On the use of formal tools to improve the security of masked implementations

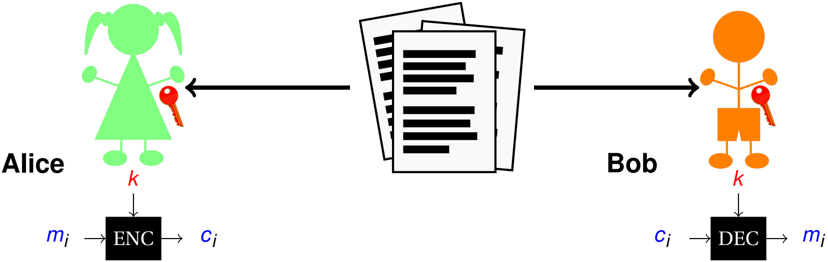
Symposium European Cyber Week

November 23, 2016

Sonia Belaïd

Cryptanalysis

- ➜ Black-box cryptanalysis
- ➜ Side-channel analysis



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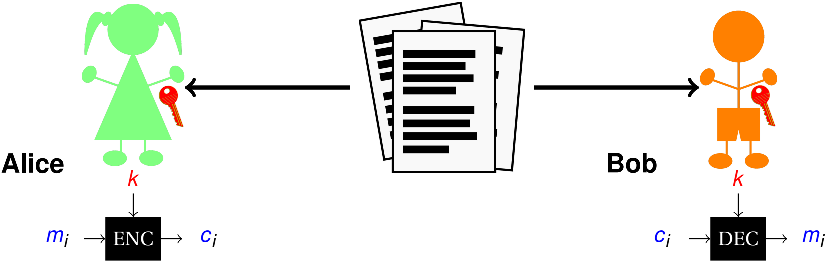

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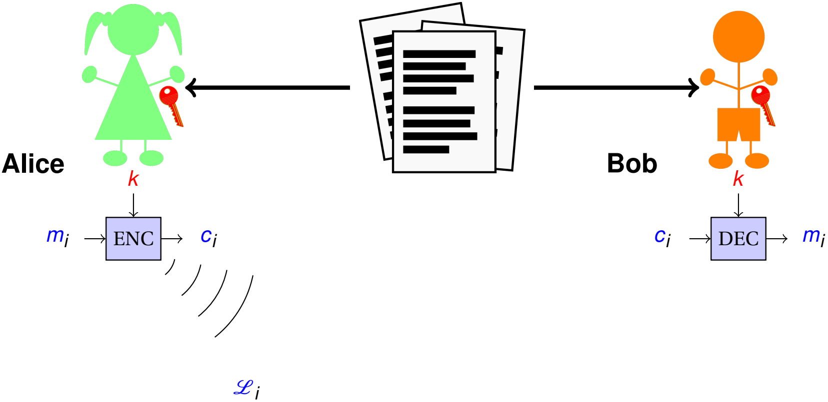
- Side-Channel Analysis: $\mathscr{A} \leftarrow (m_i, c_i, \mathscr{L}_i)$



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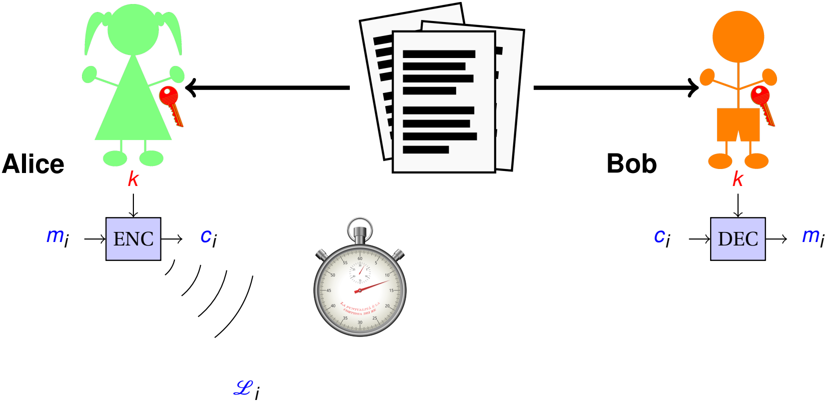

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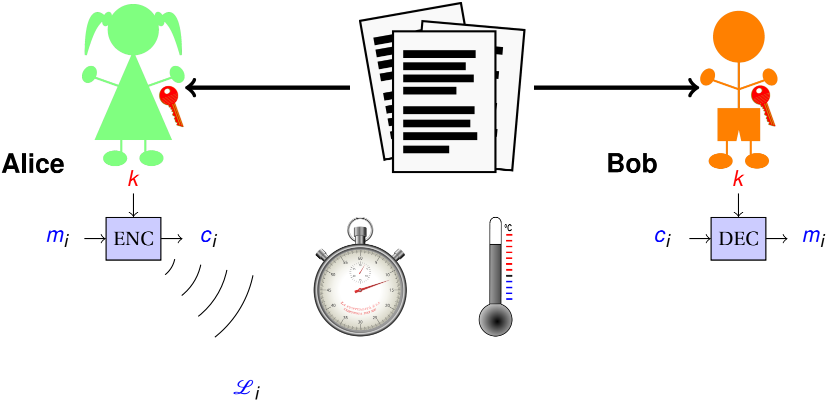

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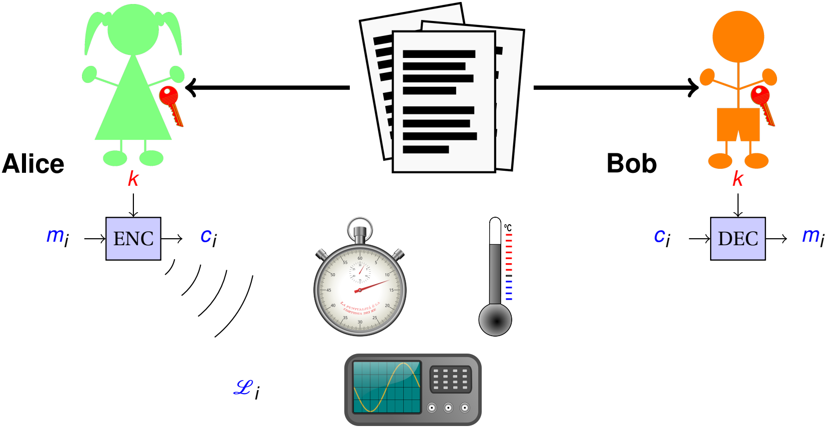

