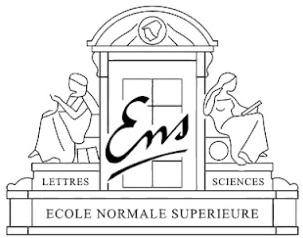


THALES

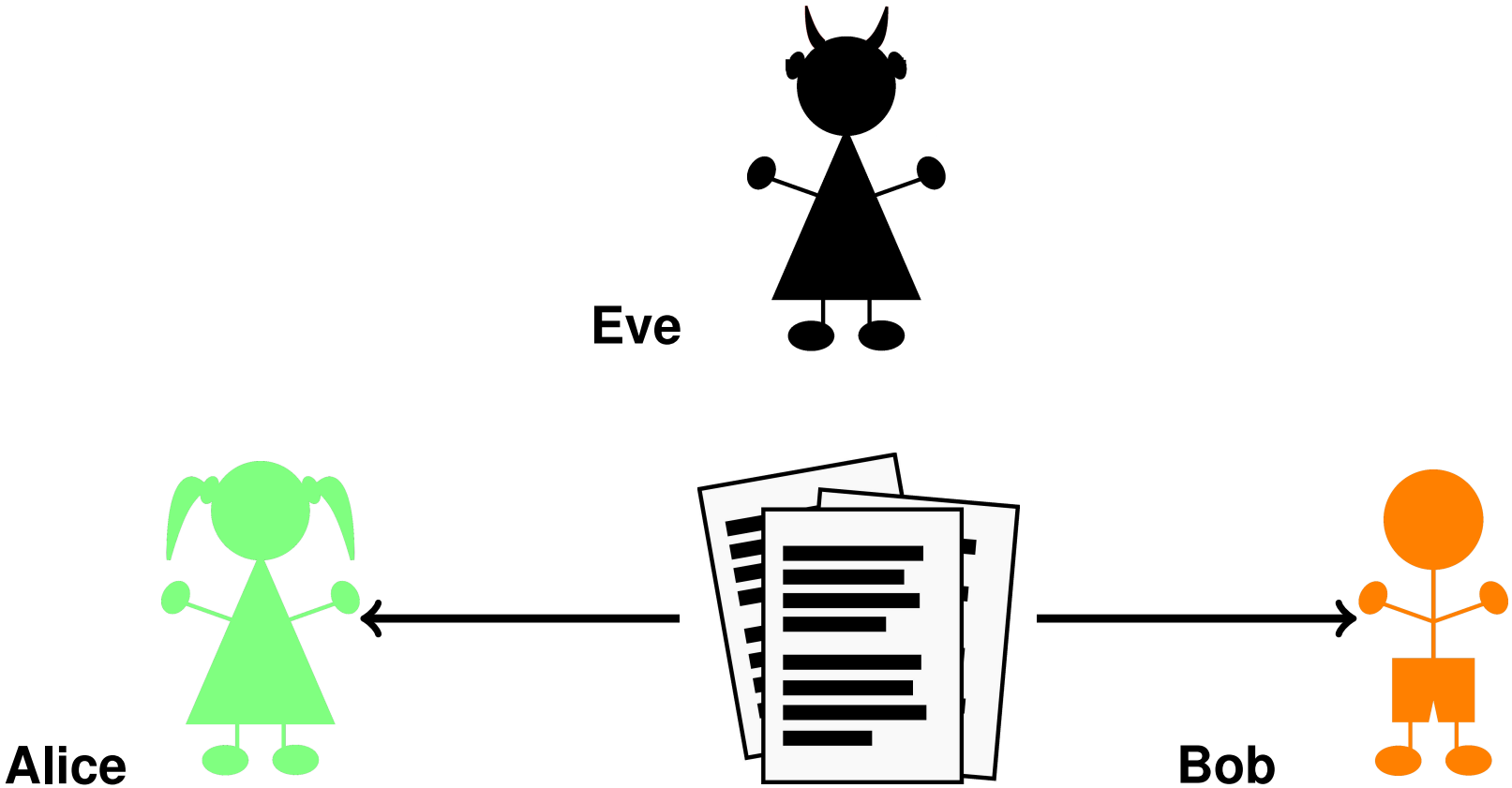
Security of Cryptosystems Against Power-Analysis Attacks

PhD Defense

October 22, 2015

Presented by Sonia Belaïd

Cryptology



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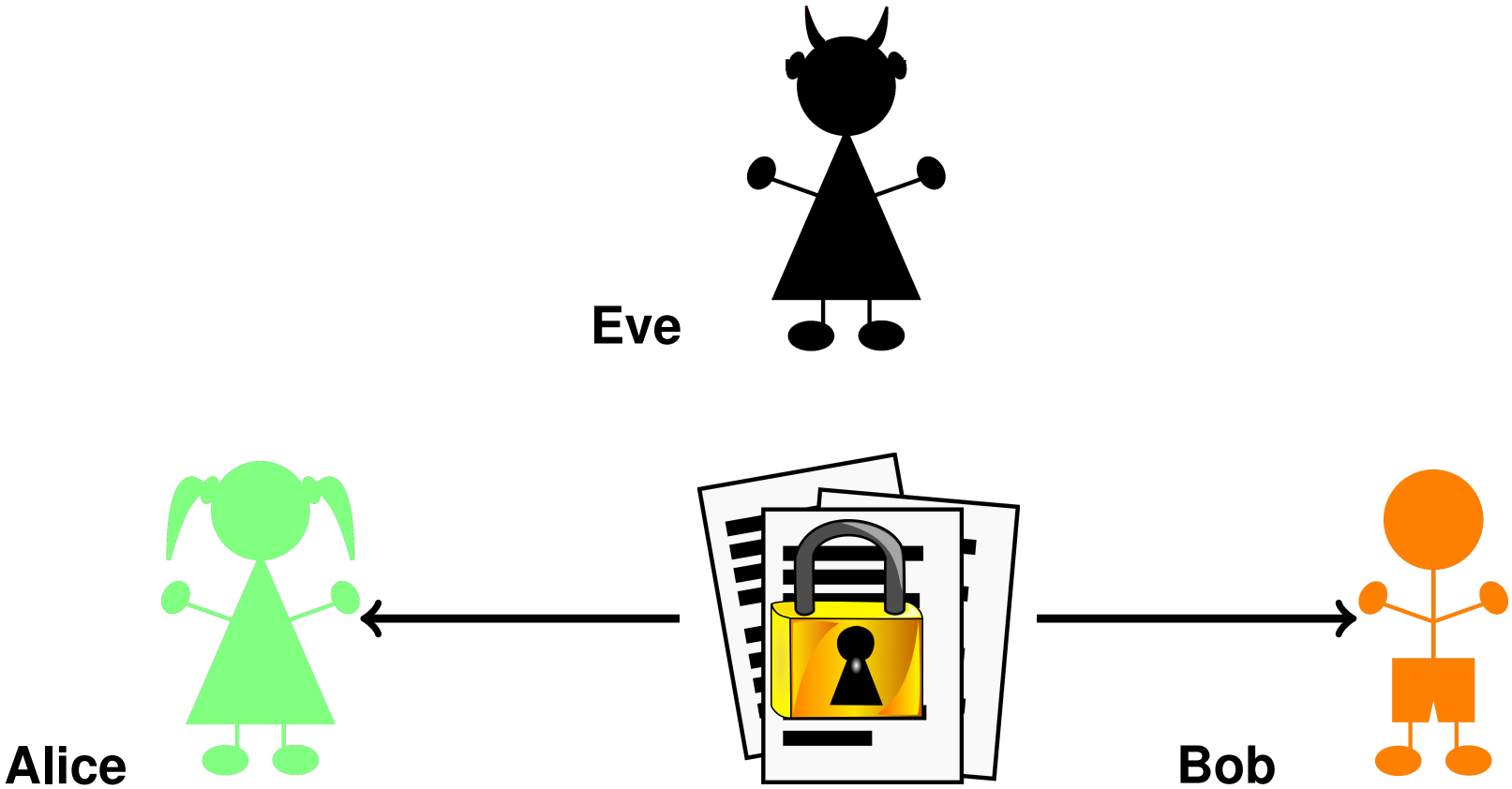
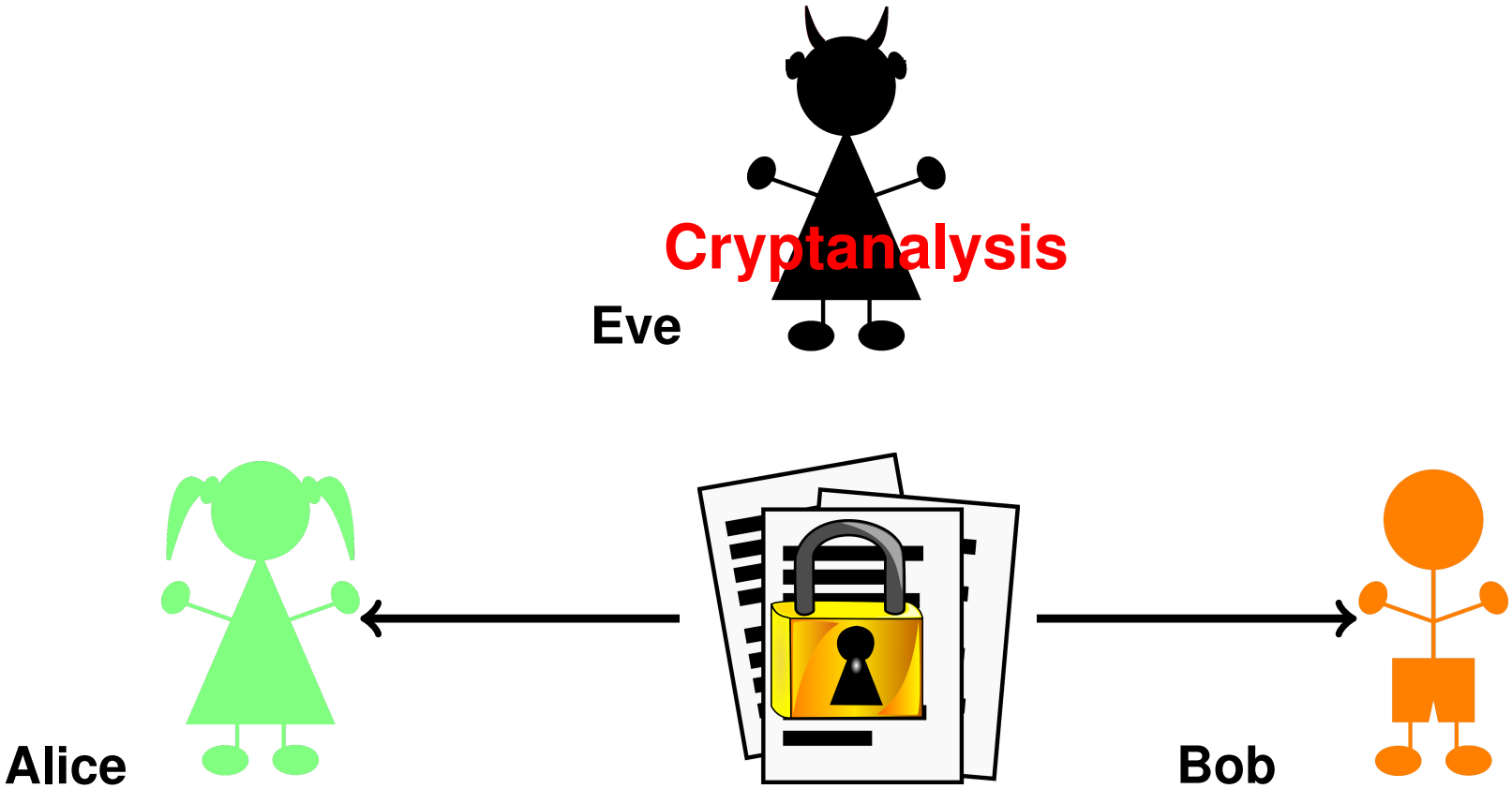


Cryptography

- ➜ Confidentiality
- ➜ Authentication
- ➜ Integrity

Cryptology



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- Asymmetric cryptography
- Symmetric cryptography

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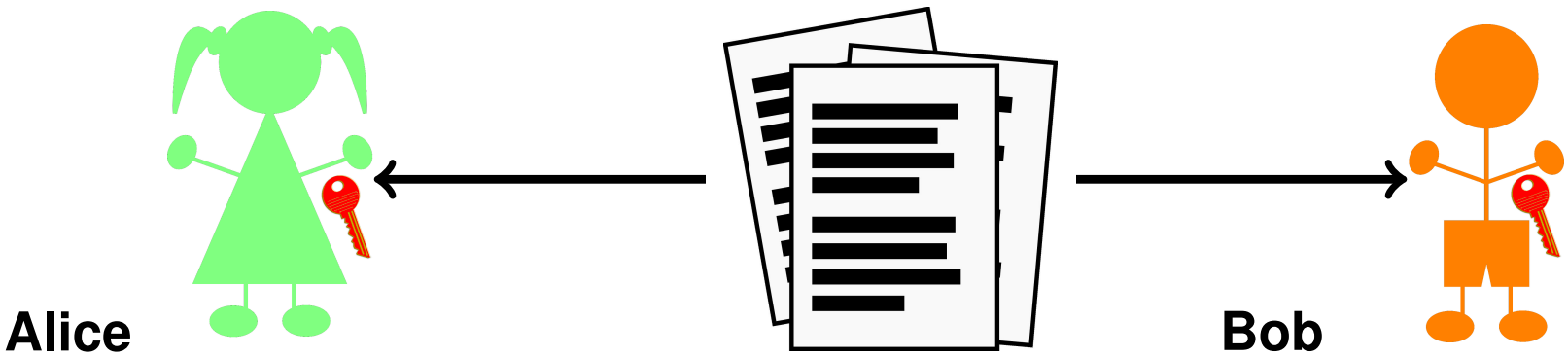

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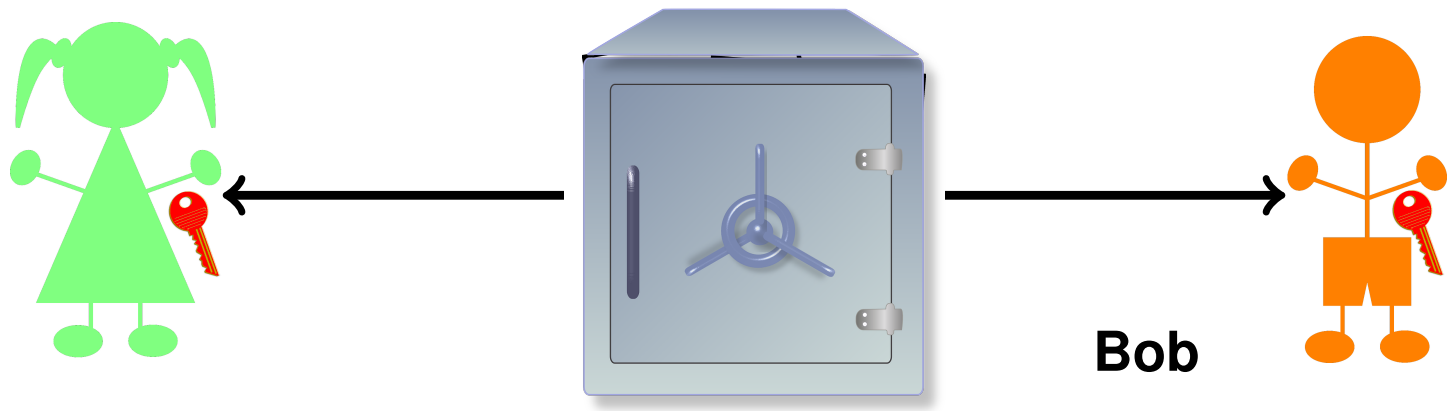

Cryptography is divided into

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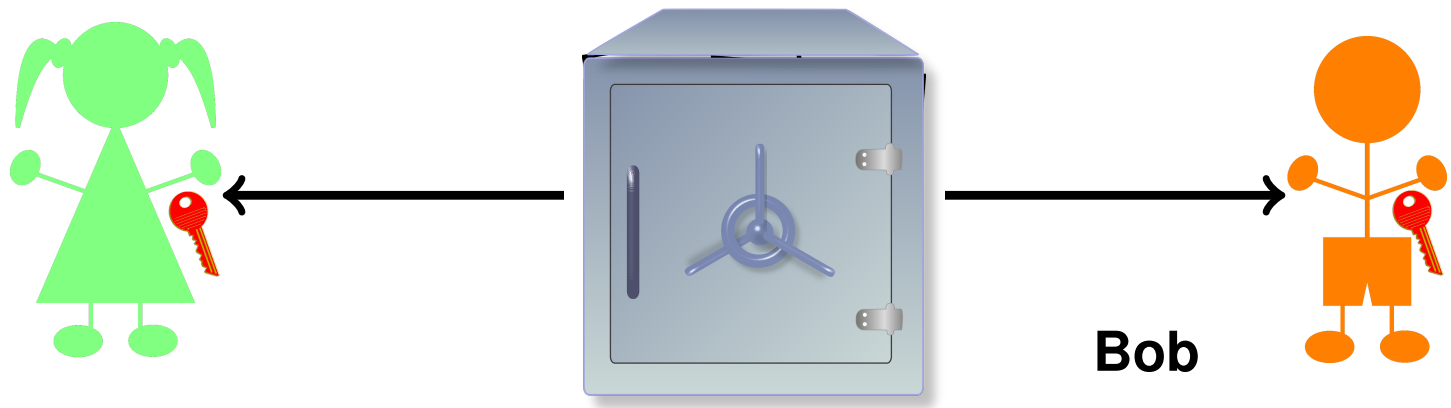
- Symmetric cryptography

c = ‘fbjdsiqfesarizom’



