Timing Leaks and Coarse-Grained Clocks

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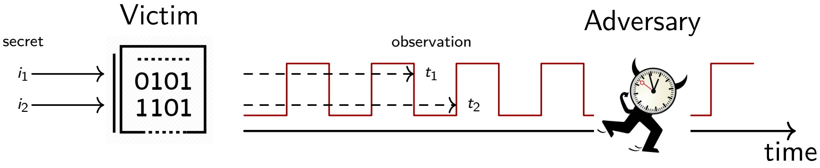
DTU Technical University of Denmark

Microsoft Research Cambridge

Timing-Channel Attacks



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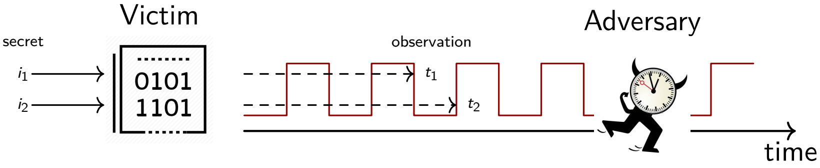

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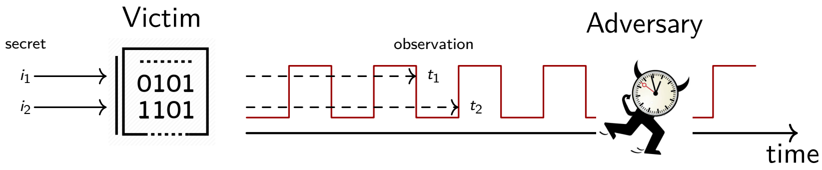

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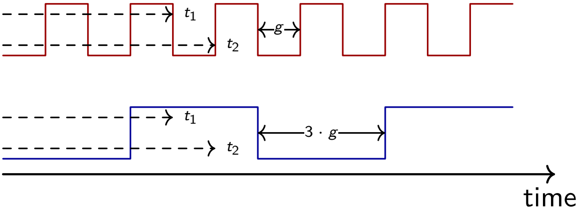
The drawback : performance overhead

Reducing Clock Resolution

A countermeasure which configures the clock



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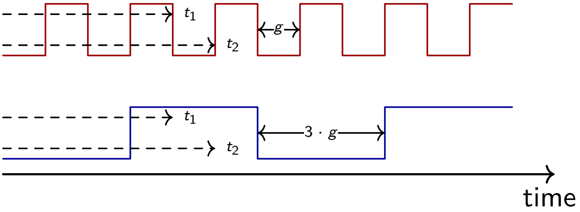

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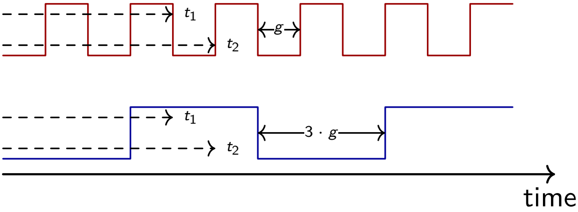

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We propose

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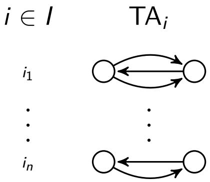
- Conditions under which a coarse-grained clock imply better security.
- A new timing technique.
- The timing techniques form a strict hierarchy in terms of information leakage.



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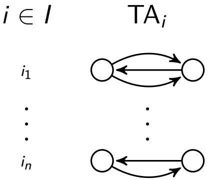
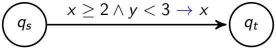
- a finite set of secrets I, and
- the family of timed automata $S = (TA_i)_{i \in I}$

Modelling Part: the Victim



Guarded edges over real-valued variables



Transitions

$$\langle q_s, [x \mapsto 3.4, y \mapsto 0] \rangle \xrightarrow{1.32, e_1} \langle q_t, [x \mapsto 0, y \mapsto 1.32] \rangle$$

Computations of the victim

$$\rho = \langle q_0, \delta_0 \rangle \xrightarrow{t_1, e_1} \ldots \xrightarrow{t_n, e_n} \langle q_n, \delta_n \rangle \xrightarrow{t_{n+1}, e_{n+1}} \ldots$$

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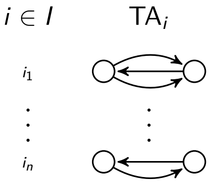

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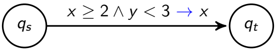

