NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

TAD

Time Side-Channel Attack Defense of Obfuscated Source Code

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Outline

Side-Channel Attacks

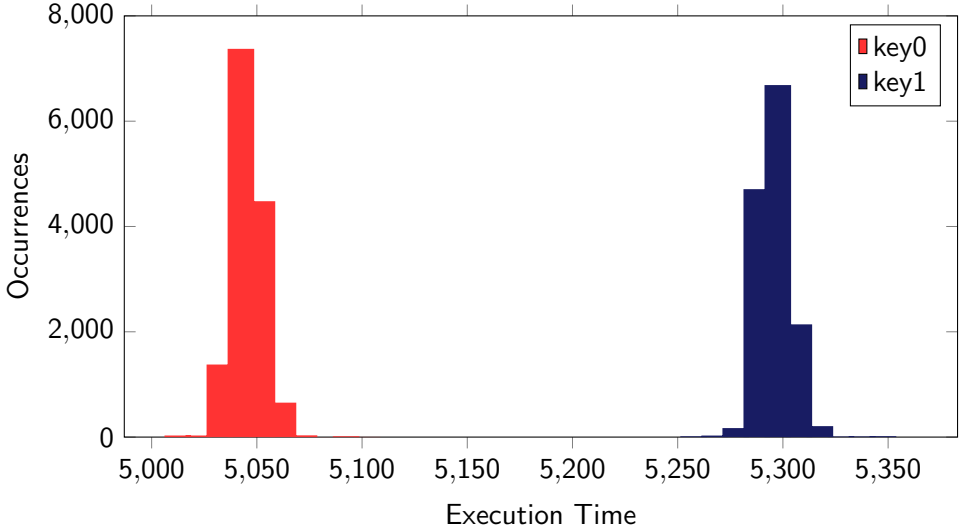
- Unintentional leakage of information through side-channels caused by variations in:
  - power consumption of the processor
  - temperature
  - electromagnetic emittance
  - duration of program execution
  - ...

Example Program

Input: data y, private key k, integer N
Output: $y^k \mod N$

```
1:  function ModExp(y, k, N)
2:      r ← 1
3:      for all ⟨k_i | i ∈ k⟩ do
4:          if (k_i = 1) then                    ▷ Critical Condition
5:              r ← (r × y) mod N
6:          end if
7:          y ← y^2 mod N
8:      end for
9:      return r mod N
10: end function
```

Execution Times of the Example Program



Reverse-Engineering Attacks

- Low-cost extraction, disassembly and analysis of binary program code of an obtained embedded system
- Obfuscation function O modifies the source code P such that

$$P(x) = O(P(x)) \text{ for all inputs } x$$

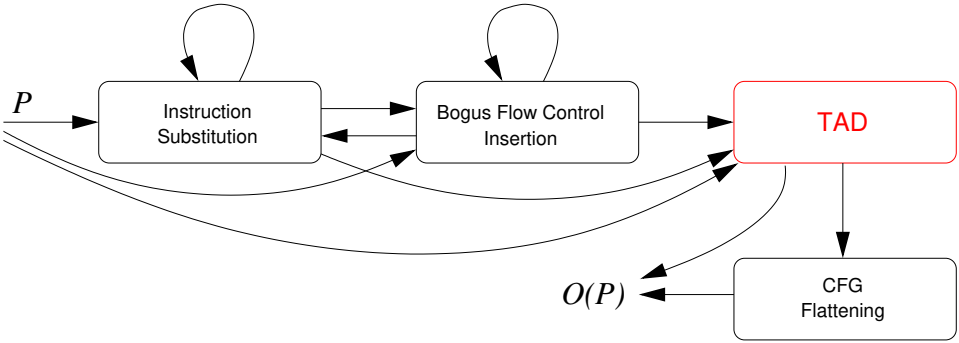
- Examples for O [1, 8, 7, 4, 5]:
  - Instruction substitution
  - Instruction set randomization
  - Flattening of control flow graph (CFG)
  - Insertion of bogus flow control
  - ...
- No cryptographic guarantee of security! [2, 6, 13, 12]