Alice

$m \leftarrow$ ‘Hello Bob’
$c \leftarrow \mathrm{ENC}_k(m)$

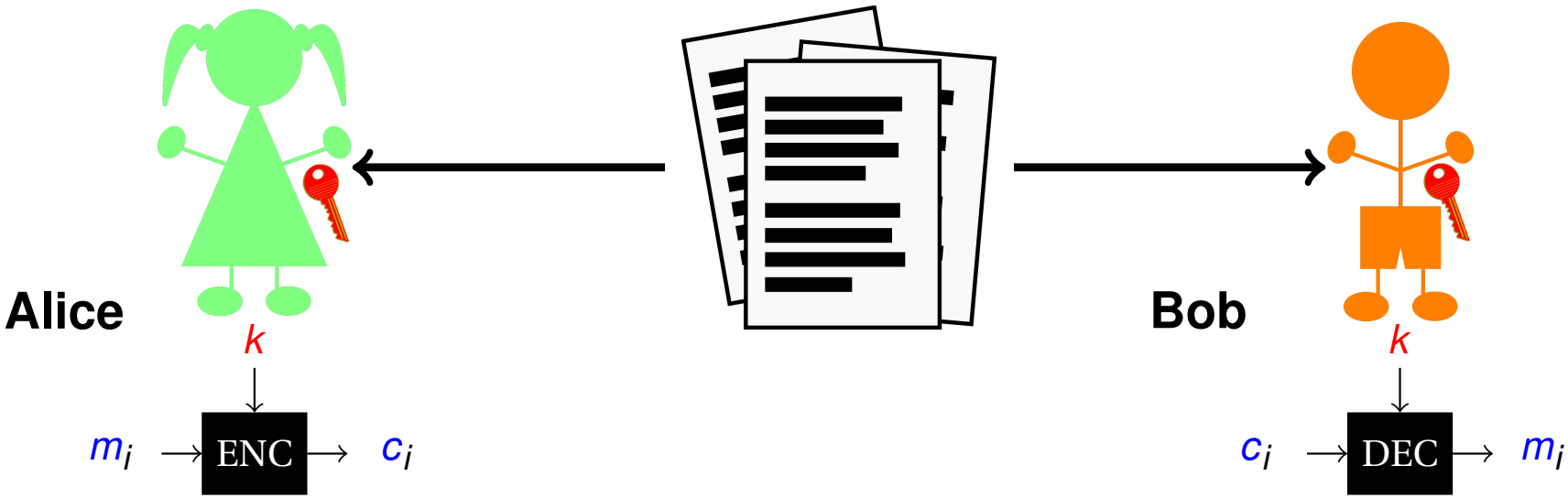
Bob

$m \leftarrow \mathrm{DEC}_k(c)$
$m =$ ‘Hello Bob’

Example: confidentiality with encryption

Cryptanalysis

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



Cryptanalysis

- ➜ Black-box cryptanalysis: $\mathscr{A} \leftarrow (m_i, c_i)$
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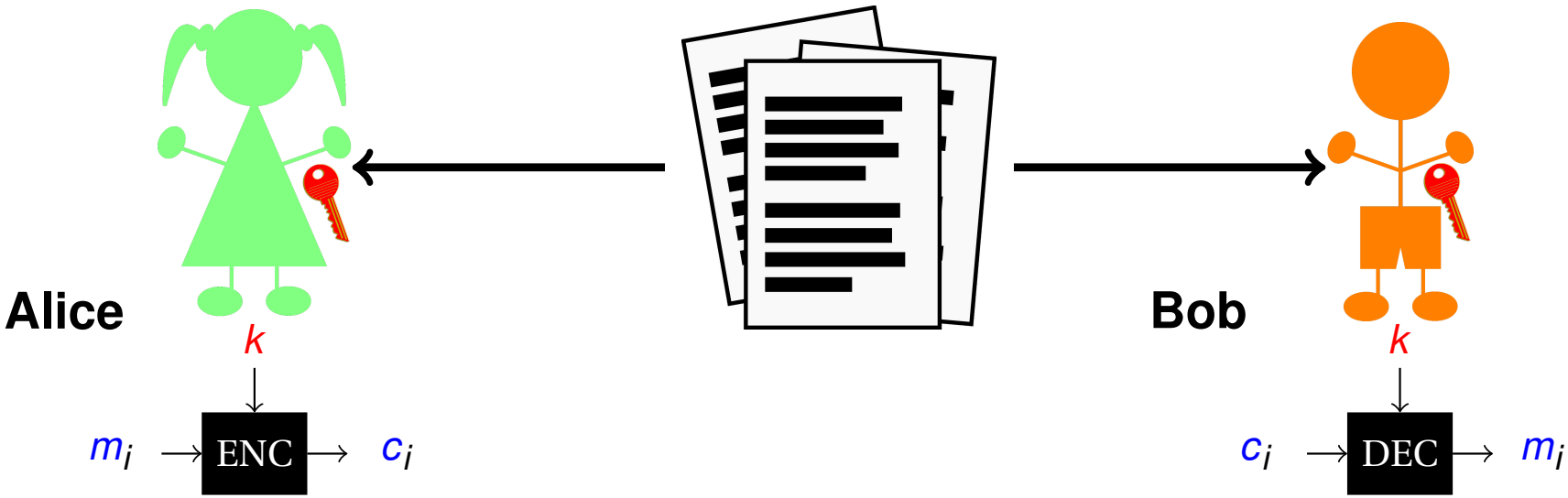
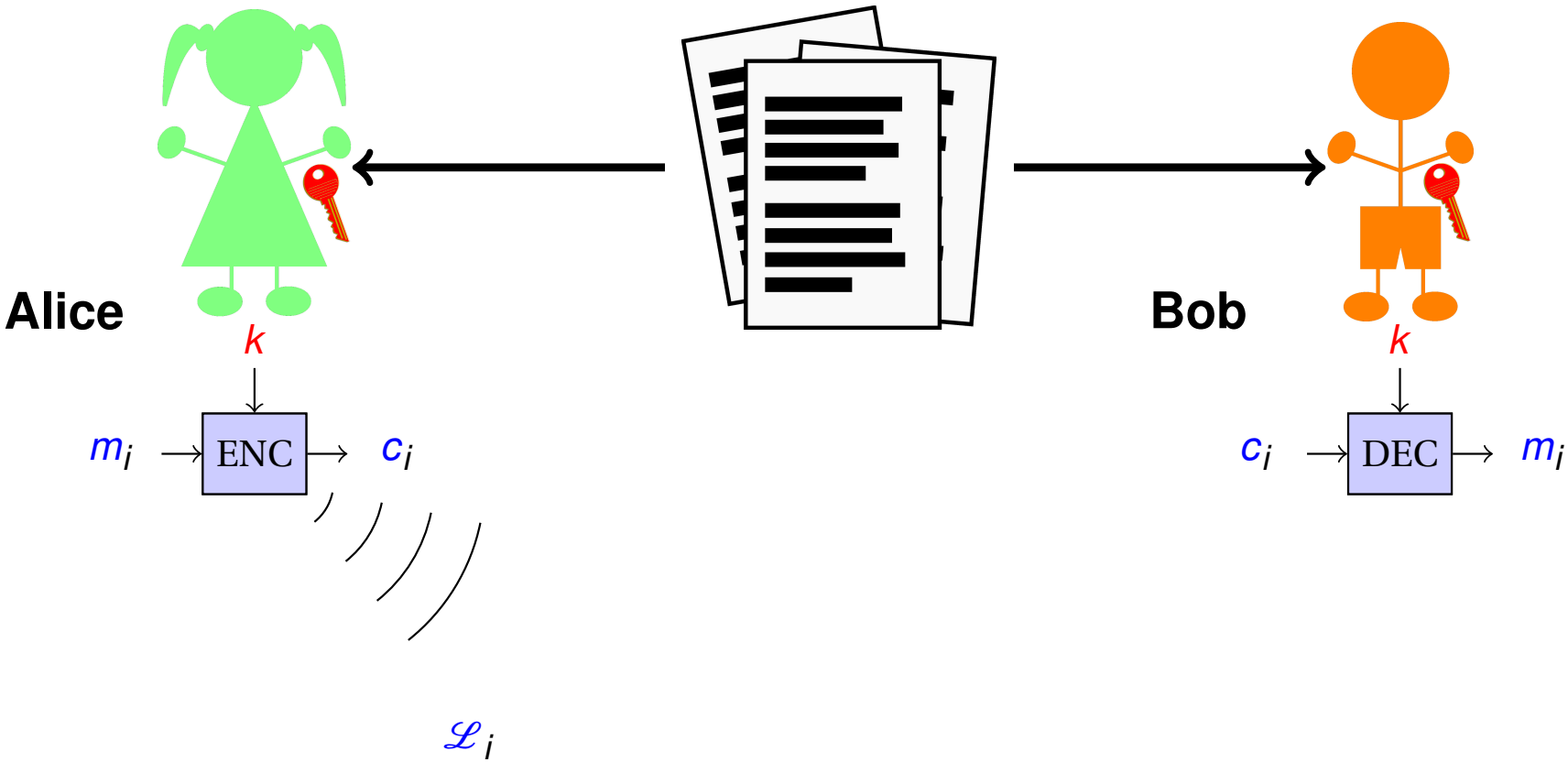


Cryptanalysis

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



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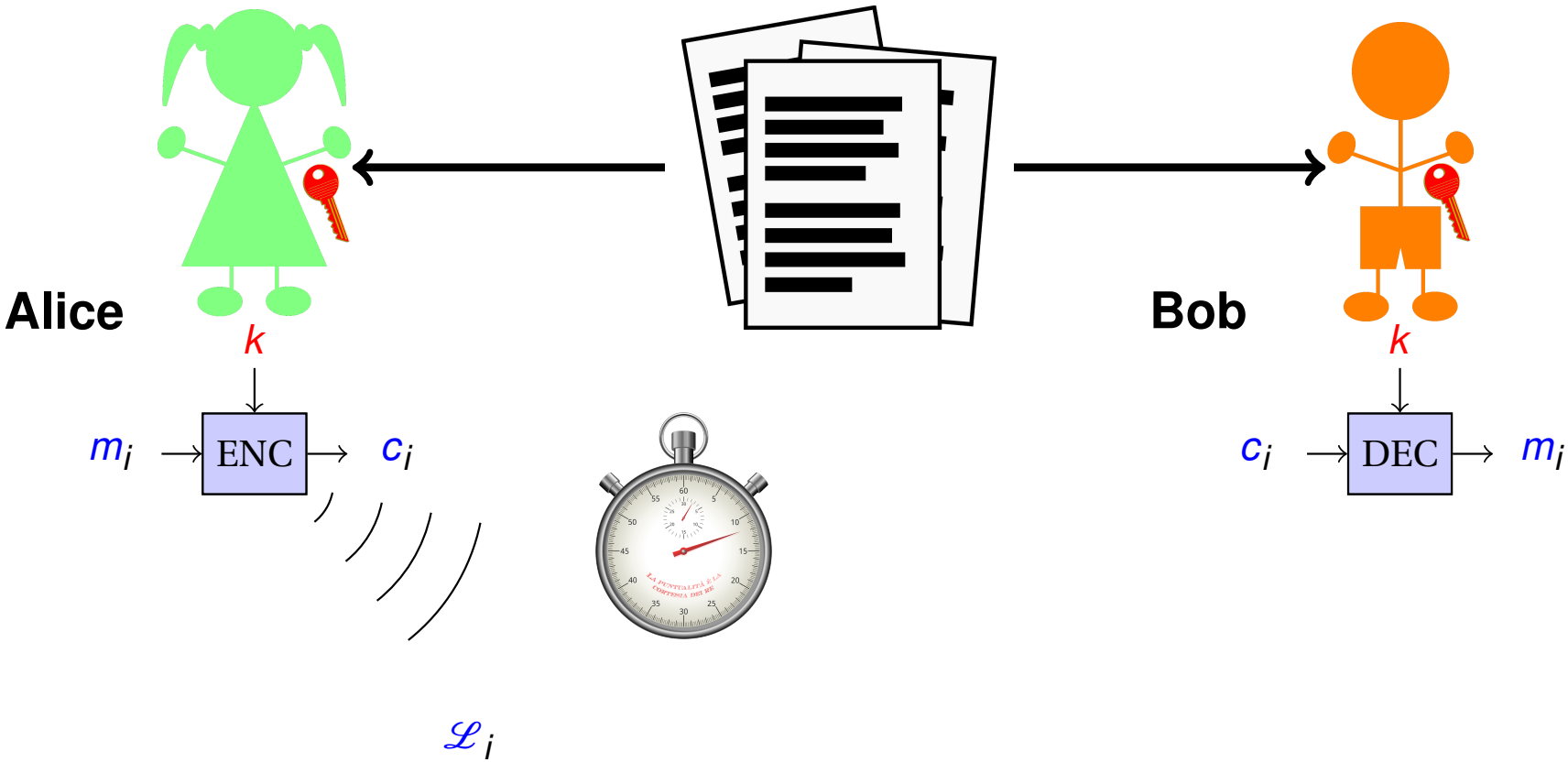

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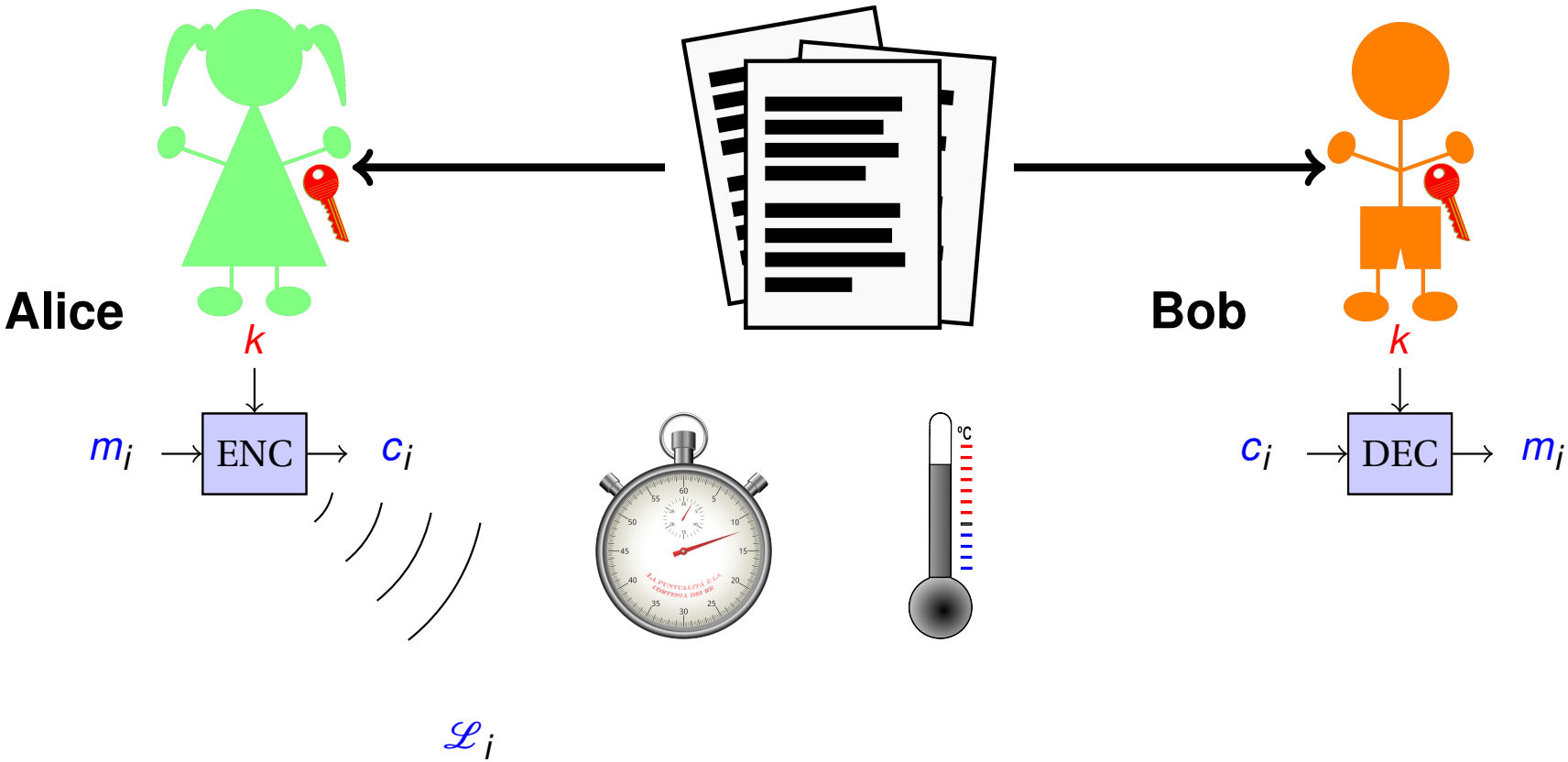