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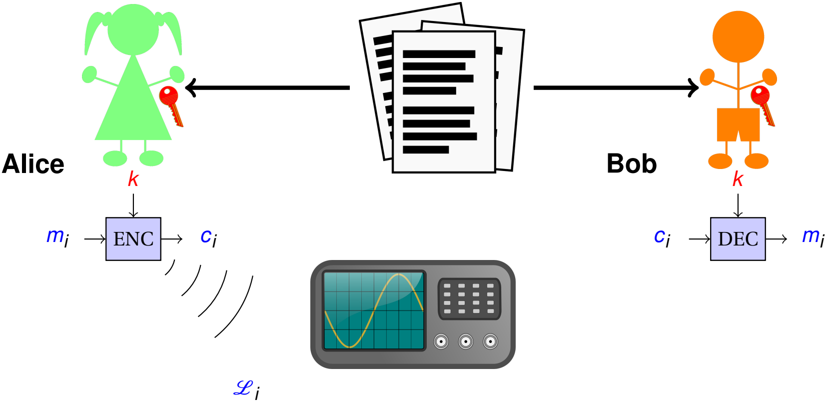
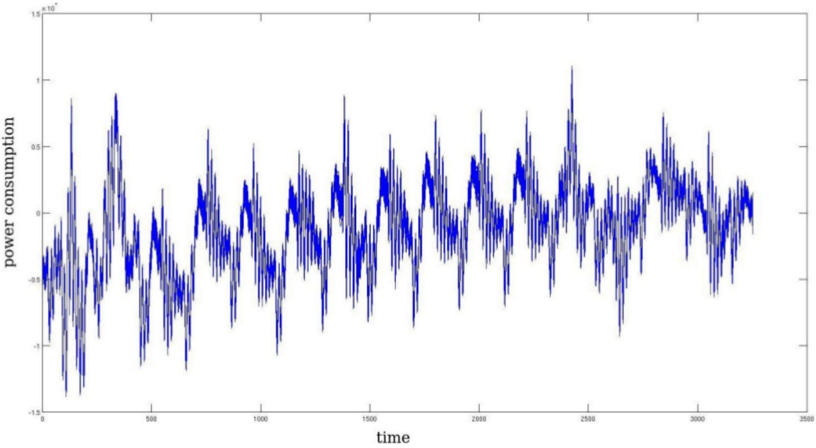


A power-analysis attack against AES-128



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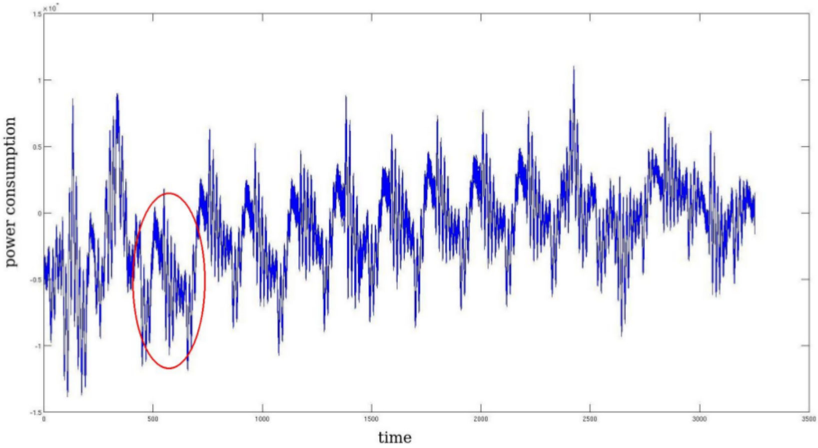

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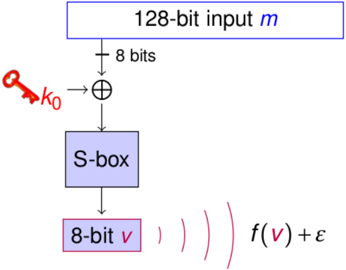
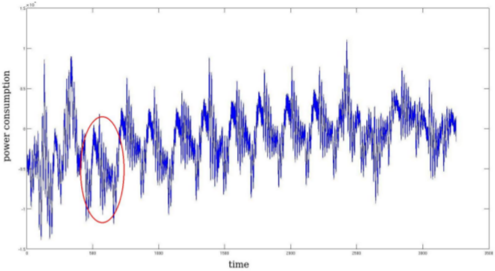
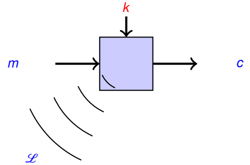




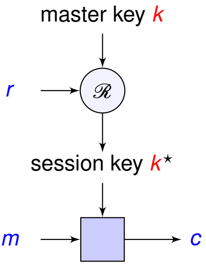
Algorithmic Countermeasures



Problem: leakage $\mathscr{L}$ is key-dependent

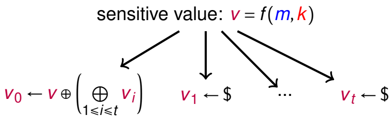
Fresh Re-keying

Idea: regularly change k



Masking

Idea: make leakage $\mathscr{L}$ random



➜ each t-uple of v_i is independent from v

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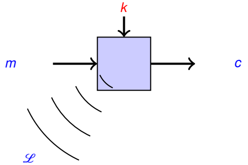

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Masking

Idea: make leakage $\mathscr{L}$ random

sensitive value: $v = f(m, k)$

$$v_0 \leftarrow v \oplus \left(\bigoplus_{1 \leqslant i \leqslant t} v_i \right) \qquad v_1 \leftarrow \$ \qquad \cdots \qquad v_t \leftarrow \$$$

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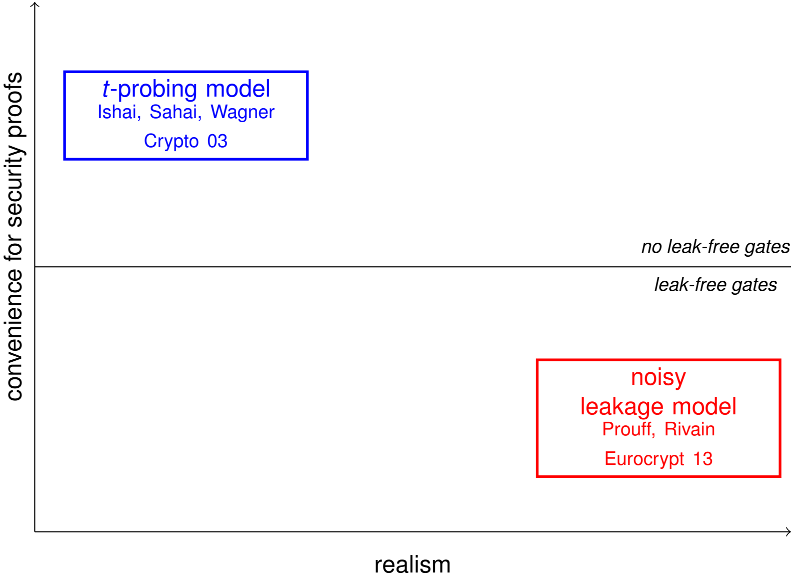
Security of Masked Programs: Leakage Model