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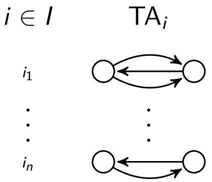

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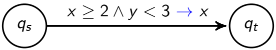

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The system S can be either

- deterministic (i.e for each i, we have a unique computation),
- or stochastic (i.e at each transition we first choose randomly a delay and then an edge)

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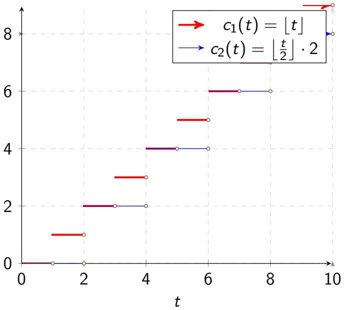

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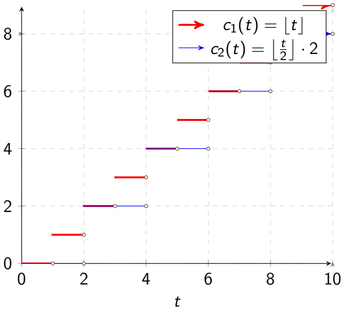

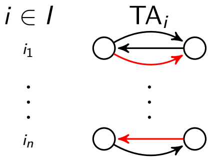

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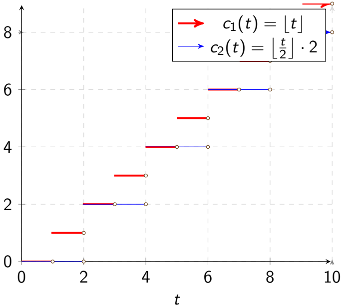

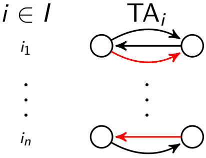

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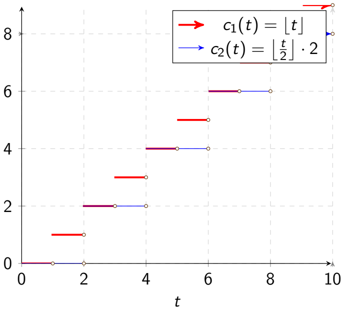

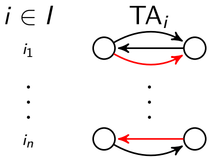

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The view of the adversary on the computation ρ is

$$\text{view}_c(\rho) = (c(t_{j_1}), \dots, c(t_{j_k}))$$

A Counterexample on the Security of Coarse-Grained Clocks

Take deterministic function f with inputs i_1, i_2 and timings 2, 3 resp.

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Increasing the grain of the clock may result to more information leakage.

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Theorem 2 (Multiple-g Security)

In deterministic systems, increasing the grain g to a multiple $g' = m \cdot g$ results always to less or equal information leakage.

Leakage Analysis Part: Quantitative Information Flow

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The leakage is defined

$$\mathrm{Leakage}(p, \mathrm{TC}) = \mathrm{H}(p) - \mathrm{H}(p, \mathrm{TC})$$

Step 1. For each $i \in I$ let $O_i = \{\mathrm{view}_c(\rho) \mid \rho \in \mathrm{Runs}(\mathrm{TA}_i)\}$.
The set of outputs is $O = \bigcup_i O_i$

Given an attack scenario $\mathrm{AS} = (\mathrm{S}, \mathrm{E}_{\mathrm{pub}}, c, k)$ we construct the timing channel TC(AS):

- **Step 1** is the output enumeration

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Step 2. Construct the timing channel $\text{TC}(\text{AS}) : I \times O \mapsto [0, 1]$, and for $i \in I$, and $o \in O$:

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We showed that for an observation $o \in O$, the set $\mathsf{view}_c^{-1}(o)$ is measurable with P_γ

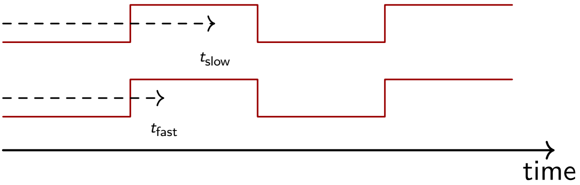
Timing Techniques

The set-up

- The victim runs a deterministic function f
- The adversary performs a constant-time operation for one, or more times after the execution of f, while it also makes queries to its clock.