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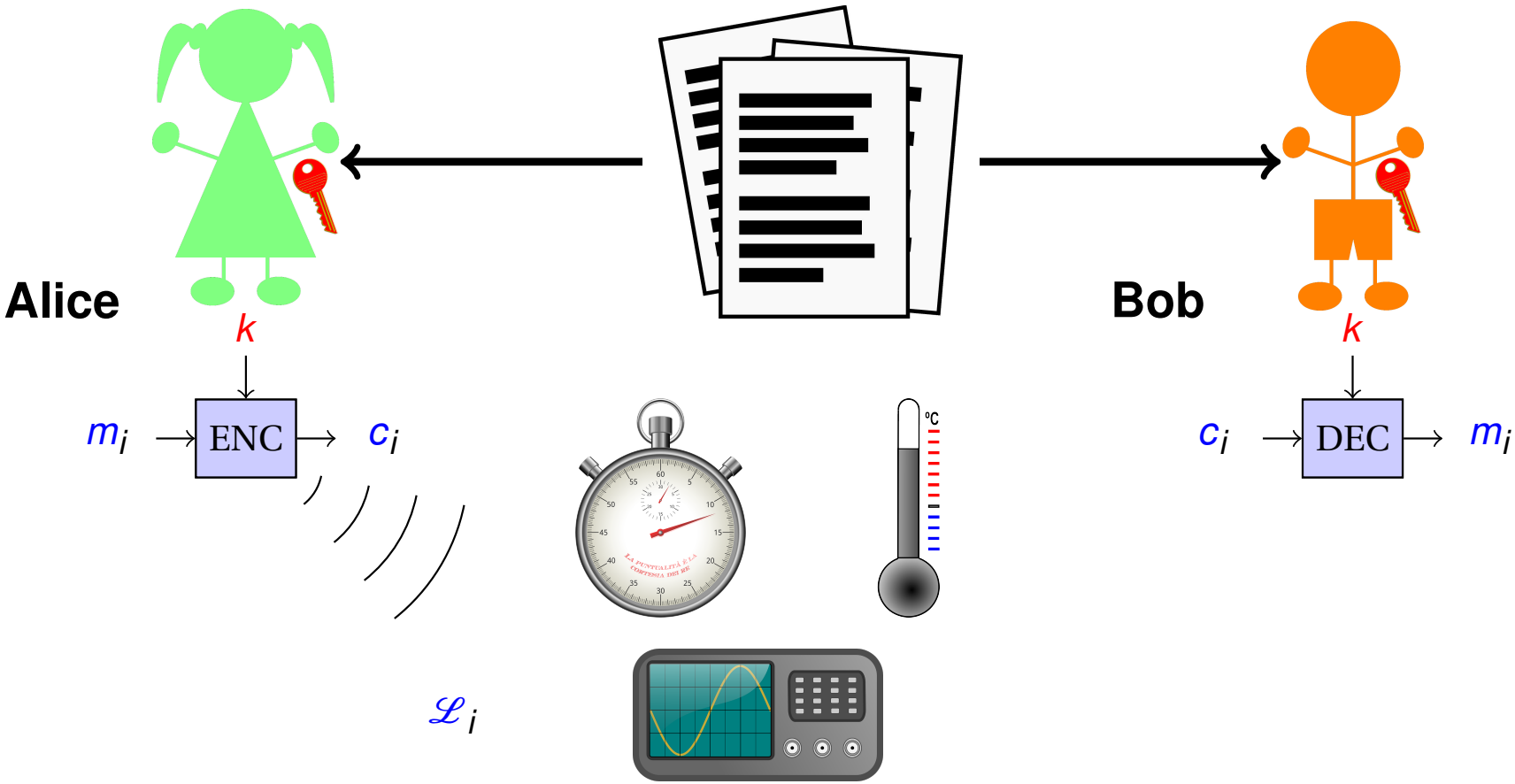

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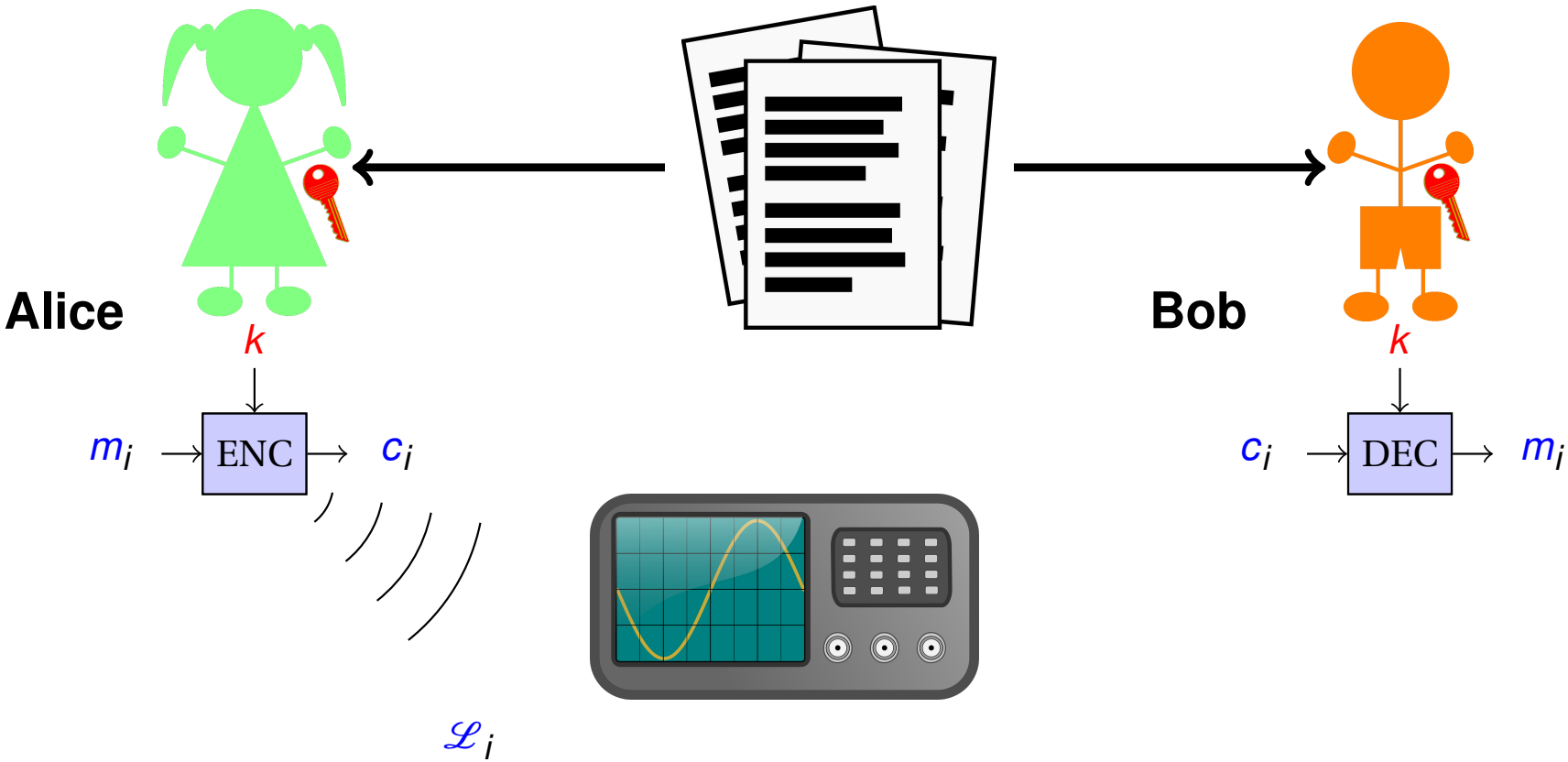
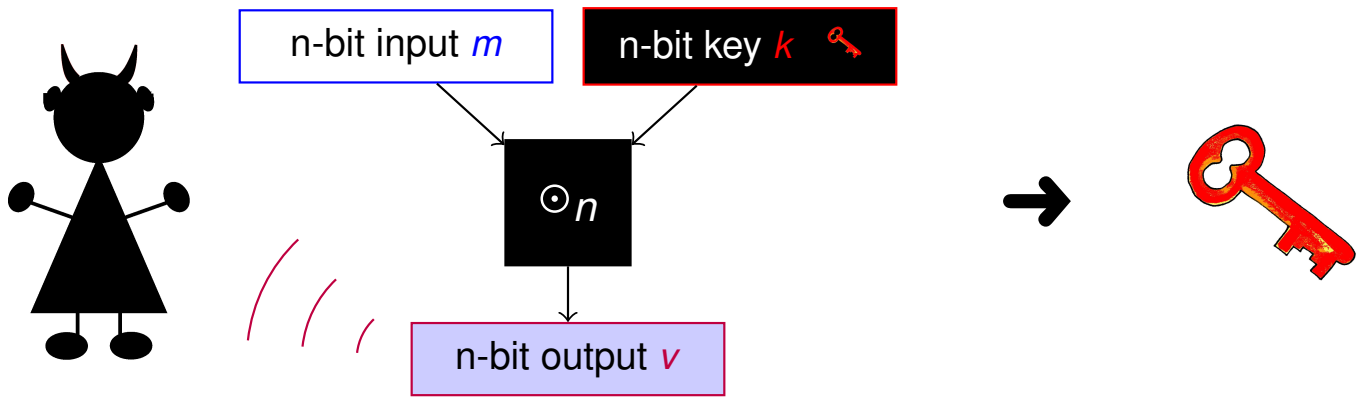
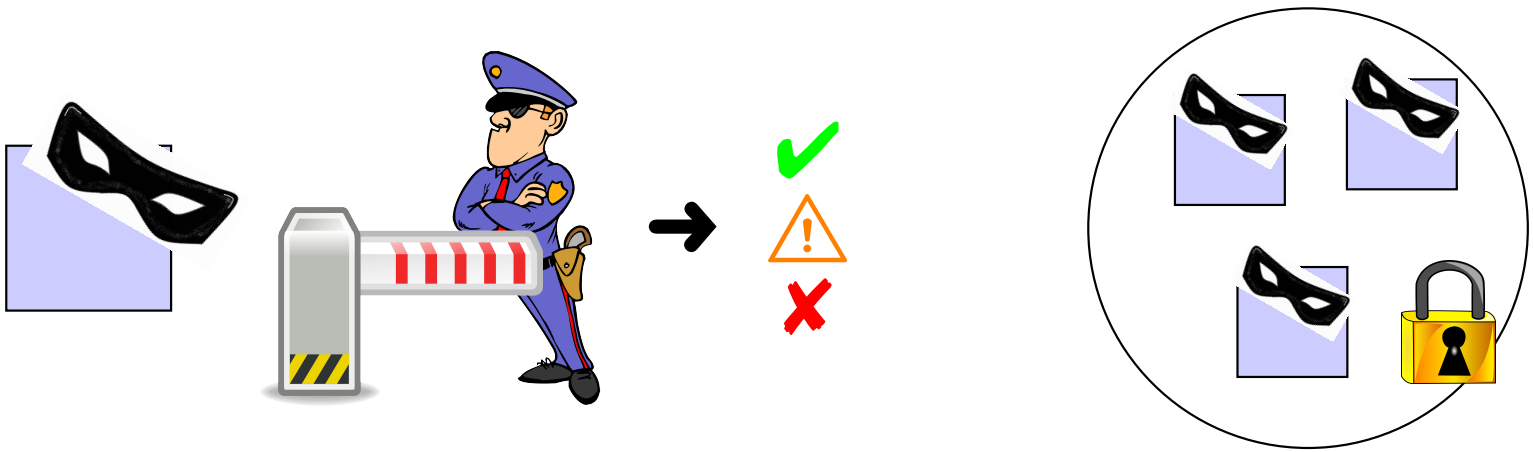


Chosen Contributions

Cryptanalysis: Power-Analysis Attacks



Cryptography: countermeasures against Power-Analysis Attacks



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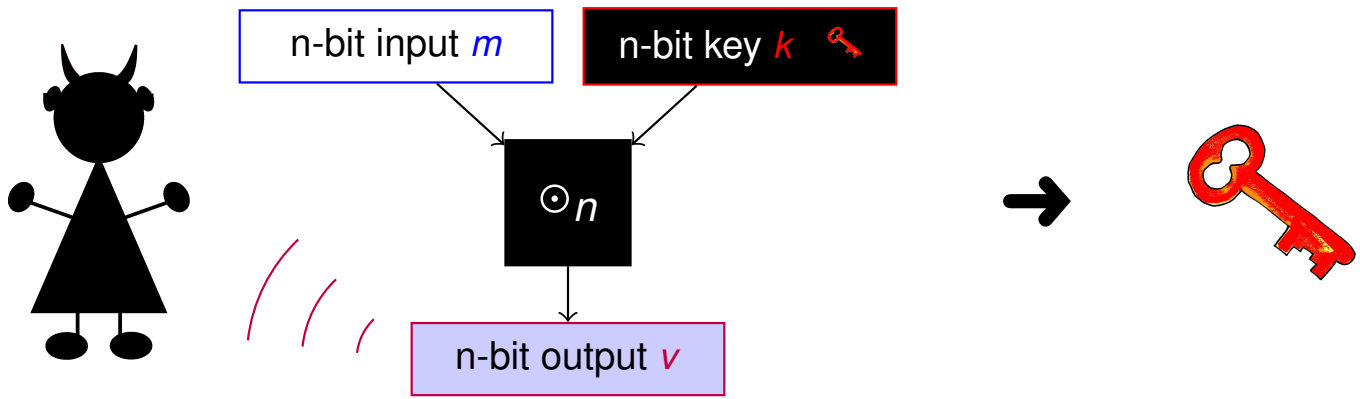

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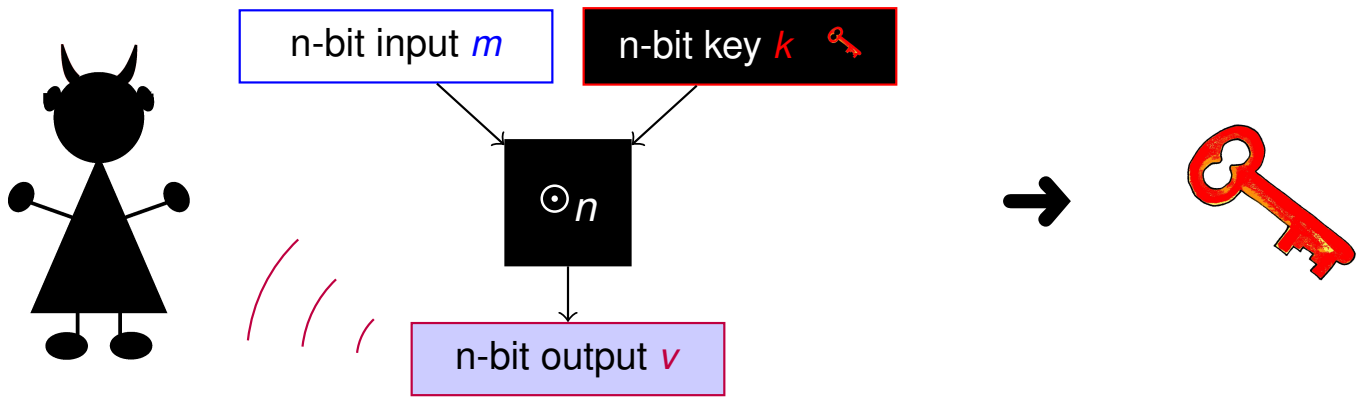

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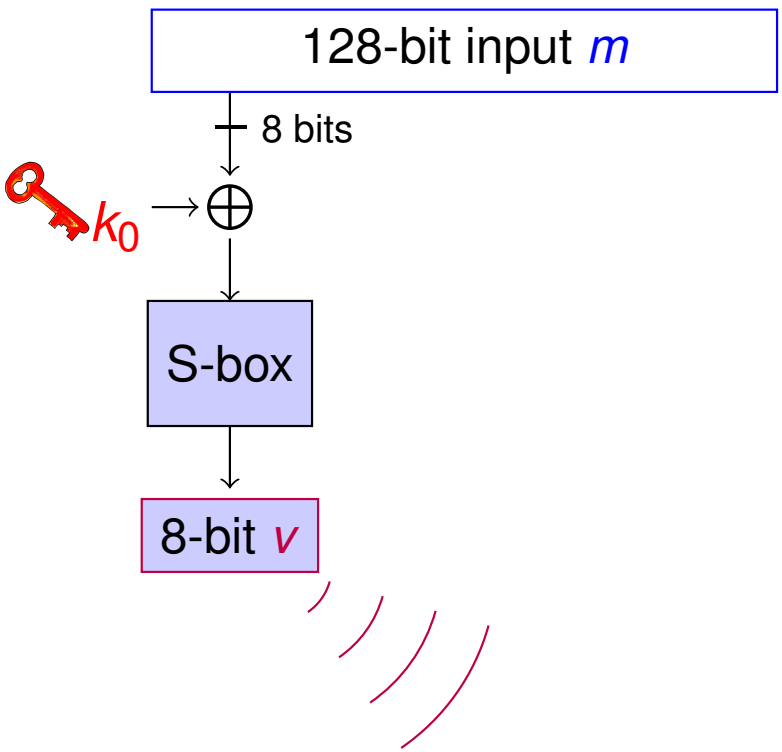
Classical Power-Analysis Attack against AES-128



Attack on 8 bits

- prediction of the outputs for the 256 possible 8-bit secret
- correlation between predictions and leakage
- selection of the best correlation to find the correct 8-bit secret

Attack on 128 bits

- repetition of the attack on 8 bits on each S-box

Power-Analysis Attack against AES-GCM authentication, multiplication-based fresh re-keying, ...