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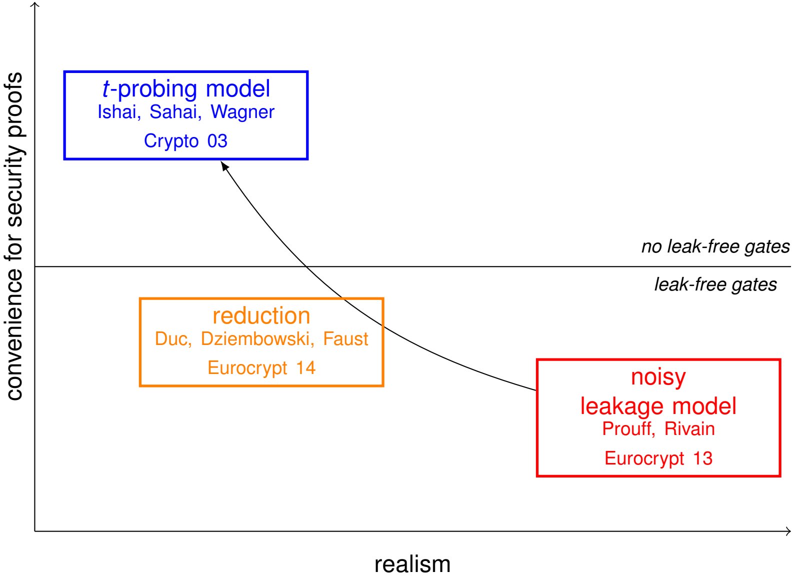
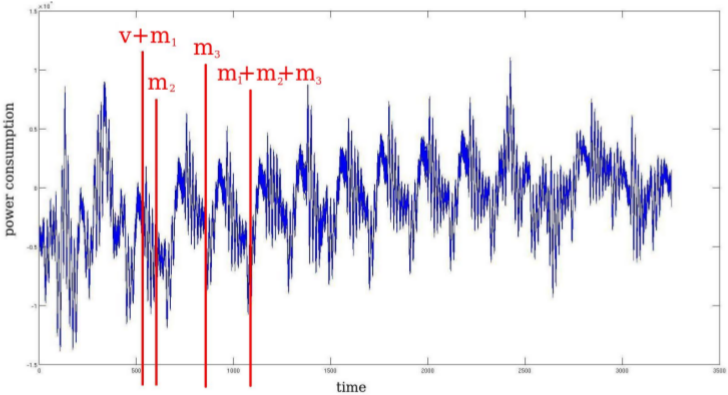


Security in the t-probing model

t-probing model assumptions:

- only one variable is leaking at a time
- the attacker can get the exact value of at most t variables

Secure if all the t-uples are independent from the secret.



Security in the t-probing model

- v: randomly generated variable
- c: known constant
- x: secret variable

function Ex-t3(x_1, x_2, x_3, x_4, c):

(* $x_1, x_2, x_3 = \$$ *)
(* $x_4 = x + x_1 + x_2 + x_3$ *)

$$
\begin{aligned}
r_1 &\leftarrow \$ \\
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2. test 286 3-uples

✘ missing cases

✘ inefficient

Security in the t-probing model

Contributions:

1. new algorithm to decide whether a t-uple is independent from the secret
   - no false positive
   - more efficient than existing works
2. new algorithm to enumerate all the t-uples
   - more efficient than existing works

Gilles Barthe, Sonia Belaïd, François Dupressoir, Pierre-Alain Fouque, Benjamin Grégoire, and Pierre-Yves Strub.
Verified proofs of higher-order masking. EUROCRYPT 2015.

1. Show that a t-uple is independent from the secret

Inputs: t intermediate variables, $b \leftarrow \text{true}$

(Rule 1) secret variables?

yes ➜ (Rule 2)

no ➜ ✔

(Rule 2) an expression v is invertible in the only occurrence of a random r?

yes ➜ $v \leftarrow r$; (Rule 1)

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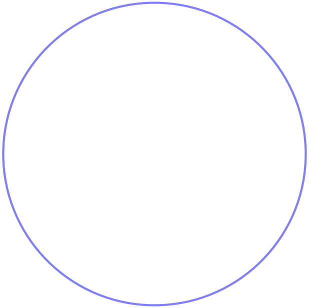

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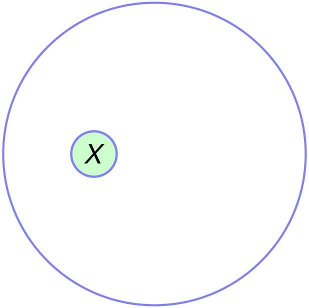

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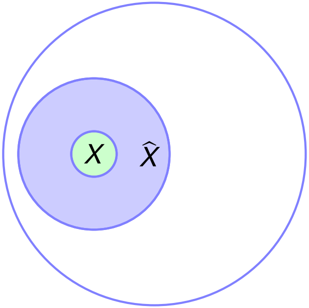

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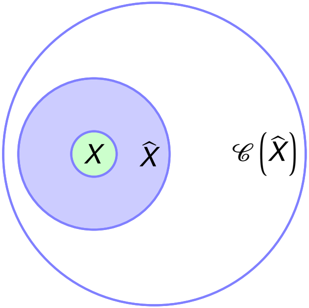

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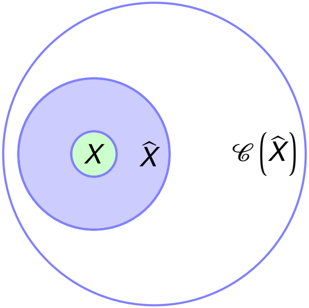

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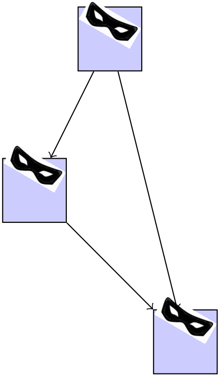
4. merge $\widehat{X}$ and $\mathscr{C}\left(\widehat{X}\right)$ once they are processed separately.

Benchmarks

Reference	Target	# tuples	Security	Complexity # sets	Complexity time (s)
First-Order Masking					
FSE13	full AES	17,206	✔	3,342	128
MAC-SHA3	full Keccak-f	13,466	✔	5,421	405
Second-Order Masking					
RSA06	Sbox	1,188,111	✔	4,104	1.649
CHES10	Sbox	7,140	1^{st}-order flaws (2)	866	0.045
CHES10	AES KS	23,041,866	✔	771,263	340,745
FSE13	2 rnds AES	25,429,146	✔	511,865	1,295
FSE13	4 rnds AES	109,571,806	✔	2,317,593	40,169
Third-Order Masking					
RSA06	Sbox	2,057,067,320	3^{rd}-order flaws (98,176)	2,013,070	695
FSE13	Sbox(4)	4,499,950	✔	33,075	3.894
FSE13	Sbox(5)	4,499,950	✔	39,613	5.036
Fourth-Order Masking					
FSE13	Sbox (4)	2,277,036,685	✔	3,343,587	879
Fifth-Order Masking					
CHES10	⊙	216,071,394	✔	856,147	45

*run on a headless VM with a dual core (only one core is used in the computation) 64-bit processor clocked at 2GHz

Current Issues in Composition



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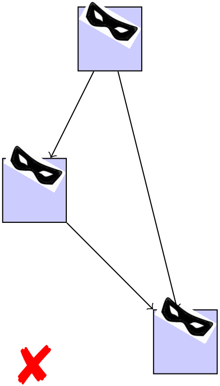

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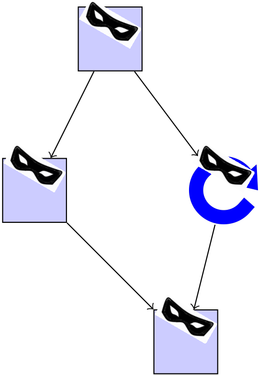