Timing Techniques: The One-Pad

The one-pad technique



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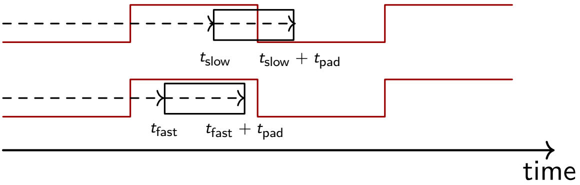

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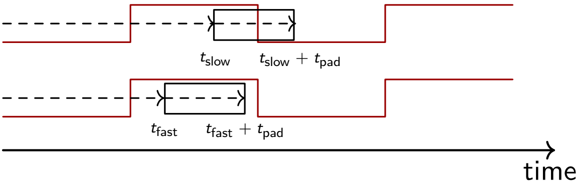
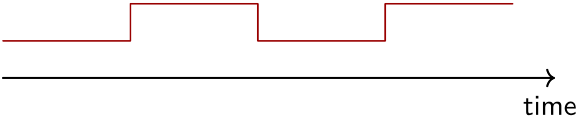


Very effective on cache side-channel attacks

The clock-edge technique (the learning phase)



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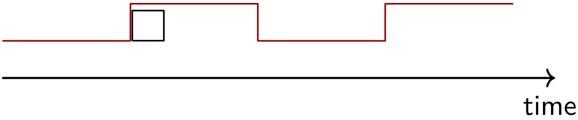

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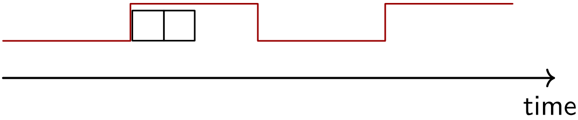

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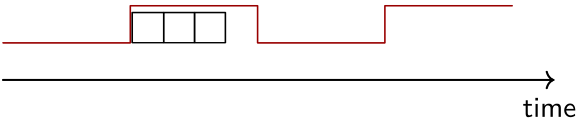

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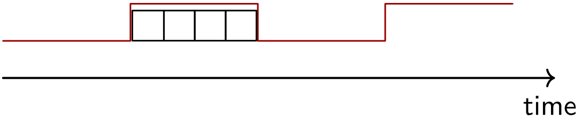

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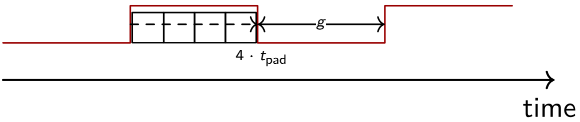

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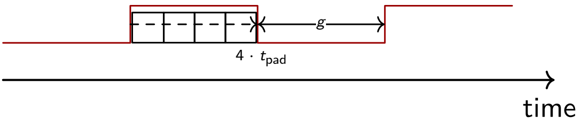

The advesrary learns:

$$t_{\text{pad}} = \frac{g}{4}$$

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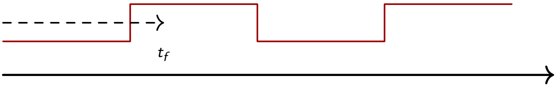

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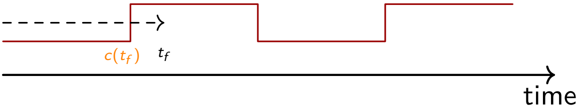

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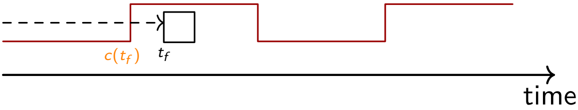

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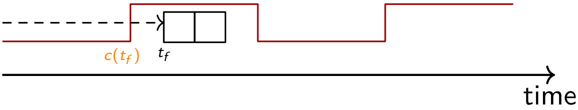

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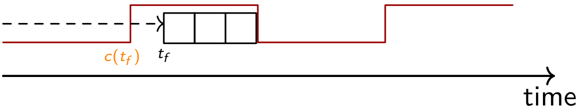

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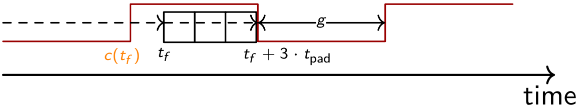