➜ k is only manipulated in multiplications

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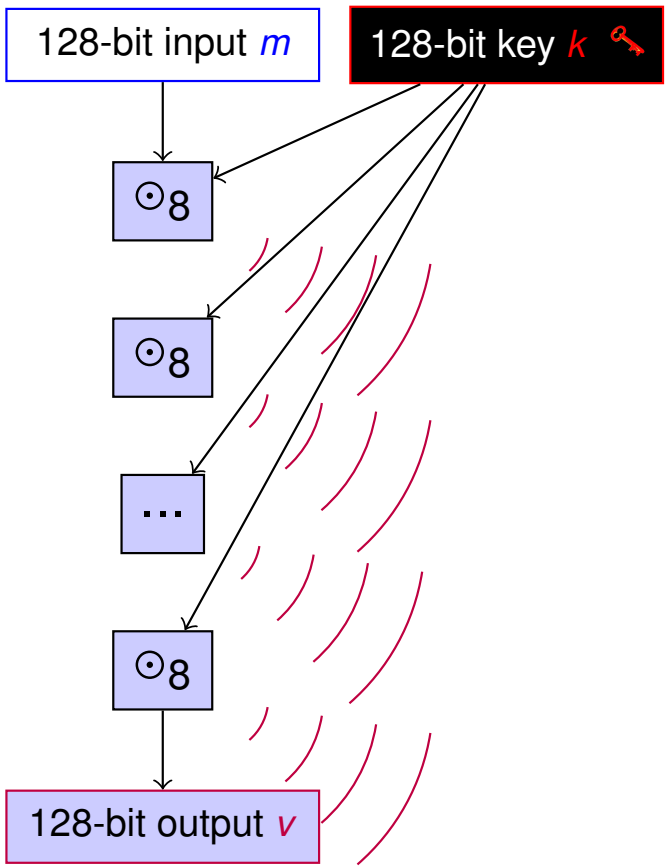

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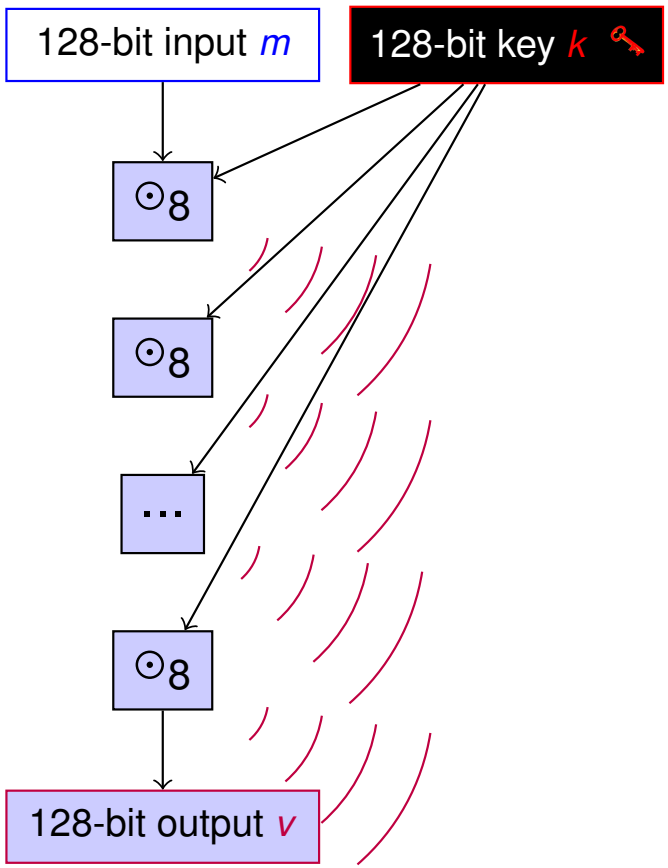
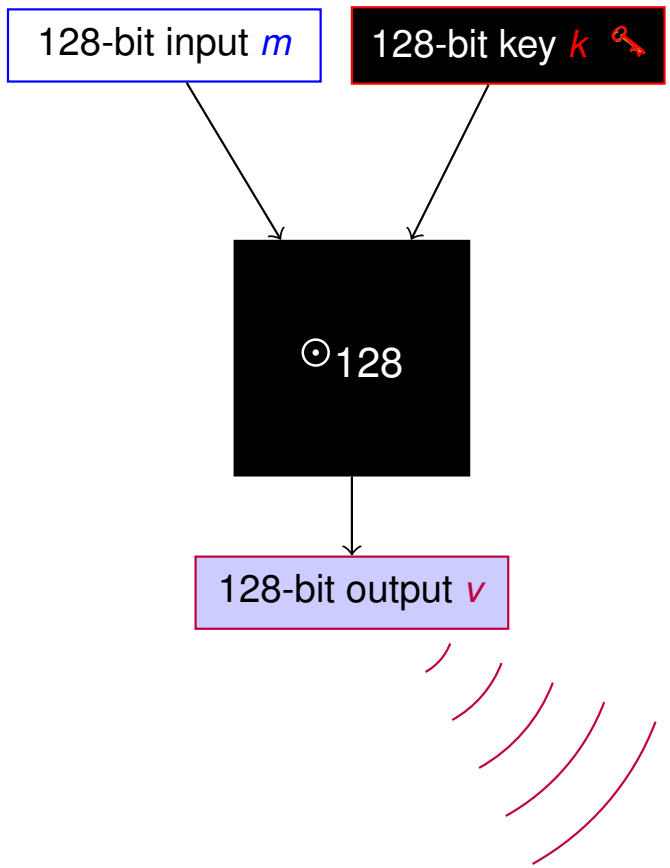


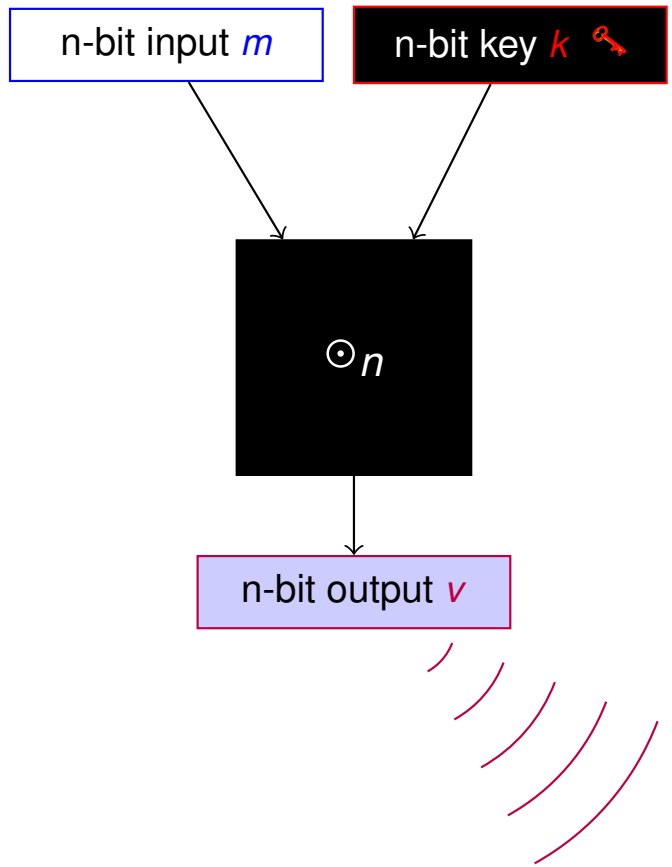


Hidden Multiplier Problem

Let $k \leftarrow \mathrm{GF}(2^n)$. Let $\ell \in \mathbb{N}$.
Given a sequence $\{m^i, \mathscr{L}^i\}_{1 \le i \le \ell}$
where

- $m^i \leftarrow \mathrm{GF}(2^n)$
- $\mathscr{L}^i = \mathrm{HW}(v^i) + \varepsilon^i,\ \varepsilon^i \sim \mathcal{N}(0, \sigma^2)$

recover k.



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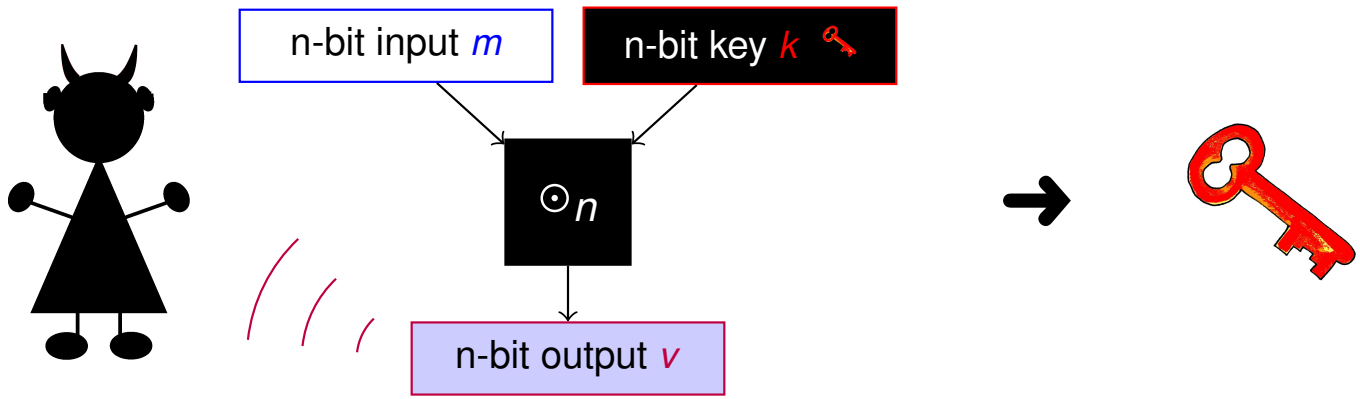

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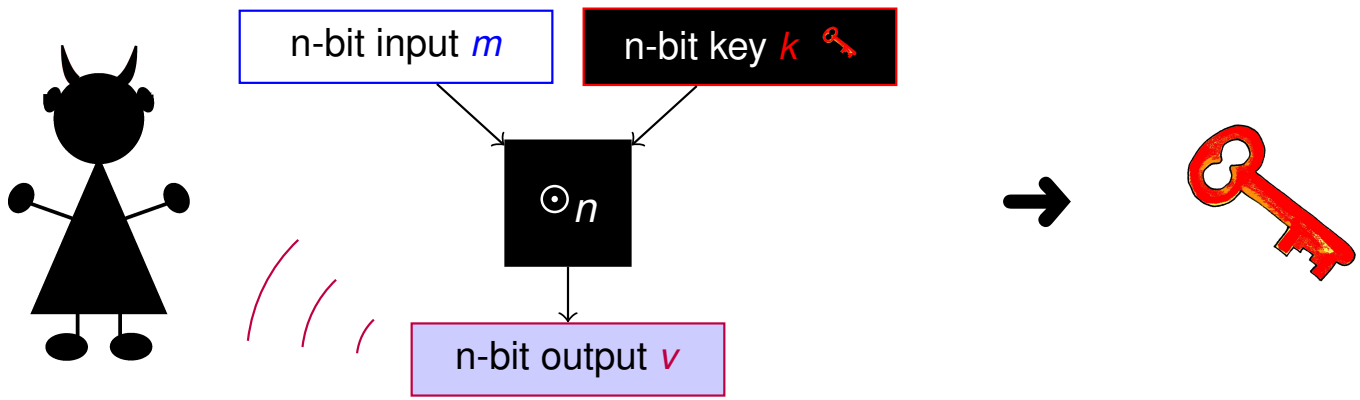

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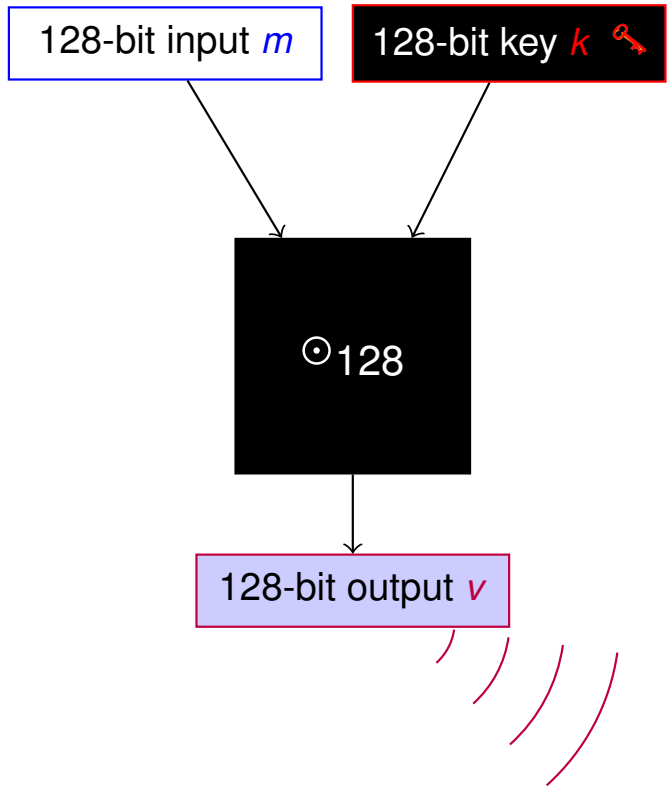
Main Observation

Current Issue: each bit of the 128-bit multiplication's result depends on all the key bits

➜ no divide-and-conquer strategy

Hypotheses:

- leakage of multiplication's outputs $\mathrm{HW}(v) + \varepsilon$
- multiplication in $\mathrm{GF}(2^{128})$



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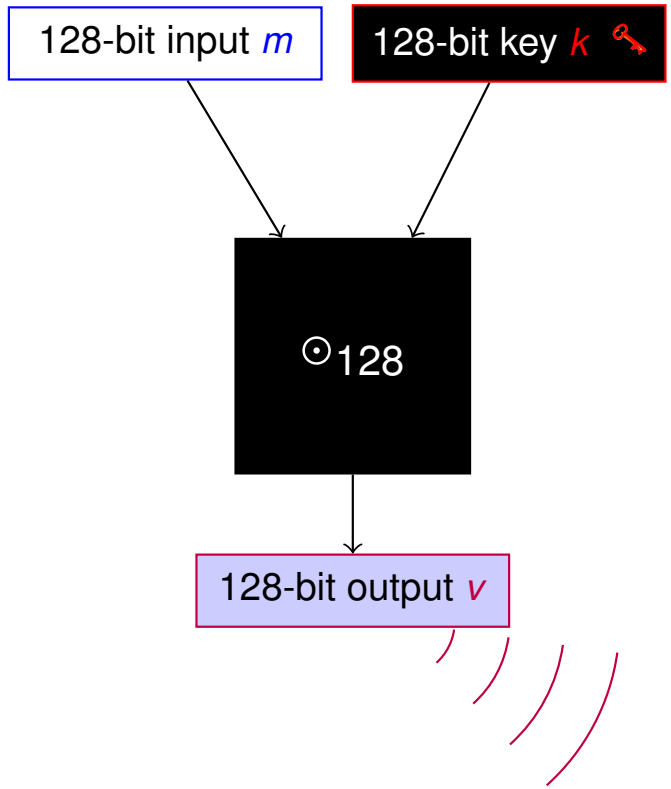