Motivation

A compiler that **automatically** modifies a program such that its functionality remains the same with an additional protection against

1. Reverse-Engineering **and**
2. Time Side-Channel Attacks

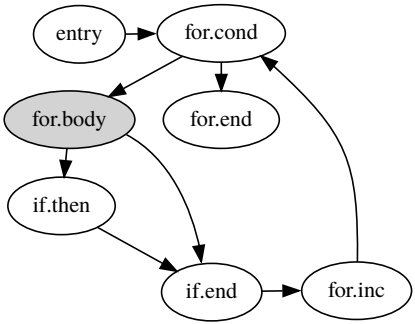
Obfuscation Function O



Time Side-Channel Attack Defense (TAD) I

Input: data y, private key k, integer N
Output: $y^k \mod N$

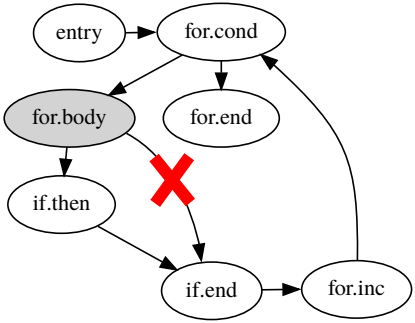
```
1:  function MODEXP(y, k, N)
2:      r ← 1
3:      for all ⟨k_i | i ∈ k⟩ do
4:          if (k_i = 1) then
5:              r ← (r × y) mod N
6:          end if
7:          y ← y^2 mod N
8:      end for
9:      return r mod N
10: end function
```



Time Side-Channel Attack Defense (TAD) II

Input: data y, private key k, integer N
Output: $y^k \mod N$

```
1:  function ModExp(y, k, N)
2:      r ← 1
3:      for all ⟨k_i | i ∈ k⟩ do
4:          if (k_i = 1) then
5:              r ← (r × y) mod N
6:          end if
7:          y ← y^2 mod N
8:      end for
9:      return r mod N
10: end function
```



Time Side-Channel Attack Defense (TAD) III

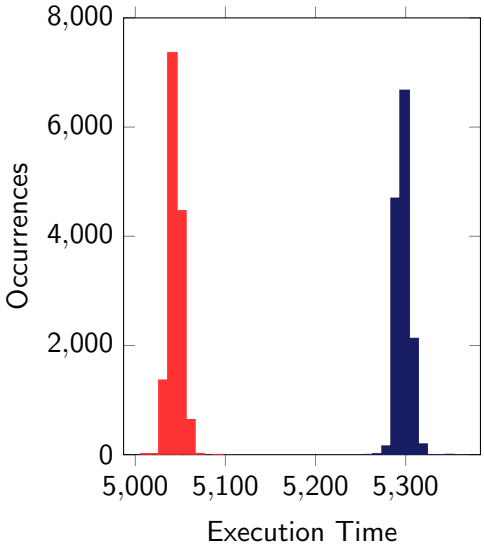
Input: data y, private key k, integer N
Output: $y^k \mod N$

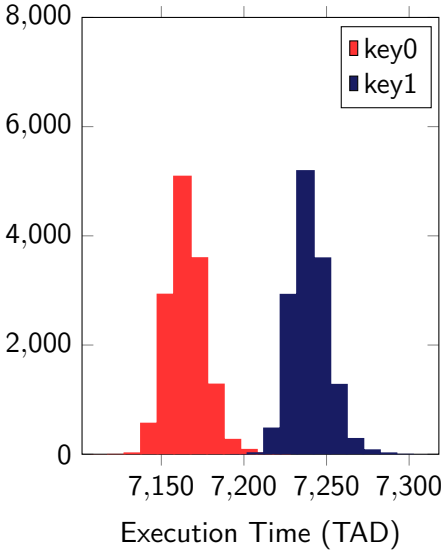
1: **function** MODEXP(y, k, N)
2: $r \leftarrow 1$
3: **for all** $\langle k_i | i \in k \rangle$ **do**
4: **if** $(k_i = 1)$ **then**
5: $r \leftarrow (r \times y) \mod N$
6: **end if**
7: $y \leftarrow y^2 \mod N$
8: **end for**
9: **return** $r \mod N$
10: **end function**

