attention!

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