Main observation:
the LSB of a variable's Hamming weight is a linear function of its bits:

$$\mathrm{lsb}_0\left(\mathrm{HW}(v)\right) = \bigoplus_{0 \leqslant i \leqslant 127} v_i = \bigoplus_{0 \leqslant i \leqslant 127} \left(\bigoplus_{0 \leqslant j \leqslant 127-i} m_j \right) k_i$$

System of Equations

With ℓ Hamming weight values $\{\mathrm{HW}(v^{(i)})\}_{0 \leqslant i < \ell}$, we recover k by solving $\mathscr{S}$:

$$\mathscr{S} = \begin{cases} \bigoplus_{0 \leqslant i \leqslant 127} \left(\bigoplus_{0 \leqslant j \leqslant 127-i} m_j^{(0)} \right) & k_i = \mathrm{lsb}_0 \left(\mathrm{HW}(v) \right)^{(0)} \\ \bigoplus_{0 \leqslant i \leqslant 127} \left(\bigoplus_{0 \leqslant j \leqslant 127-i} m_j^{(1)} \right) & k_i = \mathrm{lsb}_0 \left(\mathrm{HW}(v) \right)^{(1)} \\ \cdots & \\ \bigoplus_{0 \leqslant i \leqslant 127} \left(\bigoplus_{0 \leqslant j \leqslant 127-i} m_j^{(\ell-1)} \right) & k_i = \mathrm{lsb}_0 \left(\mathrm{HW}(v) \right)^{(\ell-1)} \end{cases}$$

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But in practice, the leakage comes with noise: $\mathscr{L} = \mathrm{HW}(v) + \varepsilon$

$$\mathrm{lsb}_0 \left(\lceil \mathscr{L} \rfloor \right) \quad = \quad \mathrm{lsb}_0 \left(\mathrm{HW}(v) \right) \oplus b_\varepsilon$$

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Complexities

Method	Signal-to-Noise Ratio			
	3.200	800	200	128
Naive method $(\mathscr{C}_s, \mathscr{C}_t)$	$(2^9, 2^{21})$	$(2^9, 2^{21})$	$(2^9, 2^{65})$	$(2^9, 2^{107})$
LPN (LF Algo) $(\mathscr{C}_s, \mathscr{C}_t)$	$(2^{12}, 2^{14})$	$(2^{21}, 2^{22})$	$(2^{33}, 2^{34})$	$(2^{49}, 2^{50})$
Linear decoding $(\mathscr{C}_s, \mathscr{C}_t)$	$(2^7, 2^6)$	$(2^7, 2^7)$	$(2^9, 2^{25})$	$(2^{10}, 2^{62})$

$$\text{Signal-to-noise ratio} = \frac{\text{signal variance}}{\text{noise variance}} = \frac{32}{\sigma^2}$$

Chosen Contributions

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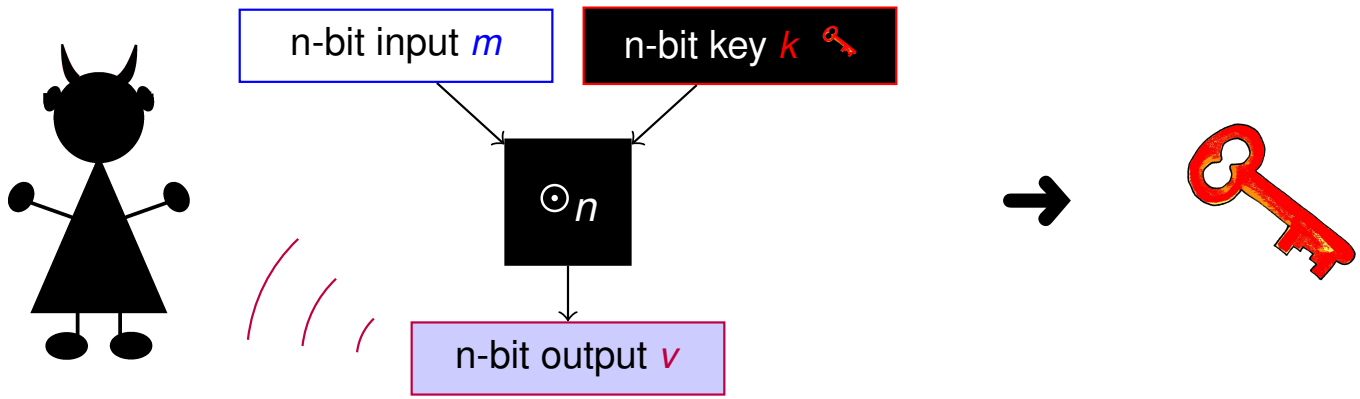

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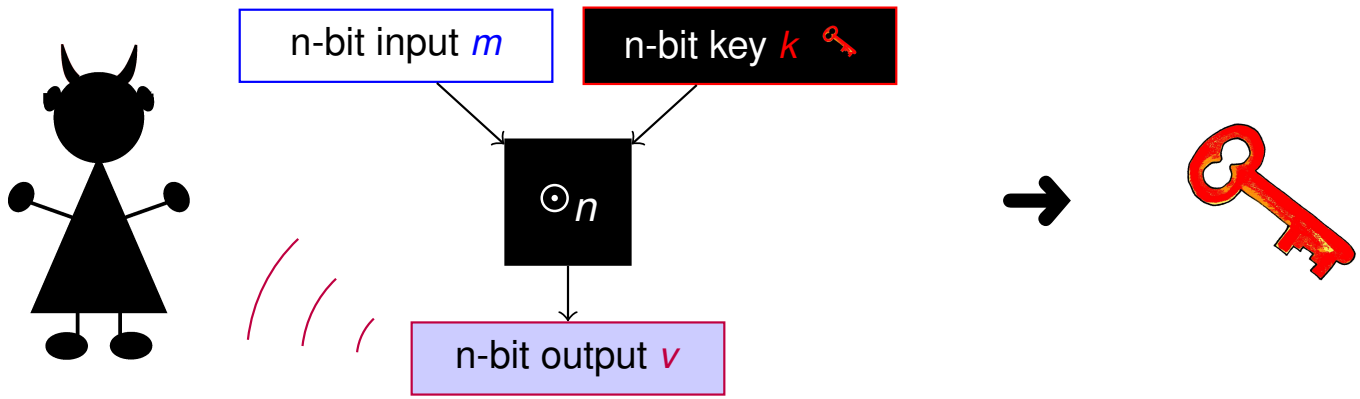

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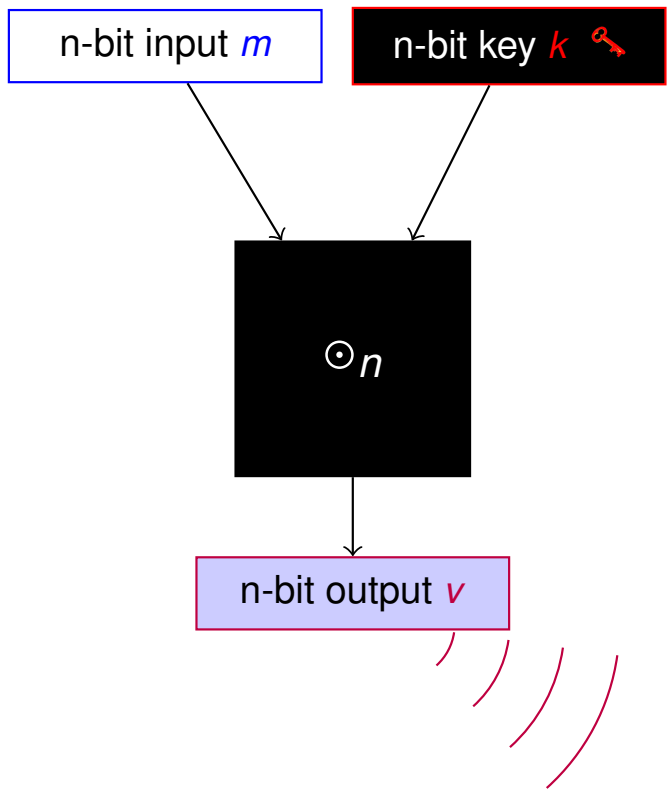
Main Observation

New Attack:

- ➜ filter the multiplication's outputs leakage to extract high and low Hamming weights
- ➜ solve a system with errors

Improvements:

- ✔ more generic
- ✔ less impacted by noise



System of Equations

Reminder:

$$\mathscr{L}(v) = \mathrm{HW}(v) + \varepsilon = \mathrm{HW}(m \odot k) + \varepsilon$$

Extreme cases:

$\mathrm{HW}(v) = 0 \rightarrow v = 0$

$$\begin{cases} v_0 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(0,j)}} m_i \right) k_j = 0 \\ v_1 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(1,j)}} m_i \right) k_j = 0 \\ \vdots \quad \vdots \quad \vdots \\ v_{n-1} = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(n-1,j)}} m_i \right) k_j = 0 \end{cases}$$

$\mathrm{HW}(v) = n \rightarrow v = 2^n - 1$

$$\begin{cases} v_0 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(0,j)}} m_i \right) k_j = 1 \\ v_1 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(1,j)}} m_i \right) k_j = 1 \\ \vdots \quad \vdots \quad \vdots \\ v_{n-1} = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(n-1,j)}} m_i \right) k_j = 1 \end{cases}$$

System of Equations

Reminder:

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Usual cases:

$\mathscr{L}(v)$ low ➜ $v \approx 0$

$$\begin{cases} v_0 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(0,j)}} m_i \right) k_j = 0 \\ v_1 = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(1,j)}} m_i \right) k_j = 0 \\ \vdots \quad \vdots \quad \vdots \\ v_{n-1} = \bigoplus_{0 \leqslant j < n} \left(\bigoplus_{i \in I^{(n-1,j)}} m_i \right) k_j = 0 \end{cases}$$

$\mathscr{L}(v)$ high ➜ $v \approx 2^n - 1$

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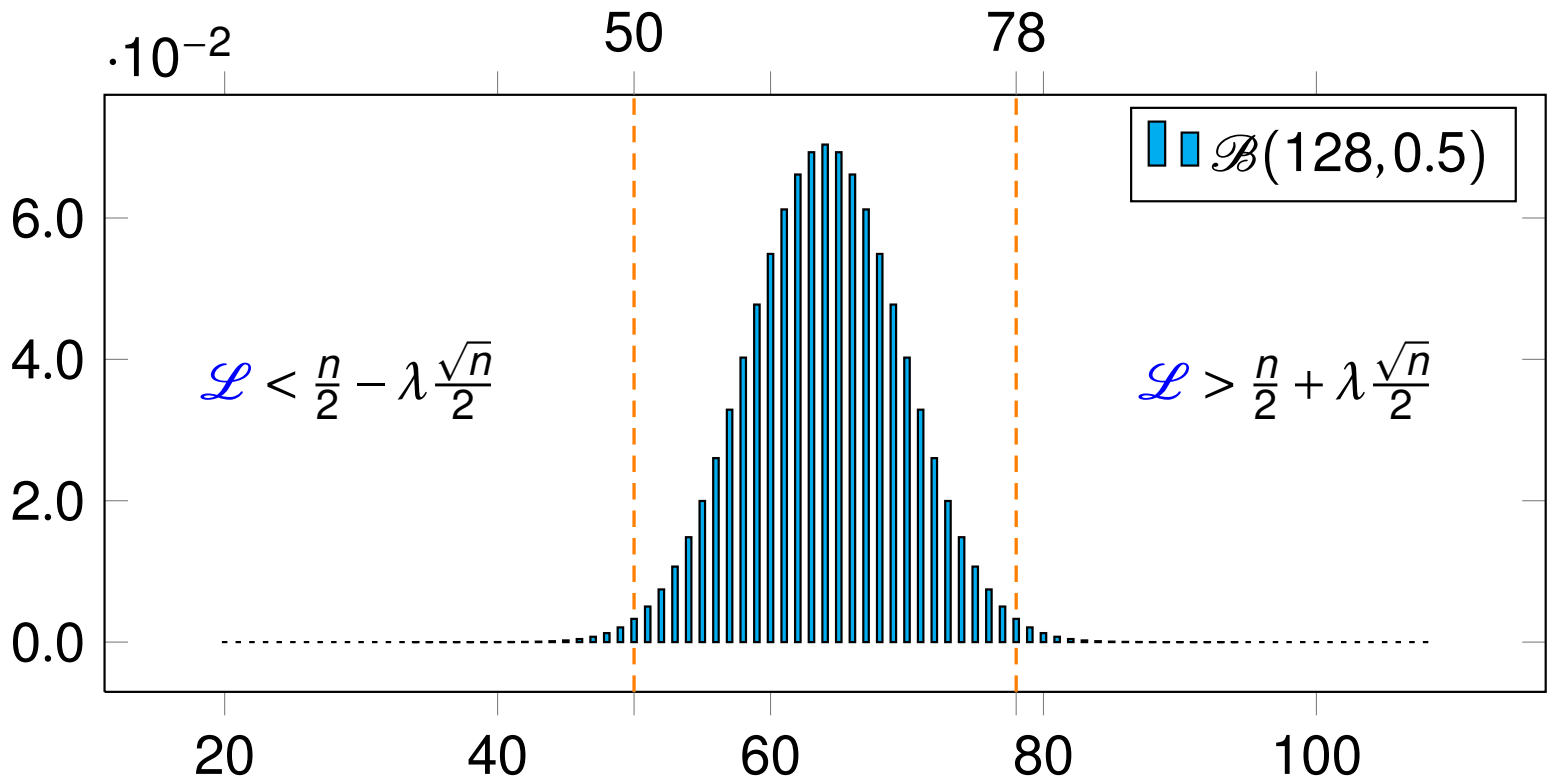
with an error probability p

Filtering



$\left.\begin{array}{l} \text{SNR} = 128 \\ n = 128 \\ \lambda \approx 2.5 \end{array}\right\}$ filtering: 1 trace over 2^5
error probability: $p \approx 0.38$

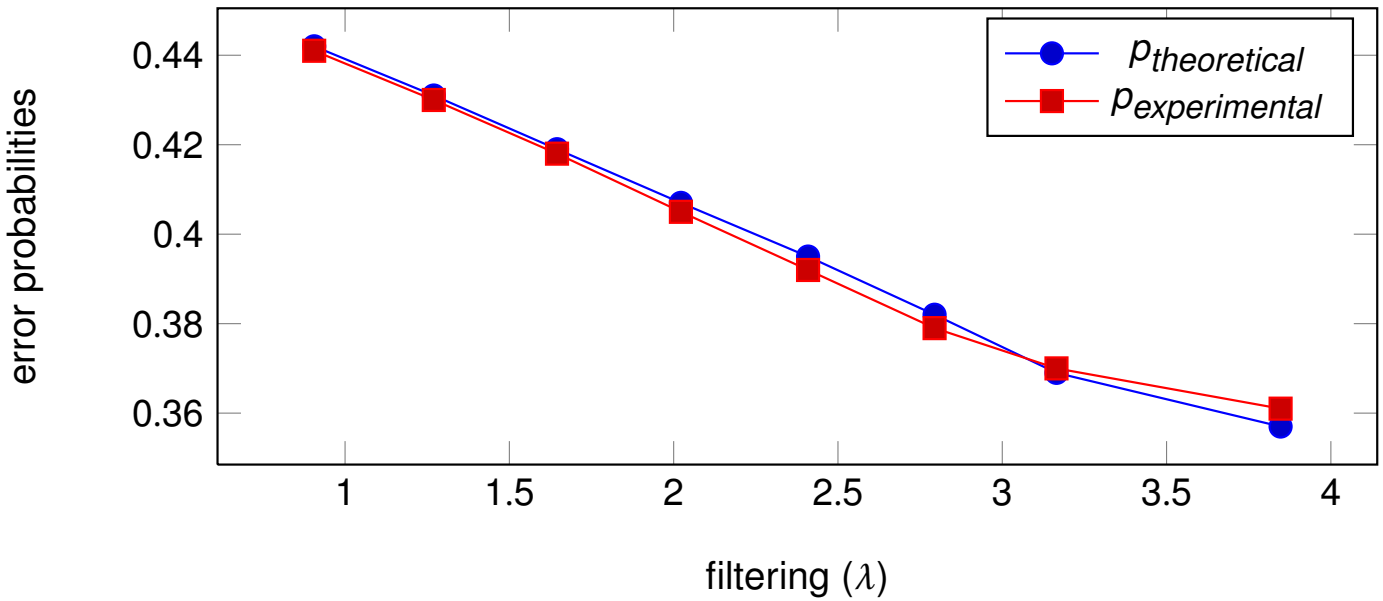
Error Probabilities

$\log_2(1/F(\lambda))$	30	25	20	15	10	5
SNR $= 128$, $\sigma = 0.5$						
λ	6.00	5.46	4.85	4.15	3.29	2.16
p	0.23	0.25	0.28	0.31	0.34	0.39
p [BFG14]	0.31					
SNR $= 8$, $\sigma = 2$						
λ	6.37	5.79	5.14	4.39	3.48	2.28
p	0.25	0.27	0.29	0.32	0.35	0.40
p [BFG14]	> 0.49					
SNR $= 2$, $\sigma = 4$						
λ	7.42	6.73	5.97	5.09	4.03	2.64
p	0.28	0.30	0.32	0.34	0.37	0.41
p [BFG14]	> 0.49					
SNR $= 0.5$, $\sigma = 8$						
λ	10.57	9.58	8.48	7.21	5.71	3.73
p	0.34	0.36	0.37	0.39	0.41	0.44
p [BFG14]	> 0.49					

$$\text{Signal-to-noise ratio} = \frac{\text{signal variance}}{\text{noise variance}} = \frac{32}{\sigma^2}$$