Input: data y, private key k, integer N
Output: $y^k \mod N$

1: **function** MODEXP(y, k, N)
2: $r \leftarrow 1$
3: **for all** $\langle k_i | i \in k \rangle$ **do**
4: $m \leftarrow k_i \times (-1)$
5: $rr \leftarrow (r \times y) \mod N$
6: $r \leftarrow (m \wedge rr) \vee (\neg m \wedge r)$
7: $y \leftarrow y^2 \mod N$
8: **end for**
9: **return** $r \mod N$
10: **end function**

TAD - Results (bare-metal)





TAD - Conclusion

- Removing divergence in CFG is insufficient.
  - Cache
  - Variable latency instructions
  - Memory access times
  - Branch prediction
  - ...

Solution:
Instructions independent of operand values $\rightarrow$ TAD with Custom Instructions and hardware diversification (TADCI)

TADCI - Modified Example Program

Let $CI_1 = \times$ and $CI_2 = \text{mod}$

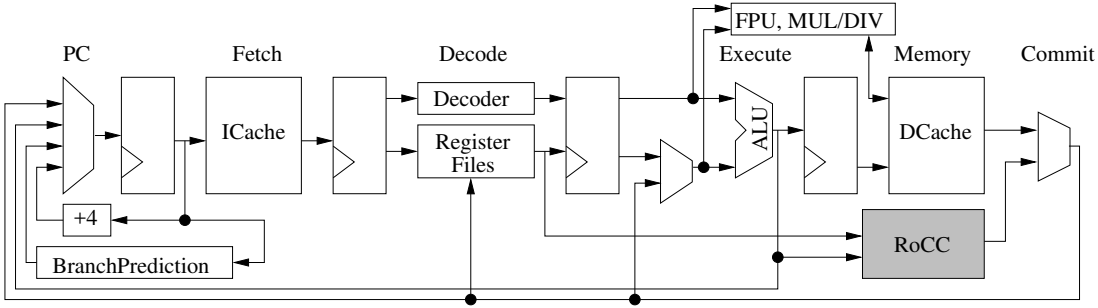
Input: data y, private key k, integer N
Output: $y^k \mod N$

1: **function** MODEXP(y, k, N)
2: $r \leftarrow 1$
3: **for all** $\langle k_i | i \in k \rangle$ **do**
4: $m \leftarrow k_i \times (-1)$
5: $rr \leftarrow (r \times y) \mod N$
6: $r \leftarrow (m \wedge rr) \vee (\neg m \wedge r)$
7: $y \leftarrow y^2 \mod N$
8: **end for**
9: **return** $r \mod N$
10: **end function**

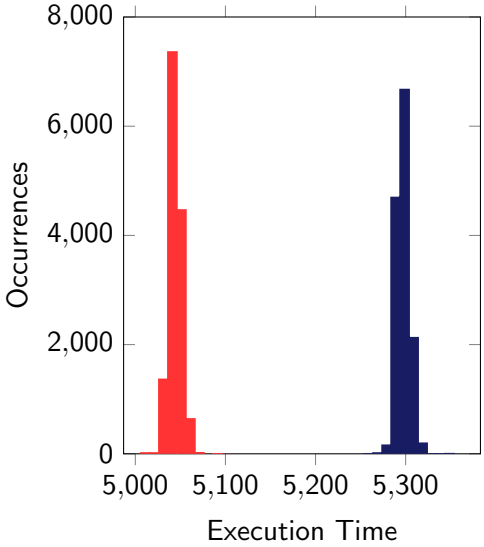
Input: data y, private key k, integer N
Output: $y^k \mod N$