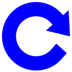

A refresh algorithm takes as input a sharing $(x_i)_{i\geq 0}$ *of* x *and returns a new sharing* $(x'_i)_{i\geq 0}$ *of* x *such that* $(x_i)_{i\geq 1}$ *and* $(x'_i)_{i\geq 1}$ *are mutually independent.*

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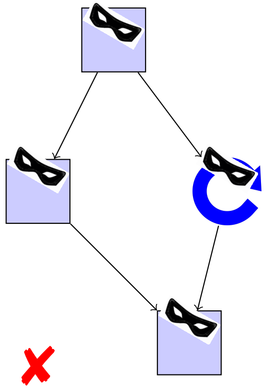
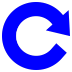
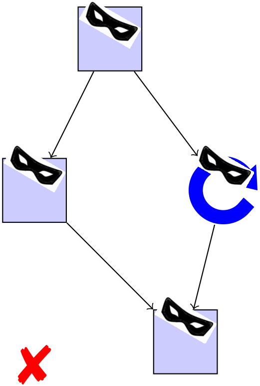
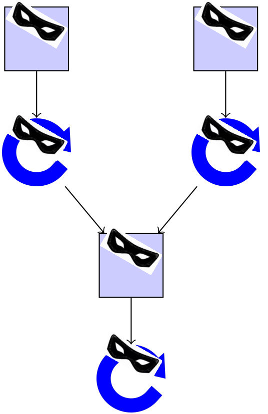


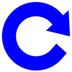


A refresh algorithm takes as input a sharing $(x_i)_{i\geq 0}$ of x and returns a new sharing $(x'_i)_{i\geq 0}$ of x such that $(x_i)_{i\geq 1}$ and $(x'_i)_{i\geq 1}$ are mutually independent.

Current Issues in Composition







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Composition in the t-probing model

Contributions:

1. new algorithm to verify the security of compositions
   - formal security
   - any order
2. compiler to build a higher-order secure from any C implementation
   - efficient
   - any order

Gilles Barthe, Sonia Belaïd, François Dupressoir, Pierre-Alain Fouque, Benjamin Grégoire, Pierre-Yves Strub, and Rebecca Zucchini.
Strong Non-Interference and Type-Directed Higher-Order Masking. CCS 2016.

Security properties in the t-probing model

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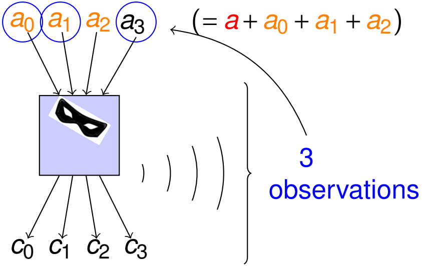
- if t is fixed: show that any set of t intermediate variables is independent from the secret
- if t is not fixed: show that any set of t intermediate variables can be simulated with at most t shares of each input



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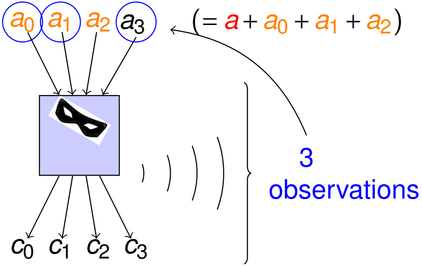

function Linear-function-t($a_0, \ldots, a_i, \ldots a_t$):

for $i = 0$ to t

$c_i \leftarrow f(a_i)$

return $(c_0, \ldots, c_i, \ldots, c_t)$

➜ straightforward for linear functions

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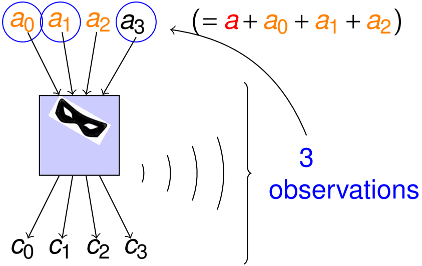

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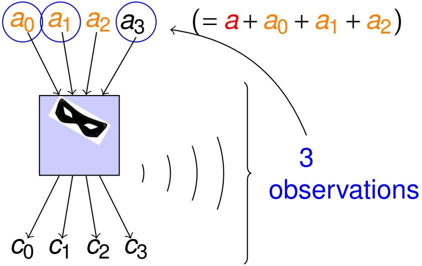

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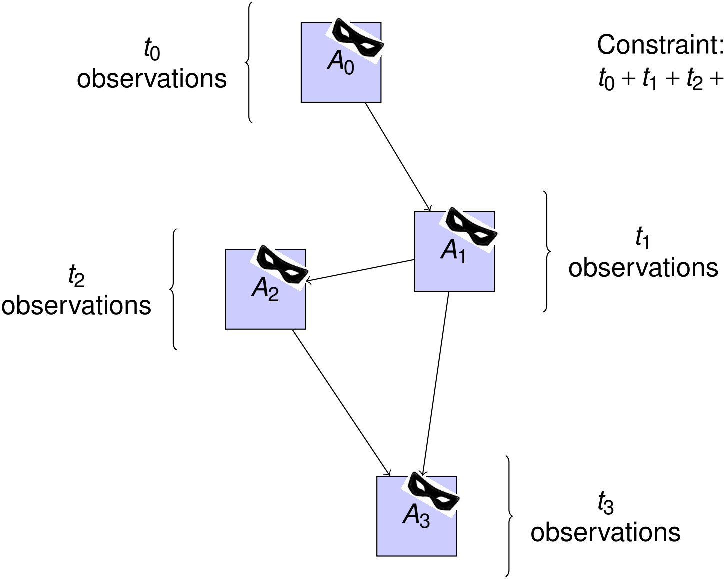
- ➜ straightforward for linear functions
- ➜ formal proofs with EasyCrypt and pen-and paper proofs for small non-linear functions

Current Issues

Constraint:
$t_0 + t_1 + t_2 + t_3 \leqslant t$



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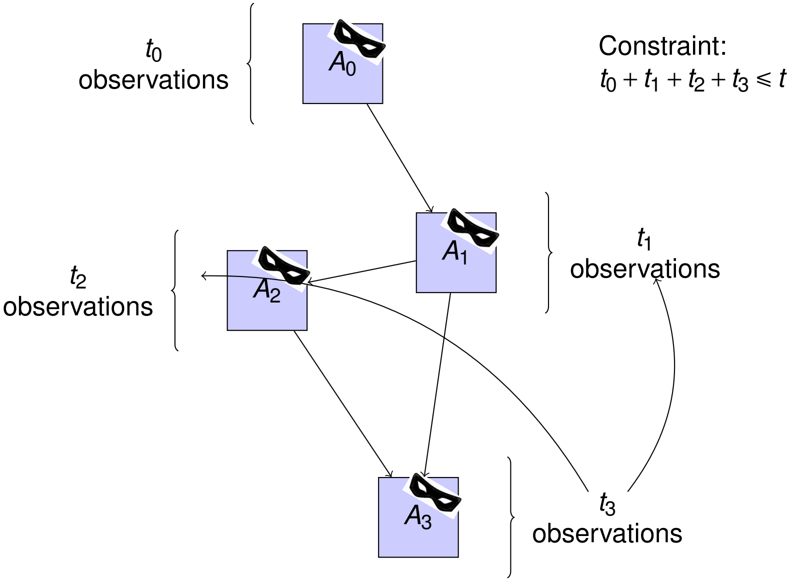