Experiments for $n = 128$

- Filtering on a Virtex 5 - 128 bits ($n = 128$) : SNR $= 8.21$, $\sigma = 7.11$

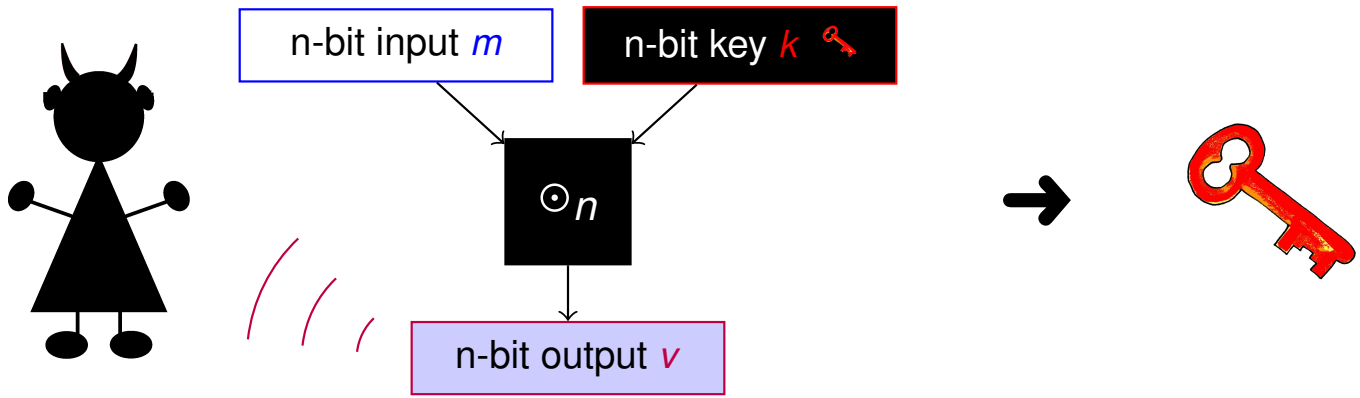


- Expected complexities to recover k with 2^{20} consumption traces

trade-offs (time , memory)	$\left(2^{59.31}, 2^{27.00}\right)$
	$\left(2^{51.68}, 2^{36.00}\right)$
	$\left(2^{50.00}, 2^{44.00}\right)$

Conclusion on the Multiplication Cryptanalysis

Cryptanalysis: Power-Analysis Attacks



Summary

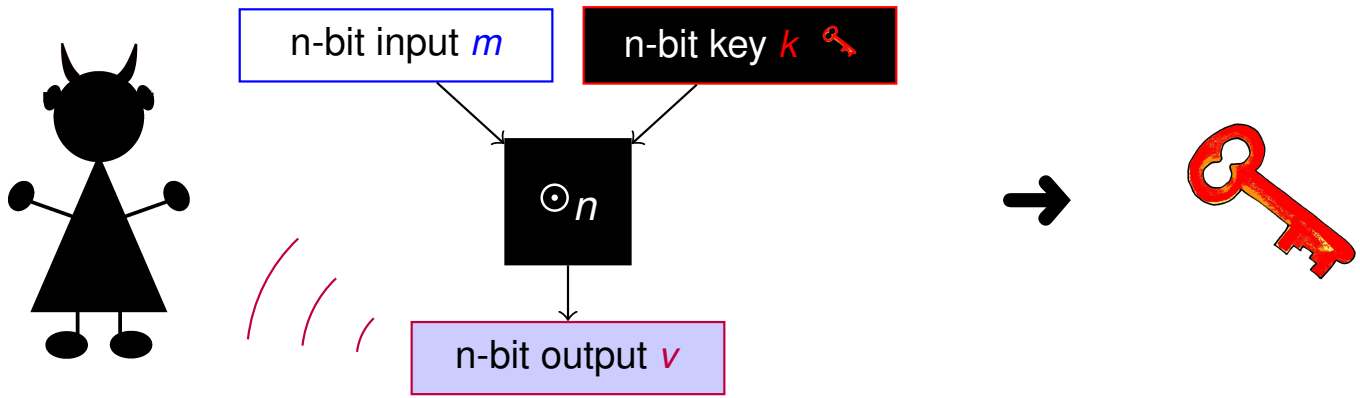
- ✔ successful attacks on multiplications from the output's leakage
- ✔ practical for $n = 128$ (use cases: AES-GCM, re-keying)

Further Work

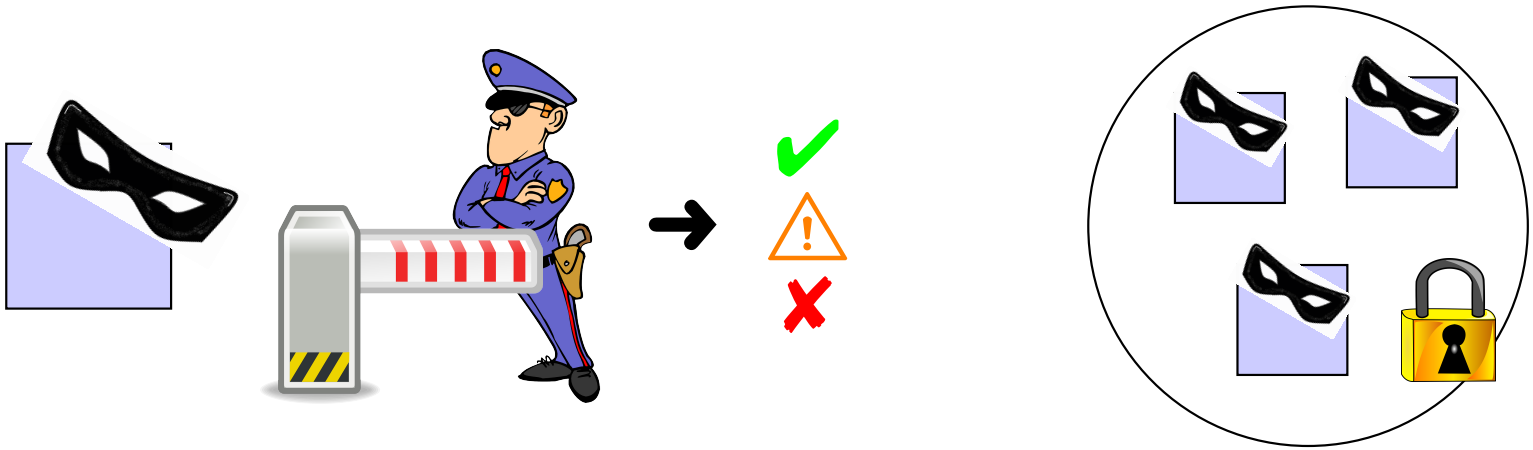
- ➜ application of similar attacks on other primitives
- ➜ deeper analysis of LPN techniques in the context of side-channel analysis

Chosen Contributions

Cryptanalysis: Power-Analysis Attacks



Cryptography: countermeasures against Power-Analysis Attacks



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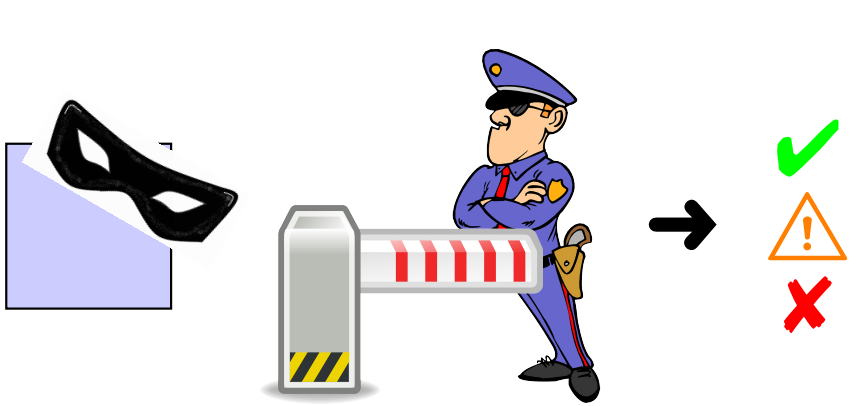

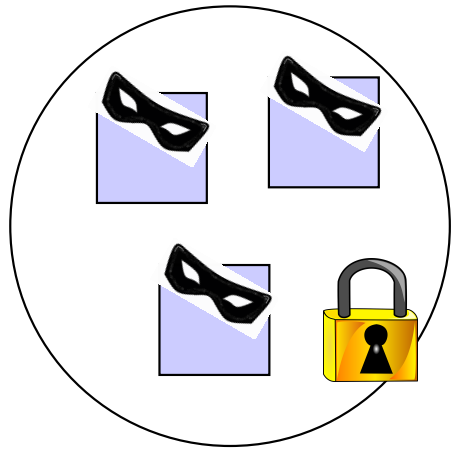

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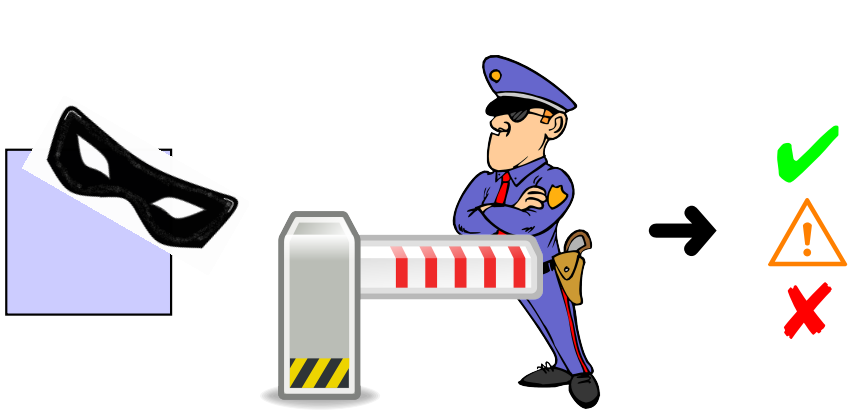
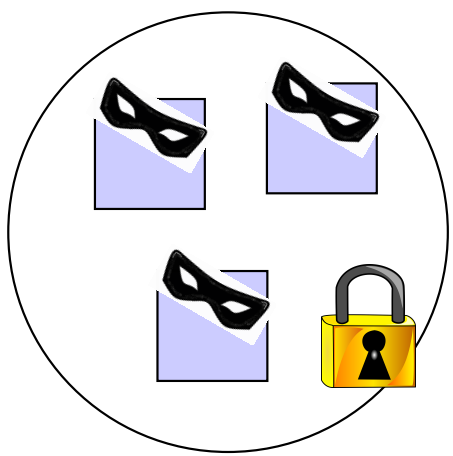
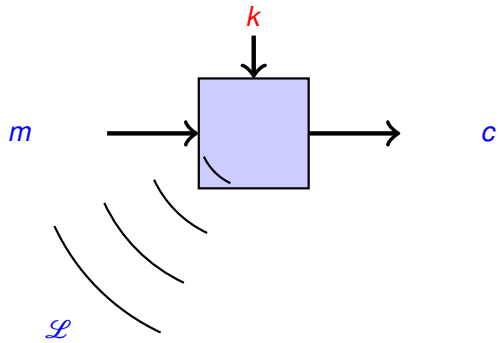




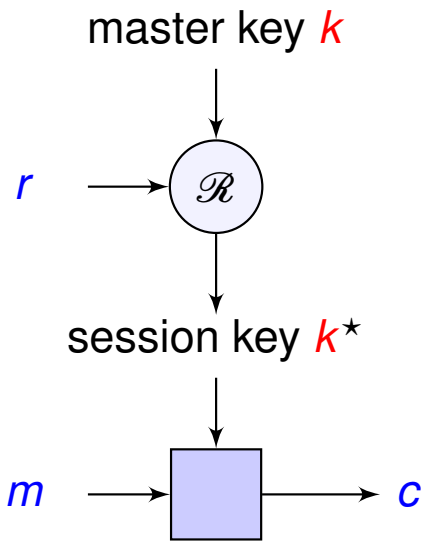
Countermeasures against Power-Analysis Attacks



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

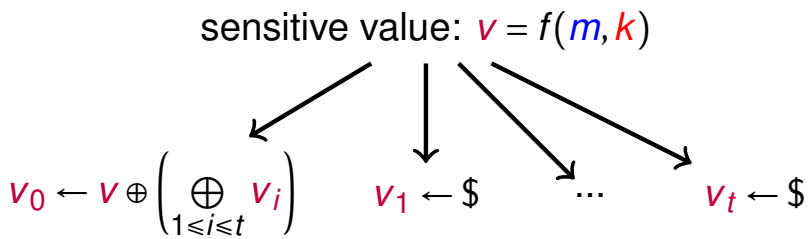
Fresh Re-keying

Idea: regularly change k



Masking

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



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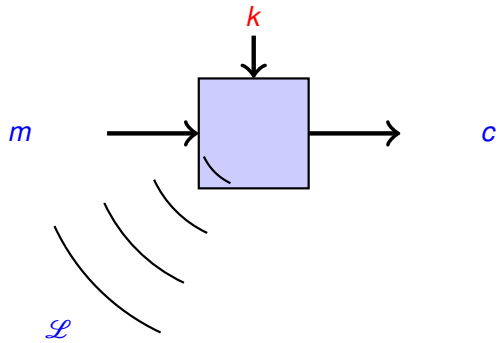
Countermeasures against Power-Analysis Attacks



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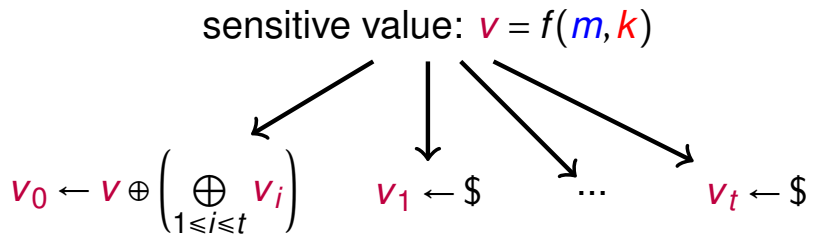