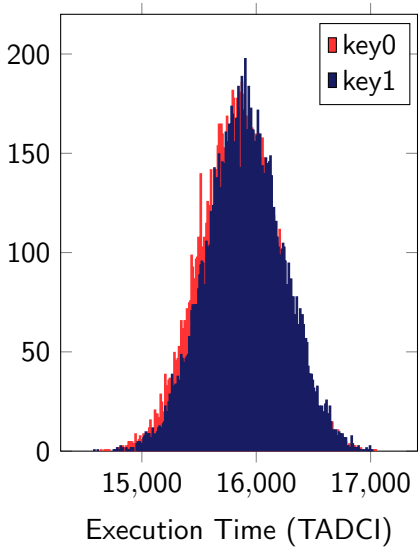
1: **function** MODEXP(y, k, N)
2: $r \leftarrow 1$
3: **for all** $\langle k_i | i \in k \rangle$ **do**
4: $m \leftarrow k_i \times (-1)$
5: $rr \leftarrow (r \, CI_1 \, y) \, CI_2 \, N$
6: $r \leftarrow (m \wedge rr) \vee (\neg m \wedge r)$
7: $y \leftarrow (y \, CI_1 \, y) \, CI_2 \, N$
8: **end for**
9: **return** $r \, CI_2 \, N$
10: **end function**

TADCI - Architecture Overview



TADCI - Results (bare-metal)