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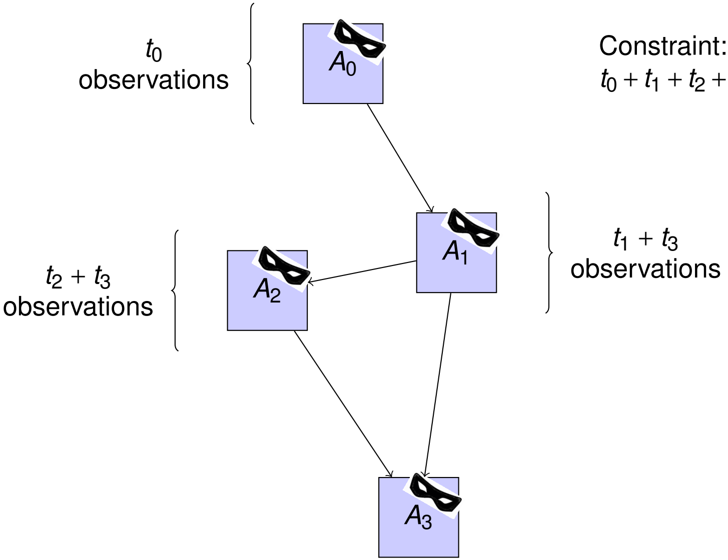

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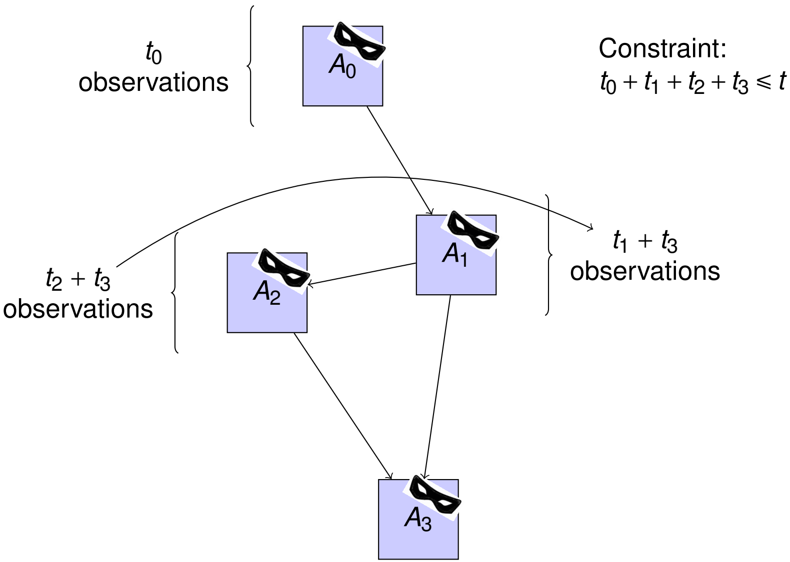

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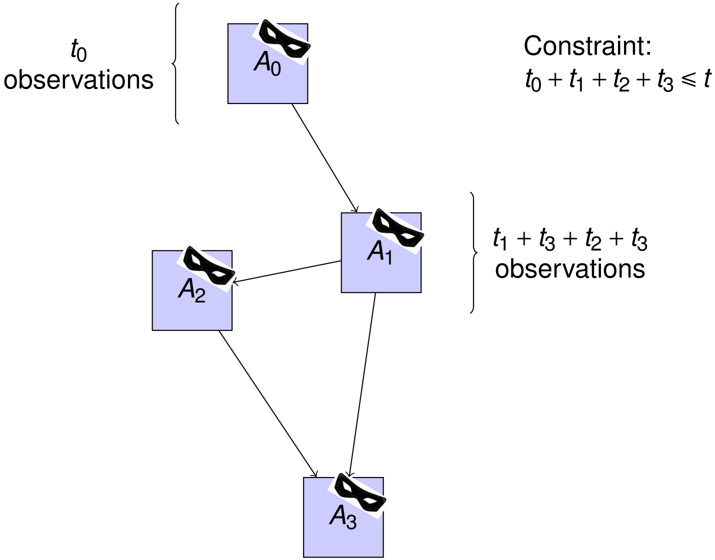

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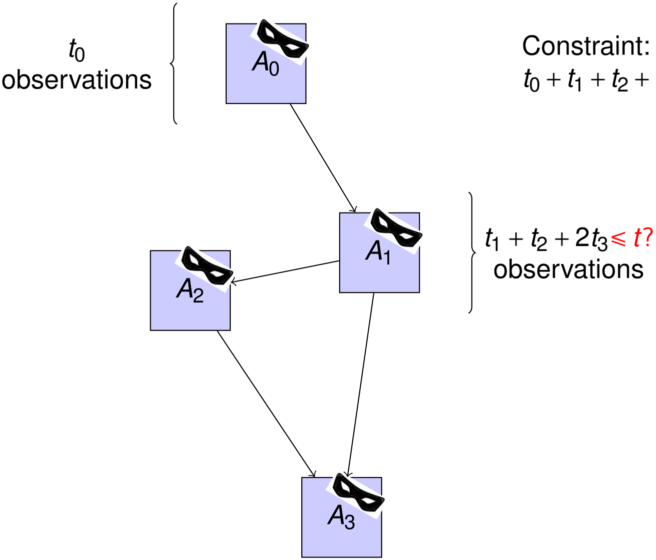
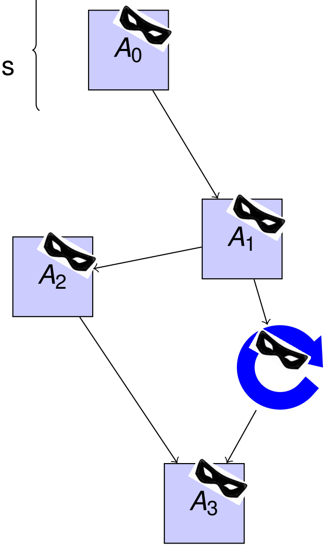