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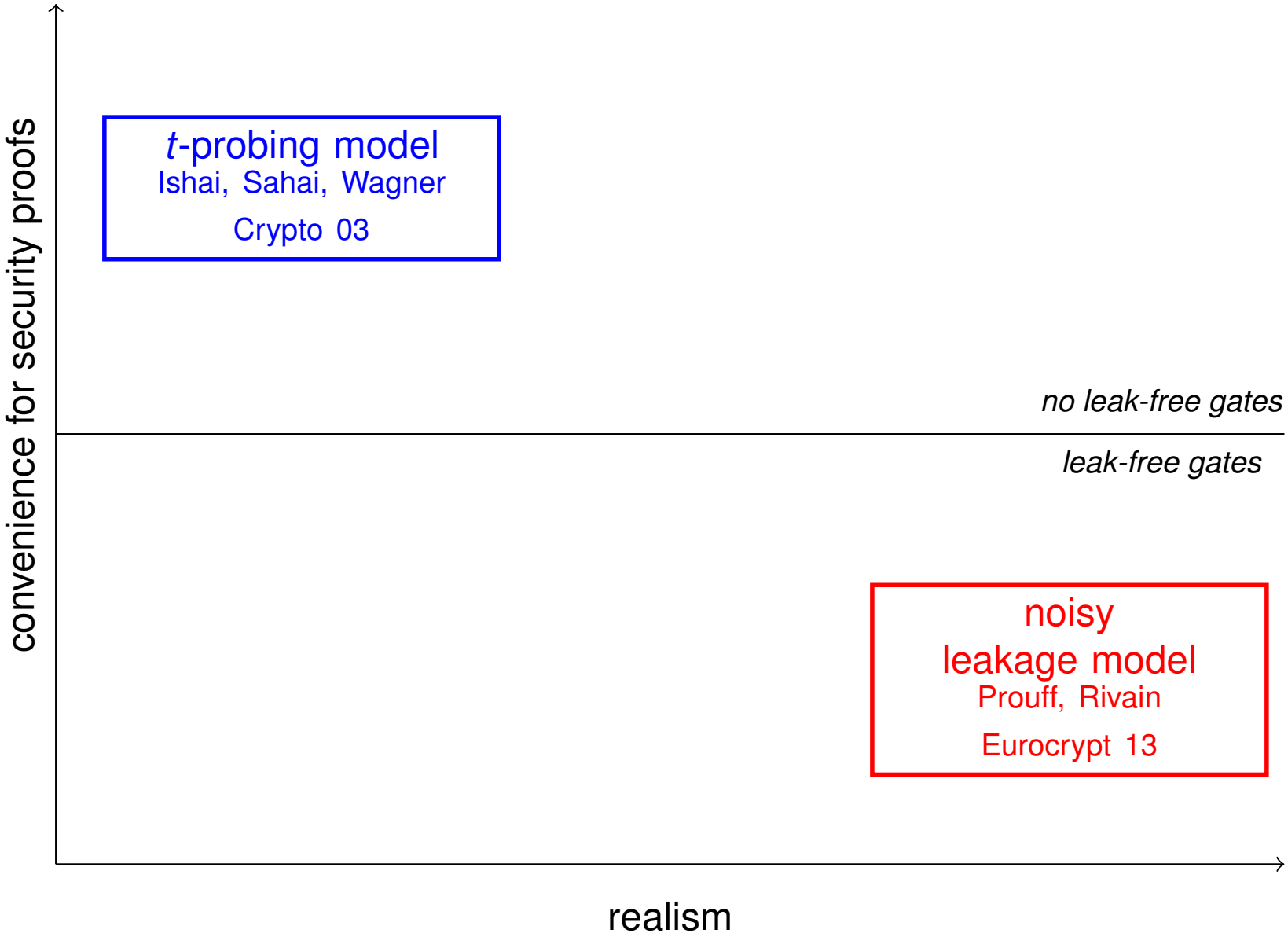
Security of Masked Programs: Leakage Model



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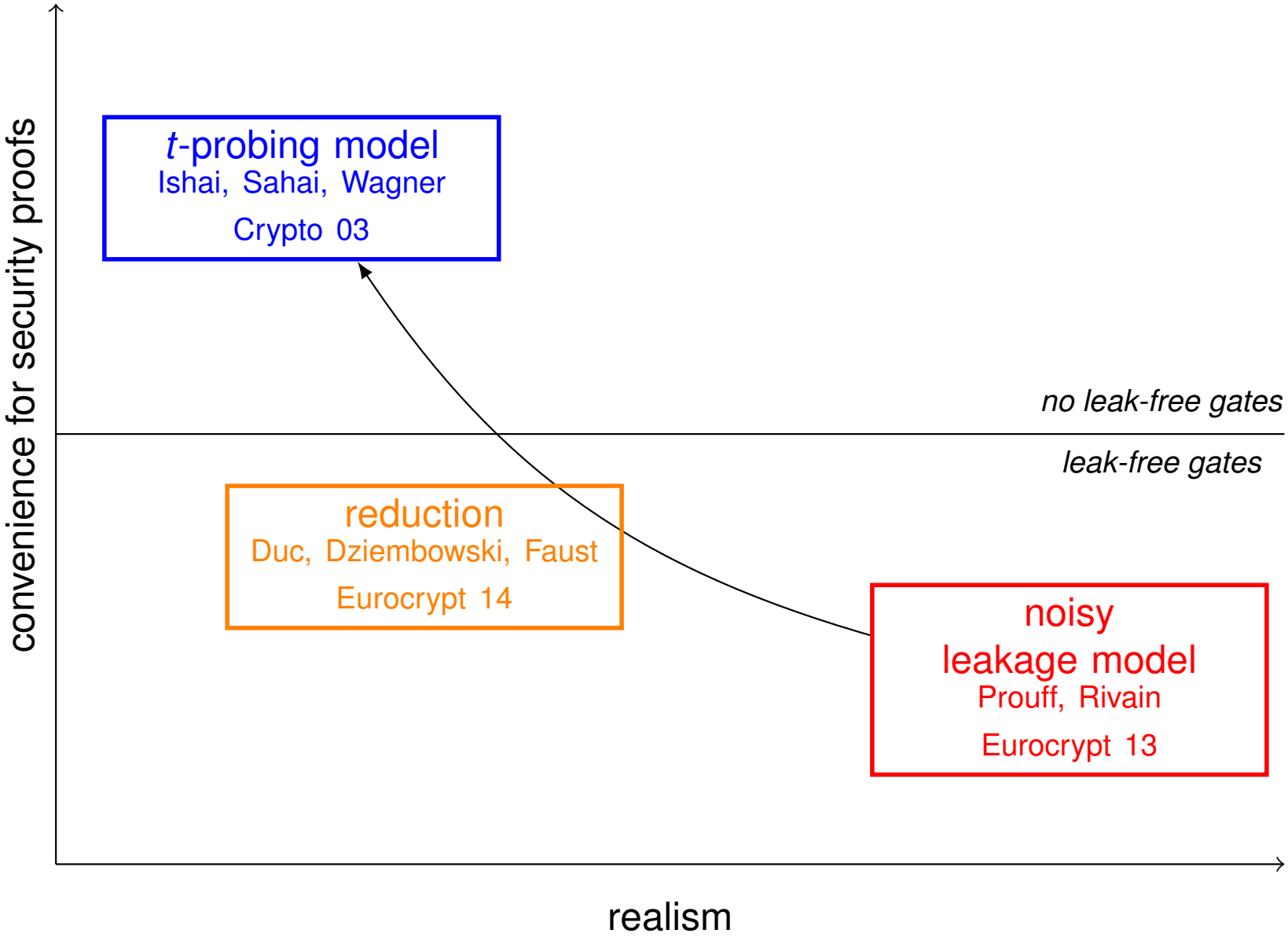

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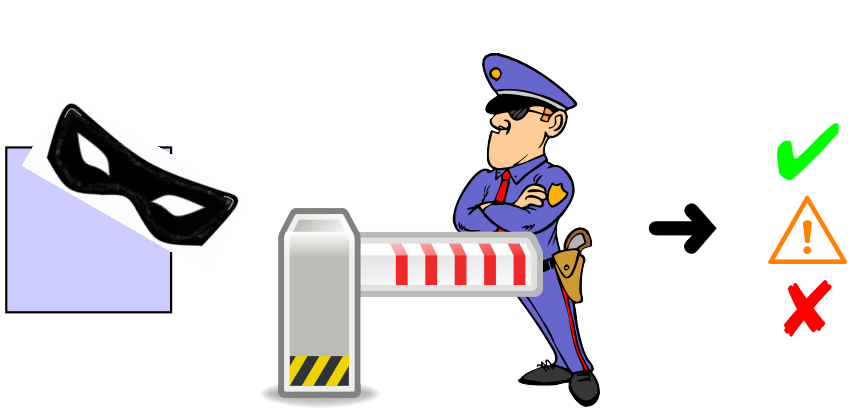

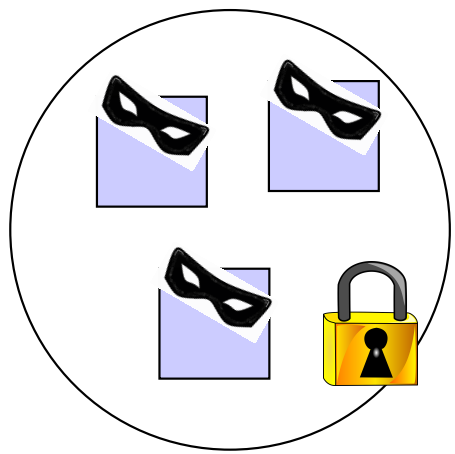

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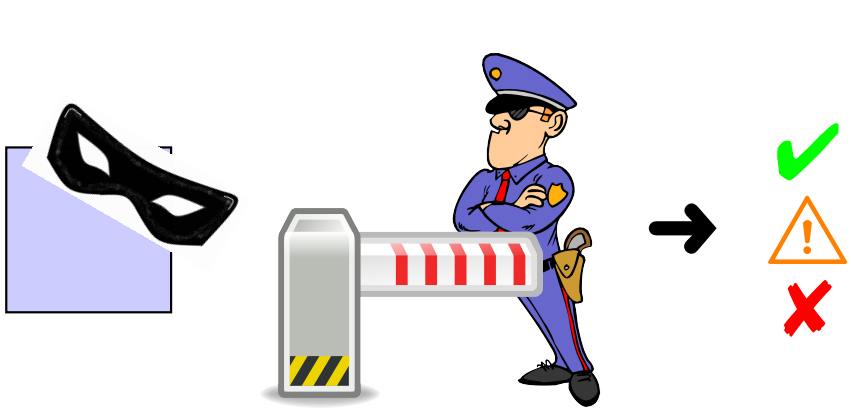

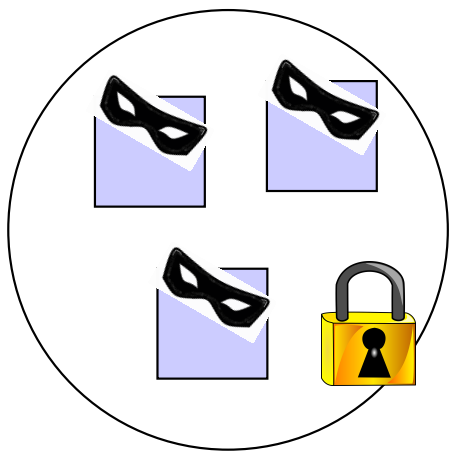

Security in the t-probing model

1. show that a t-uple is independent from the secret
2. test all the possible t-uples

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

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

$r_1 \leftarrow \$$
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2. test 286 3-uples

✘ missing cases
✘ inefficient

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

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Problem: n intermediate variables ➜ $\binom{n}{t}$ proofs

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- two algorithms efficient in practice

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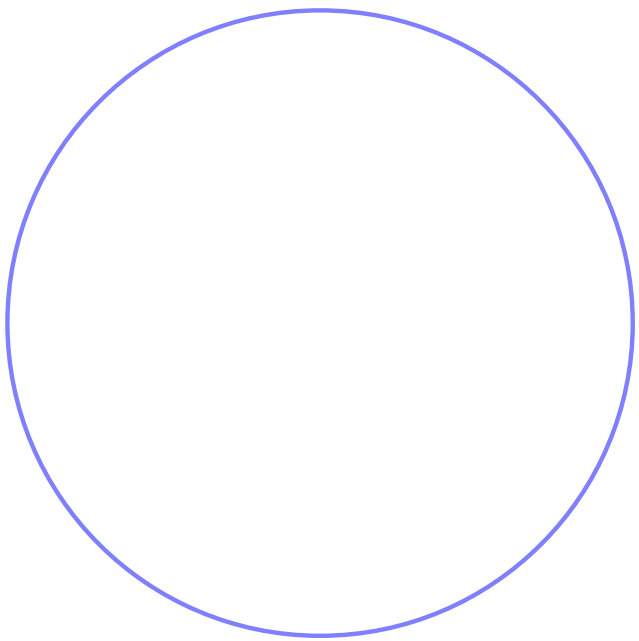

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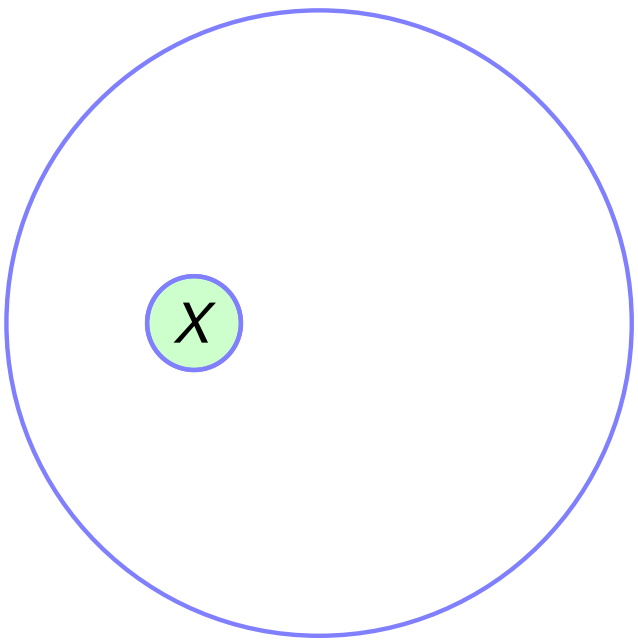

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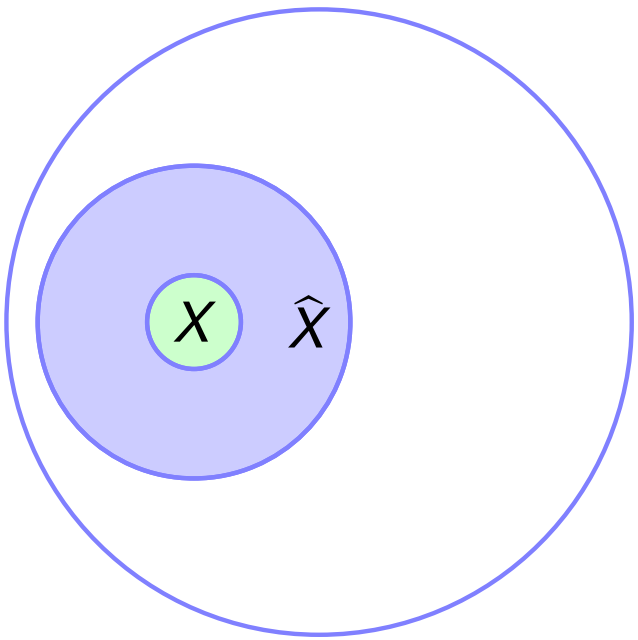

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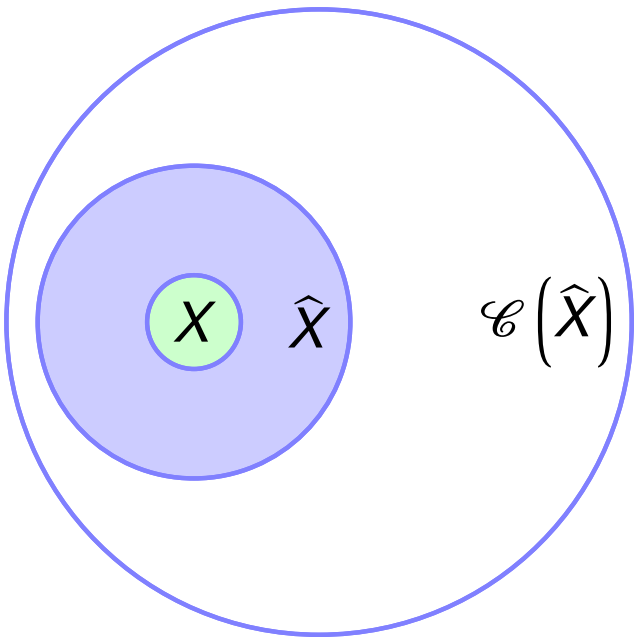

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3. recursively descend in set $\mathscr{C}\left(\hat{X}\right)$

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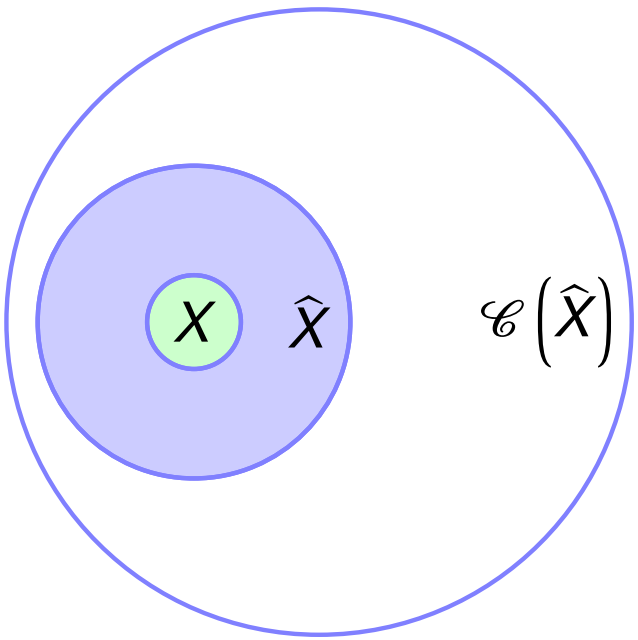
- find larger sets which cover all the intermediate variables is a hard problem
- two algorithms efficient in practice



Algorithm 1:

1. select $X = (t \text{ variables})$ and prove its independence
2. extend X to $\widehat{X}$ with more observations but still independence
3. recursively descend in set $\mathscr{C}\left(\widehat{X}\right)$
4. merge $\widehat{X}$ and $\mathscr{C}\left(\widehat{X}\right)$ once they are processed separately.