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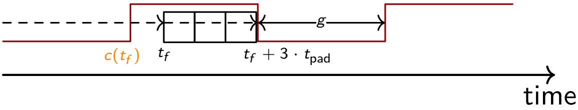
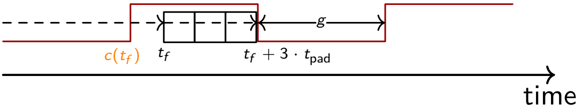


The adversary learns

$$c(t_f) + g = t_f + 3 \cdot t_{\text{pad}}$$

Timing Techniques: The Clock-Edge

The clock-edge technique (the attack phase)



The adversary learns

$$
\begin{aligned}
& c(t_f) + g = t_f + 3 \cdot t_{\text{pad}} \\
\Leftrightarrow \quad & t_f = c(t_f) + g - 3 \cdot t_{\text{pad}}
\end{aligned}
$$

Timing Techniques

Basic idea behind the timing techniques:

- Distinguish t_1, t_2, when

$$(c(t_1), c(t_1 + t_{\text{pad}}), \ldots, c(t_1 + m \cdot t_{\text{pad}}))$$

$$\neq$$

$$(c(t_2), c(t_2 + t_{\text{pad}}), \ldots, c(t_2 + m \cdot t_{\text{pad}}))$$

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Question (1): How many times should I add my padding?

Question (2): Does the time t_{pad} need to be fast?

We showed that:

$$(c(t_1), c(t_1 + t_{\text{pad}}), \ldots, c(t_1 + m \cdot t_{\text{pad}}))$$

$$\neq$$

$$(c(t_2), c(t_2 + t_{\text{pad}}), \ldots, c(t_2 + m \cdot t_{\text{pad}}))$$

iff

$$(c(t_1), c(t_1 + (t_{\text{pad}} \bmod g)), \ldots, c(t_1 + (m \cdot t_{\text{pad}} \bmod g)))$$

$$\neq$$

$$(c(t_2), c(t_2 + (t_{\text{pad}} \bmod g)), \ldots, c(t_2 + (m \cdot t_{\text{pad}} \bmod g)))$$

Timing Techniques: The Co-Prime

We showed that:

$$(c(t_1), c(t_1 + t_{\text{pad}}), ..., c(t_1 + m \cdot t_{\text{pad}}))$$

$$\neq$$

$$(c(t_2), c(t_2 + t_{\text{pad}}), ..., c(t_2 + m \cdot t_{\text{pad}}))$$

iff

$$(c(t_1), c(t_1 + (t_{\text{pad}} \bmod g)), ..., c(t_1 + (m \cdot t_{\text{pad}} \bmod g)))$$

$$\neq$$

$$(c(t_2), c(t_2 + (t_{\text{pad}} \bmod g)), ..., c(t_2 + (m \cdot t_{\text{pad}} \bmod g)))$$

Question (1): How many times should I add my padding?
Answer: g times.

Question (2): Does the time t_{pad} need to be fast?
Answer: Not always. t_{pad} needs to be co-prime with g.

Timing Techniques: a Hierarchy

Theorem 2

$$\mathsf{TC}(\mathsf{AS}_{\text{1-pad}}) \preceq \mathsf{TC}(\mathsf{AS}_{\text{clock-edge}}) \preceq \mathsf{TC}(\mathsf{AS}_{\text{co-prime}})$$

Limitations and Solutions to them

Scalability issues:

- The set of outputs O can be large
- the number of observations k can be large
- the stochastic case involves calculations of the form

$$\mathrm{P}(...) = \int_{t_1 \in C_1} ... \int_{t_n \in C_n} \mathrm{d}\mu_n(t_n)...\mathrm{d}\mu_1(t_1)$$

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However, there are cases where we can do better:

- In deterministic systems we have that min-leakage $= \log|O|$. Any over-approximation $O^{\#} \supseteq O$ gives us a direct upper bound on the information leakage i.e $\log|O| \leq \log|O^{\#}|$
- In stochastic systems with independent observations, calculating the channel for a single observation can be used to give us bounds on the information leakage for k observations.

Conclusions

We performed the first principled information-flow analysis of timing leaks w.r.t. adversaries with clocks of reduced resolution. Our analysis relies on a novel translation of timed automata to information-theoretic channels, which we used to derive the following:

- A coarse-grained clock might leak more information than a fine-grained one.
- A sufficient condition for when increasing the grain we achieve better security.
- A new timing technique.
- The timing techniques form a strict hierarchy in terms of information leakage.

Questions?