Constraint:
$t_0 + t_1 + t_2 + t_3 \leqslant t$

Current Issues

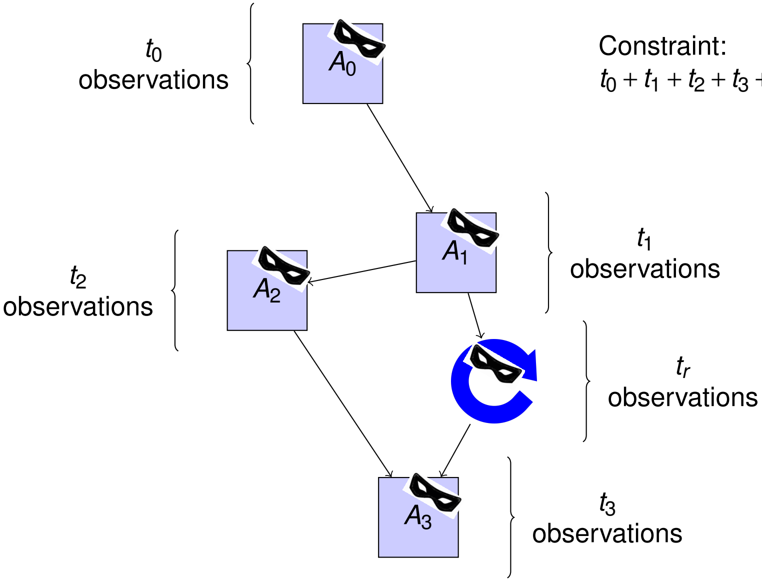
t_0
observations



Constraint:
$t_0 + t_1 + t_2 + t_3 \leqslant t$

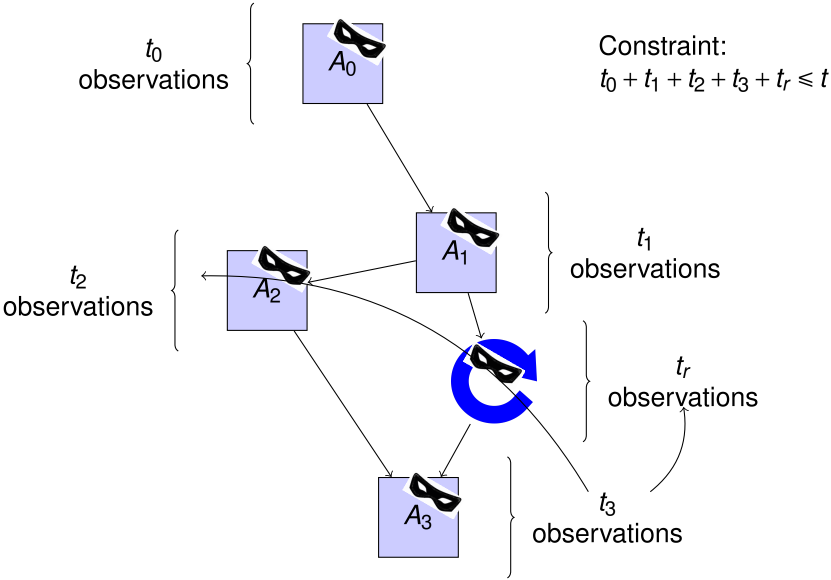
$t_1 + t_2 + 2t_3 \leqslant t?$
observations

Current Issues



Constraint:
$t_0 + t_1 + t_2 + t_3 + t_r \leqslant t$

Current Issues



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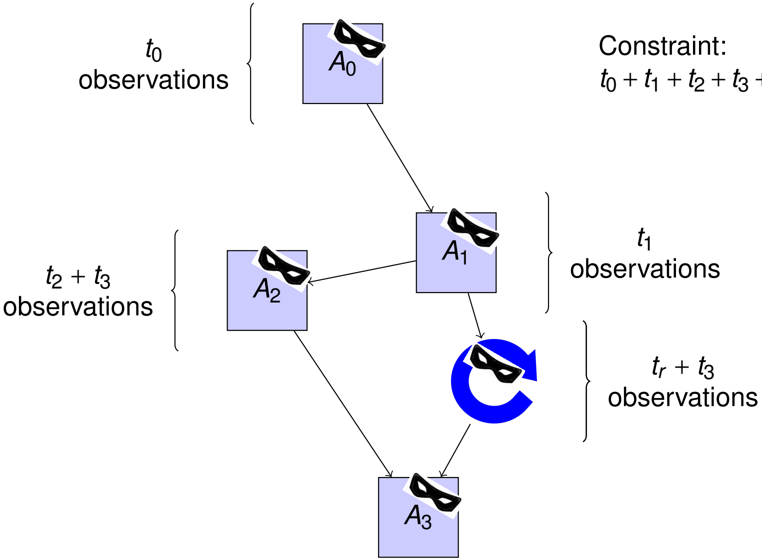

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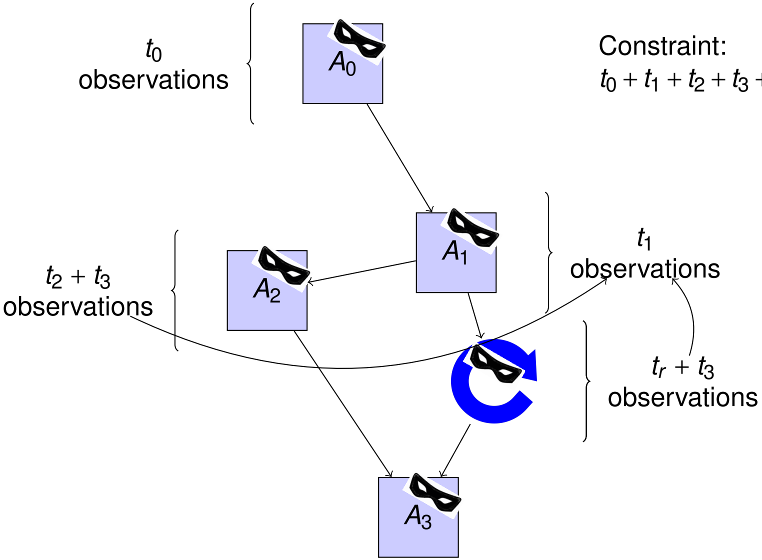
Current Issues



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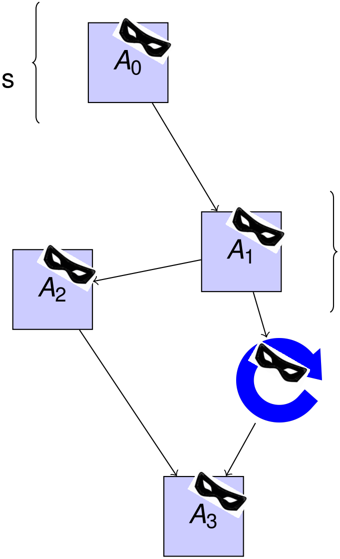
Current Issues

t_0
observations



Constraint:
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$t_1 + t_2 + 2t_3 + t_r \leqslant t?$
observations

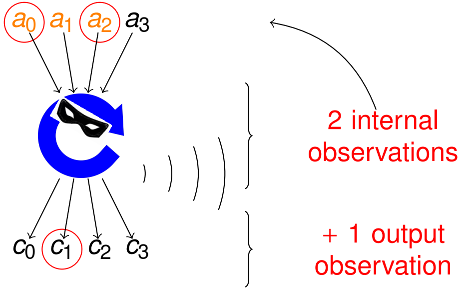
Stronger security property for Refresh

Strong Non-Interference in the t-probing model:

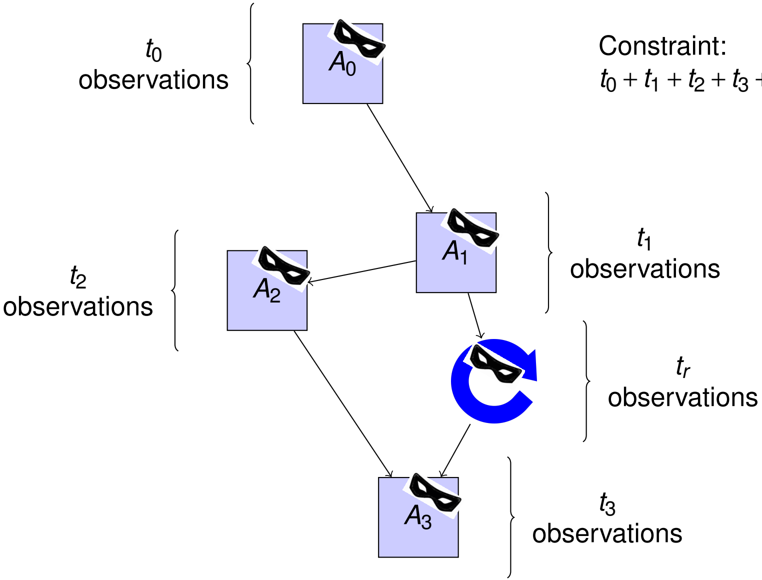
if t is not fixed: show that any set of t intermediate variables with

- t_1 on internal variables
- $t_2 = t - t_1$ on the outputs

can be simulated with at most t_1 shares of each input



Secure Composition



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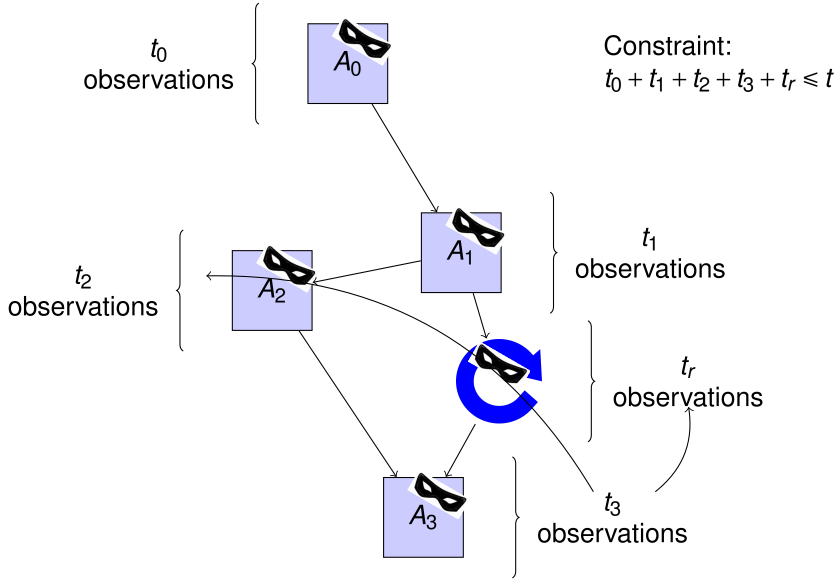
Secure Composition



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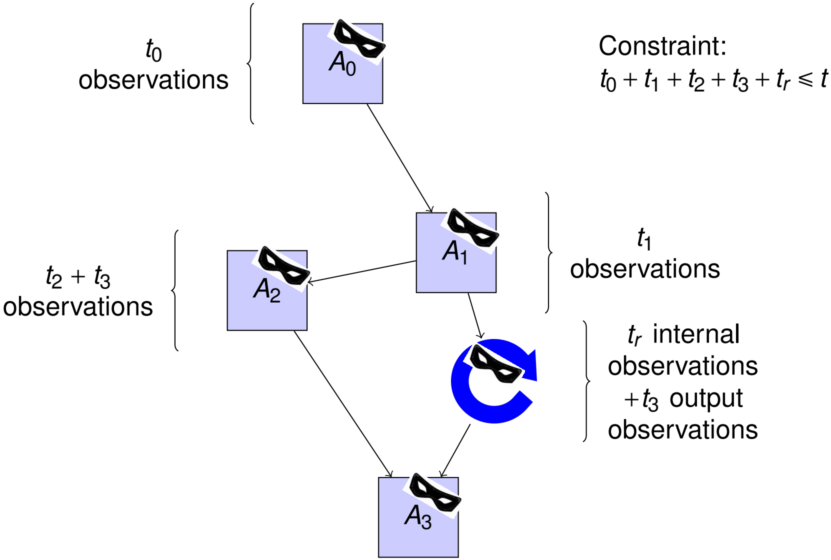

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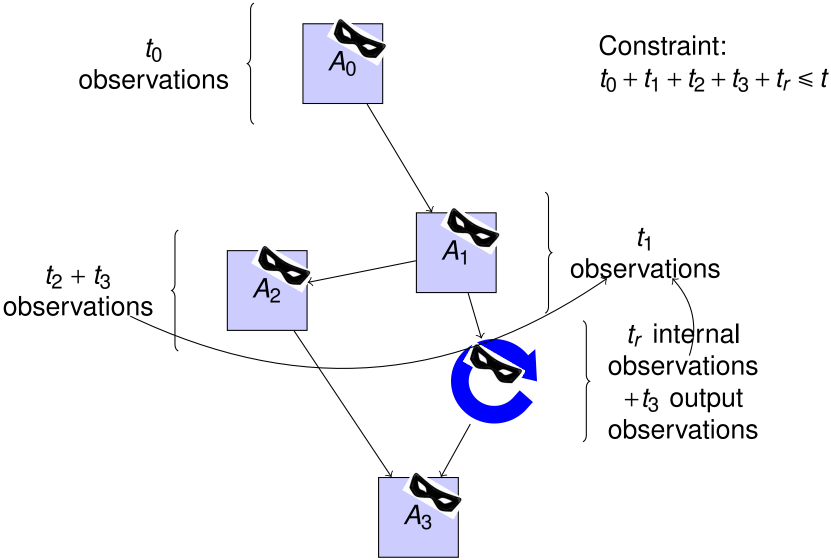

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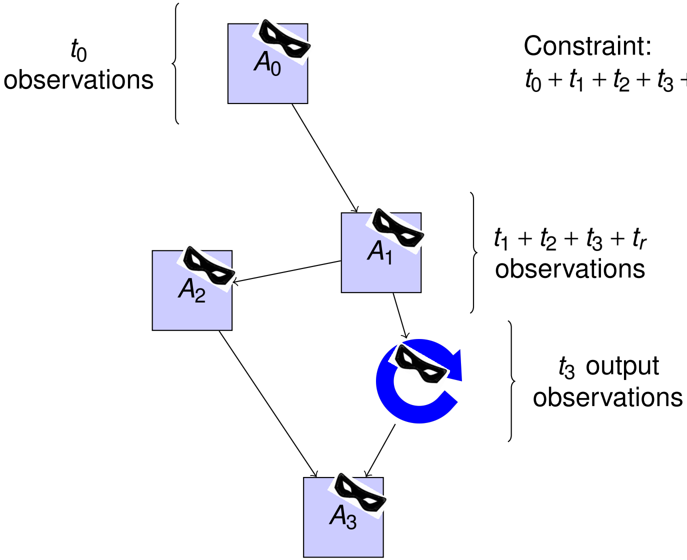