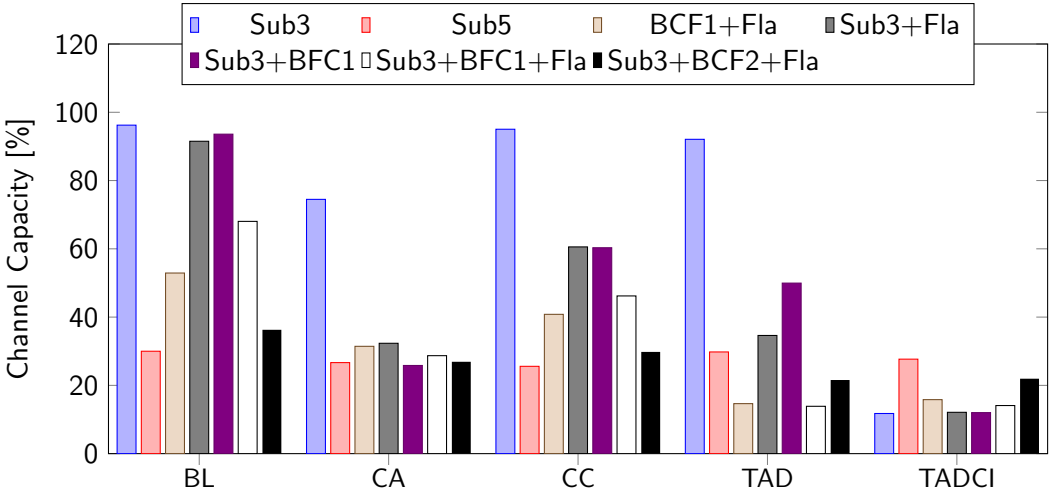




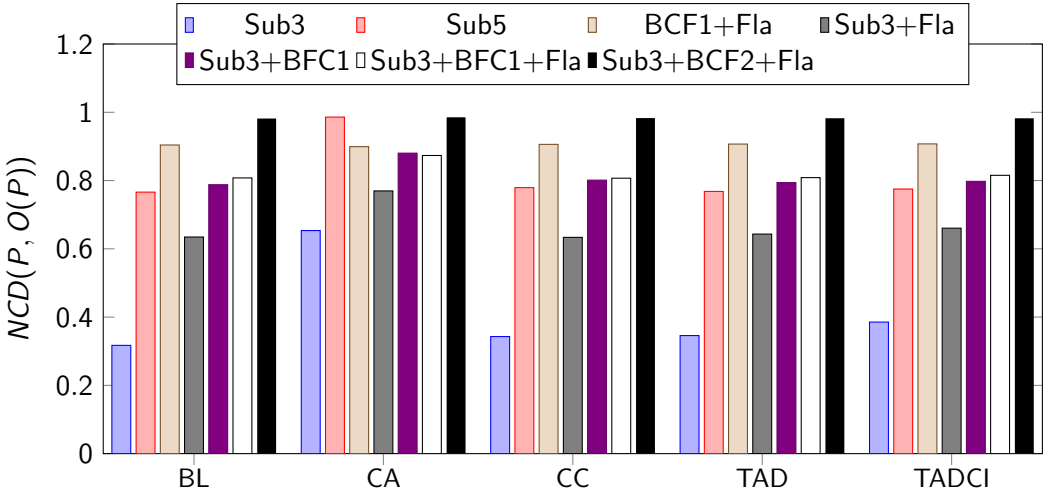
Test Environment

- RISC-V Rocket Core [3] on a Zynq7000 XC7Z020 FPGA
  - 64bit
  - 50MHz
  - Branch Prediction
  - L1 Instruction and Data Cache
  - L2 Cache
  - FPU
  - H/W Multiplier and Division Unit with Early Out
  - Rocket Chip Co-Processor
- Bare Metal Program Execution
  - RSA modular exponentiation (MODEXP) to encrypt or decrypt a message [11] from the benchmark suite introduced in [10]
  - Modular multiplication (MULMOD16) from the IDEA cipher [9]

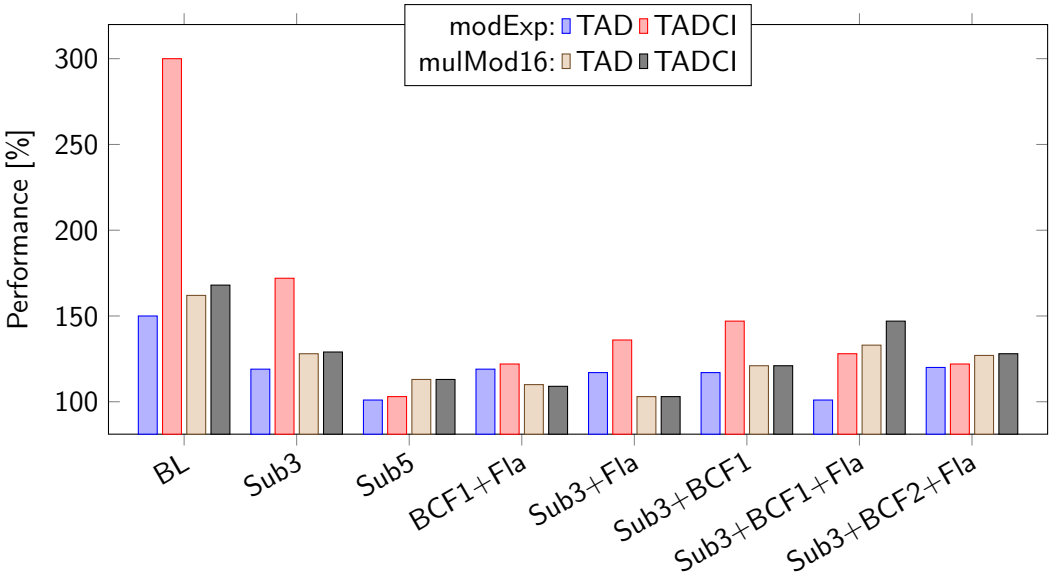
Results - Channel Capacity (modExp)



Results - Normalized Compression Distance *NCD* (modExp)



Results - Performance Impact



Hardware Requirements

Table: Hardware Resource Utilization

	RISC-V	RISC-V with RoCC	Change
LUTs	32310	32953	+2%
DSPs	15	25	+67%
BRAM	24	24	–

Conclusion

- Impact on performance, obfuscation strength and time side-channel attack mitigation depends highly on the input program.
- Minimal invasive to existing RISC-V architectures (RoCC)
- Low additional hardware resource requirements
- Suitable for low-noise environments/embedded systems
- External factors such as periphery influence time side-channel leakage

Thank You

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