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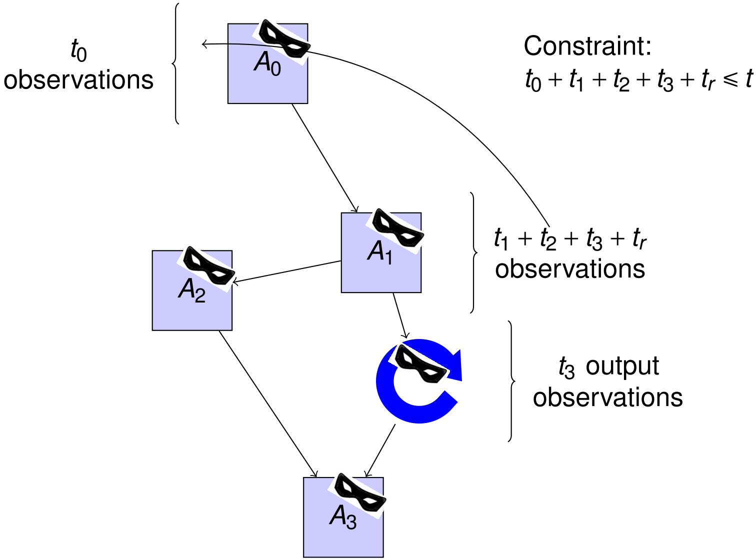
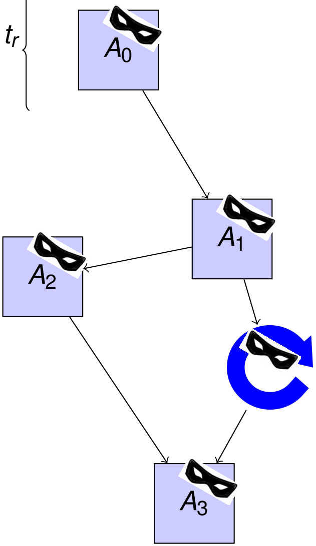


Secure Composition

$t_0 + t_1 + t_2 + t_3 + t_r$ observations

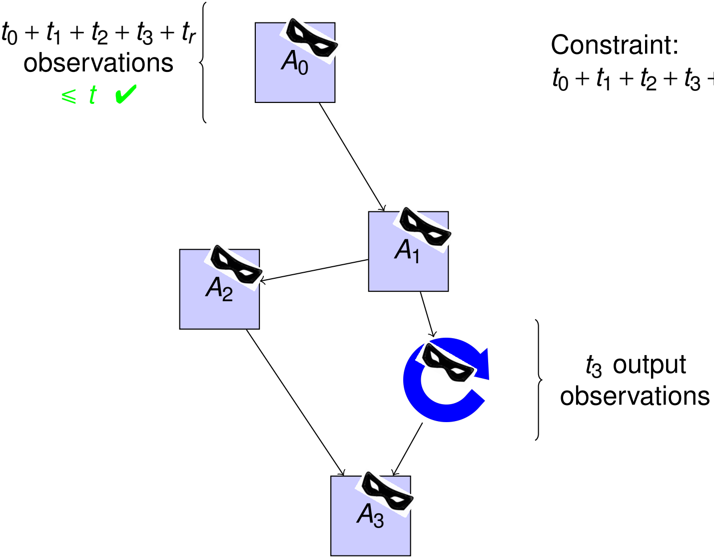
Constraint:

$t_0 + t_1 + t_2 + t_3 + t_r \leqslant t$



t_3 output observations

Secure Composition



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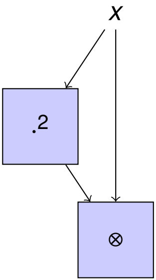
Secure Composition

Automatic tool for C-based algorithms

- unprotected algorithm ➜ higher-order masked algorithm
- example for AES S-box



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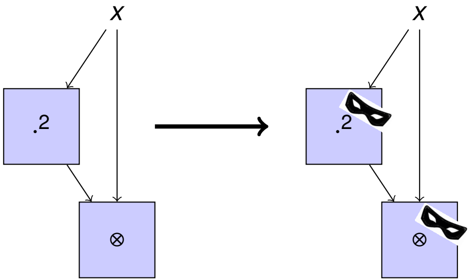

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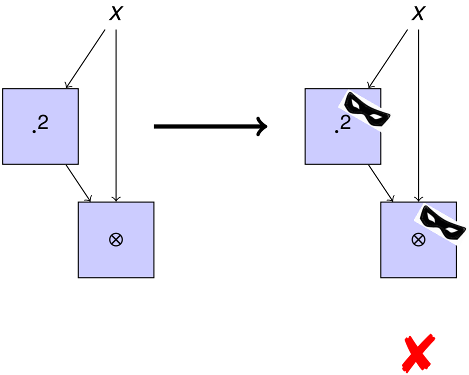

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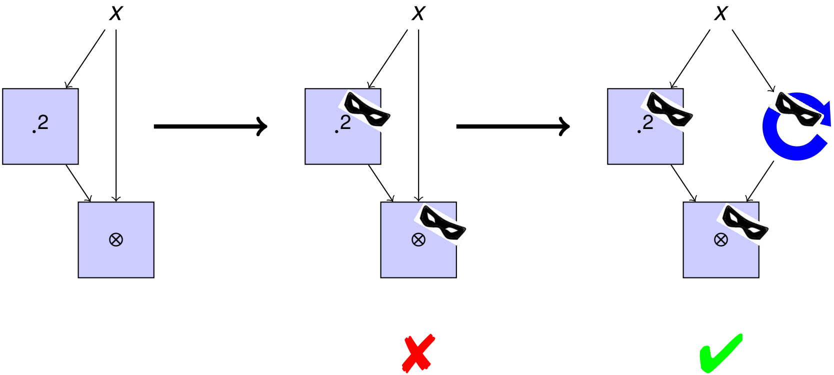

Some Results

Resource usage statistics for generating masked algorithms (at any order) from some unmasked implementations[1]

Scheme	# Refresh	Time	Memory
AES ($\odot$)	2	0.09s	4Mo
AES ($x \odot g(x)$)	0	0.05s	4Mo
Keccak with Refresh	0	121.20	456Mo
Keccak	600	2728.00s	22870Mo
Simon	67	0.38s	15Mo
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[1] On a Intel(R) Xeon(R) CPU E5-2667 0 @ 2.90GHz with 64Go of memory running Linux (Fedora)

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Conclusion

Summary

- ✔ verification of higher-order masking schemes
- ✔ efficient and proven composition
- ✔ two automatic tools

Further Work

- ➜ extend the verification to higher orders using composition
- ➜ integrate transition/glitch-based model
- ➜ build practical experiments for both attacks and new countermeasures

Conclusion

Cryptanalysis: Power-Analysis Attacks

- investigate the LPN algorithms in the context of power-analysis attacks
- analyze the operation modes

Cryptography: countermeasures against Power-Analysis Attacks

- implement and evaluate our countermeasures on real devices (software and hardware)
- make verifications and compositions as practical as possible
- use the characterization of a device as a leakage model