2. Extension to All Possible Sets: Example

function $\text{Ex-t3}(x_1, x_2, x_3, x_4, c)$:

$r_1 \leftarrow \$$

$r_2 \leftarrow \$$

$y_1 \leftarrow x_1 + r_1$

$y_2 \leftarrow (x + x_1 + x_2 + x_3) + r_2$

$t_1 \leftarrow x_2 + r_1$

$t_2 \leftarrow (x_2 + r_1) + x_3$

$y_3 \leftarrow (x_2 + r_1 + x_3) + r_2$

$y_4 \leftarrow c + r_2$

return(y_1, y_2, y_3, y_4)

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X: ✔

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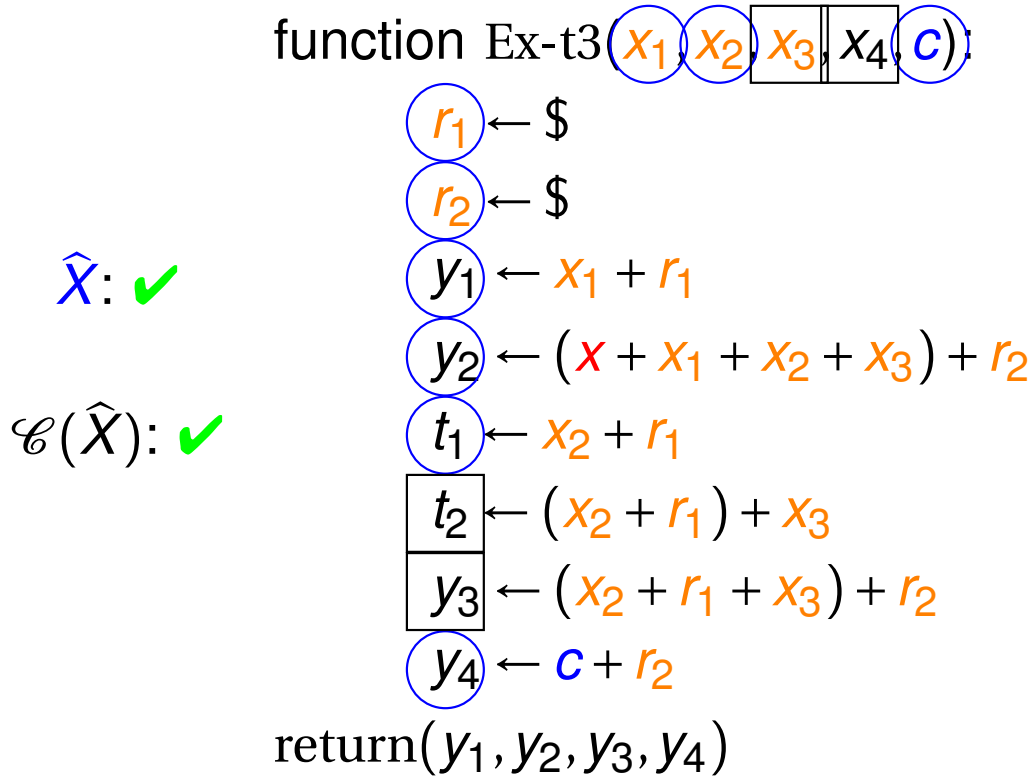

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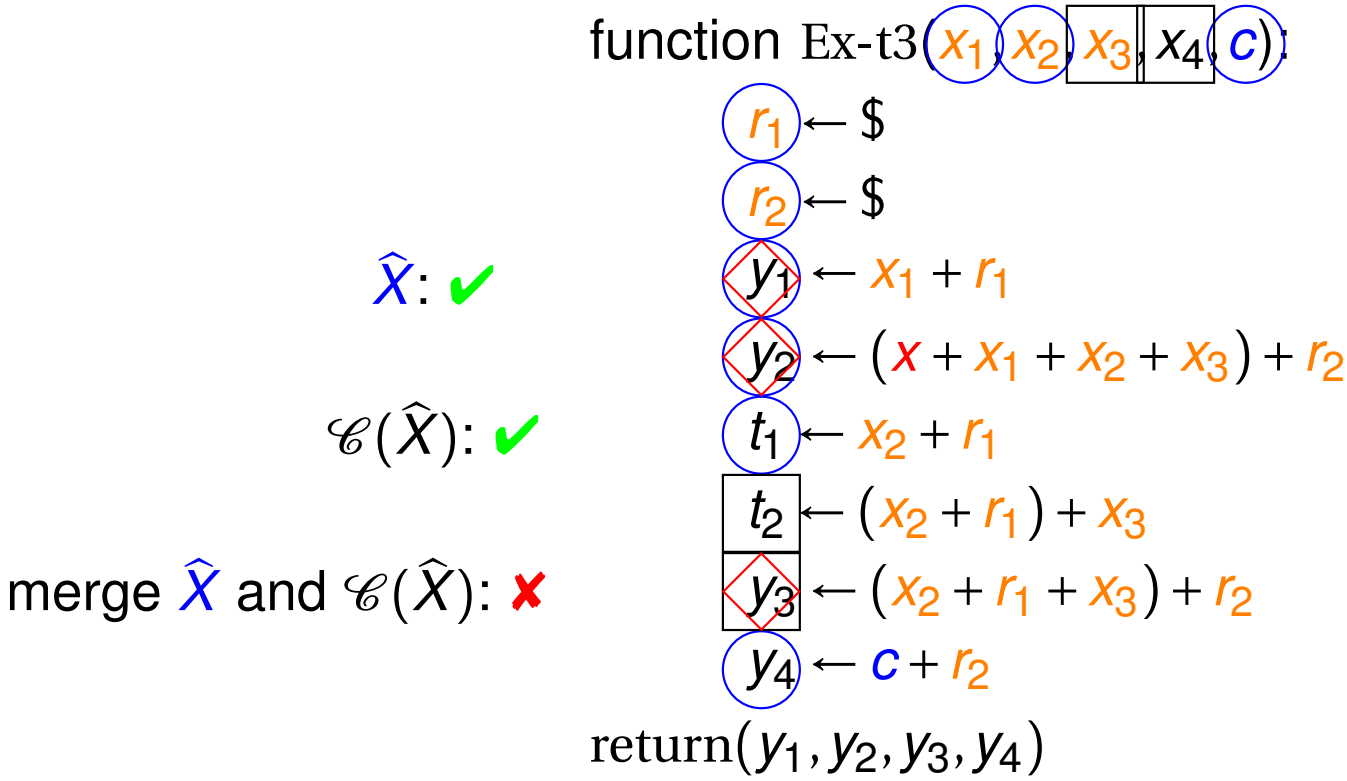

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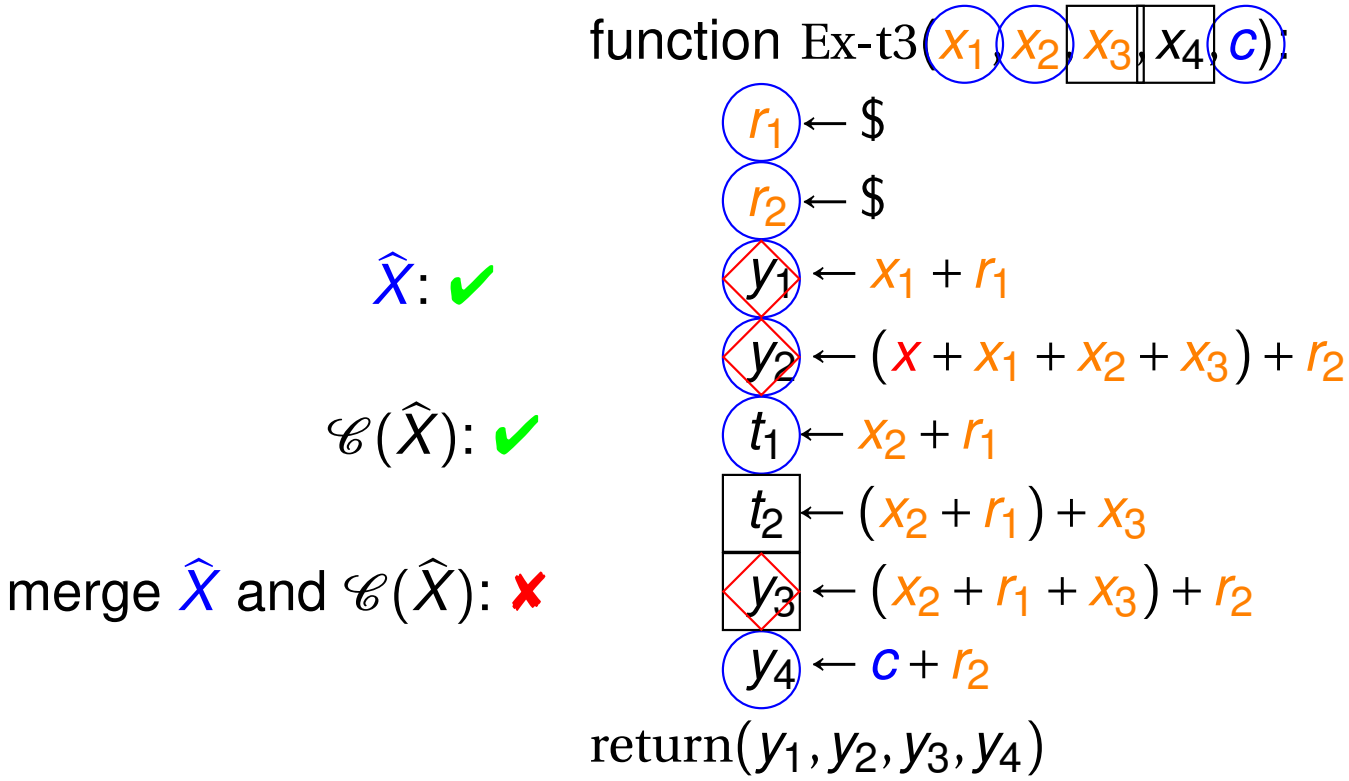


➜ 207 proofs instead of 286

Application to the Sbox [CPRR13, Algorithm 4]

Method	# tuples	Security	Complexity # sets	Complexity time*
First-Order Masking				
naive	63	✔	63	0.001s
Alg. 1			17	0.001s
Alg. 2			17	0.001s
Second-Order Masking				
naive	12,561	✔	12,561	0.180s
Alg. 1			851	0.046s
Alg. 2			619	0.029s
Third-Order Masking				
naive	4,499,950	✔	4,499,950	140.642s
Alg. 1			68,492	9.923s
Alg. 2			33,075	3.894s
Fourth-Order Masking				
naive	2,277,036,685	✔	-	unpractical
Alg. 1			8,852,144	2959.770s
Alg. 2			3,343,587	879.235s

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

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

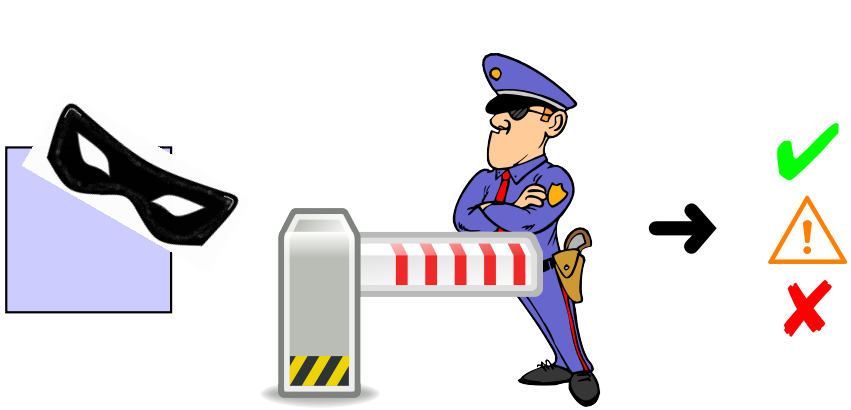
Chosen Contributions

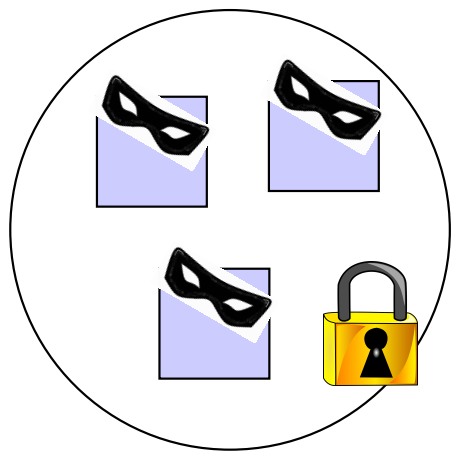
Masking and t-probing model:

1. Verified Proofs of Higher-Order Masking → G. Barthe, S. Belaïd, F. Dupressoir, P-A. Fouque, B. Grégoire, and P-Y. Strub. Eurocrypt 2015

2. Composition of Higher-Order Masking → G. Barthe, S. Belaïd, F. Dupressoir, P-A. Fouque, and B. Grégoire. ePrint 2015

Cryptography: countermeasures against Power-Analysis Attacks





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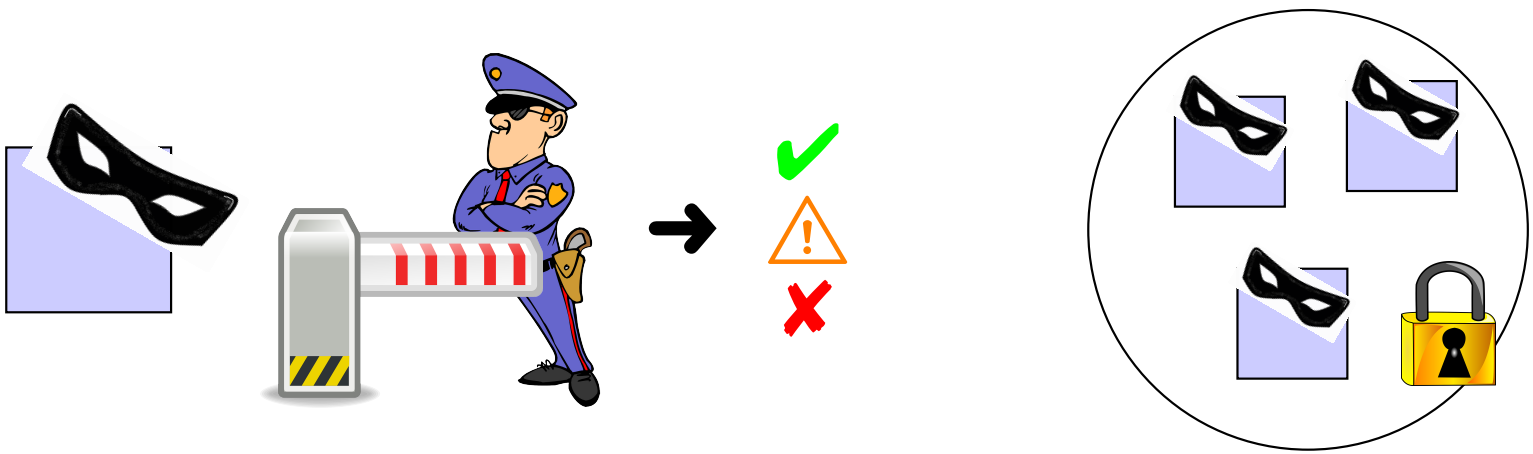
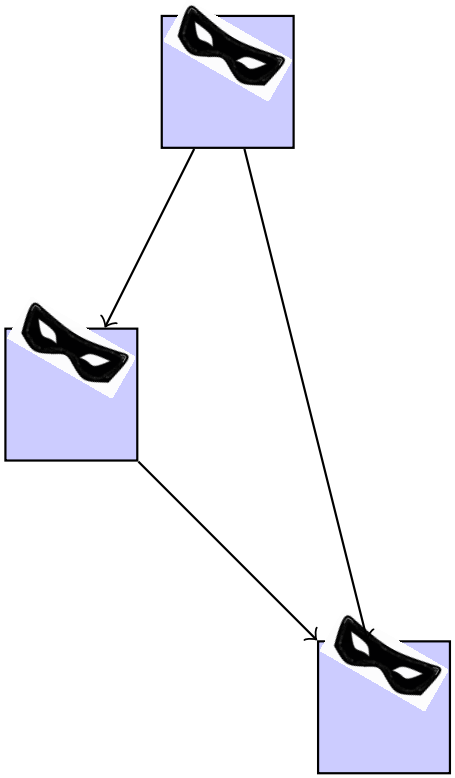


Current Issues in Composition



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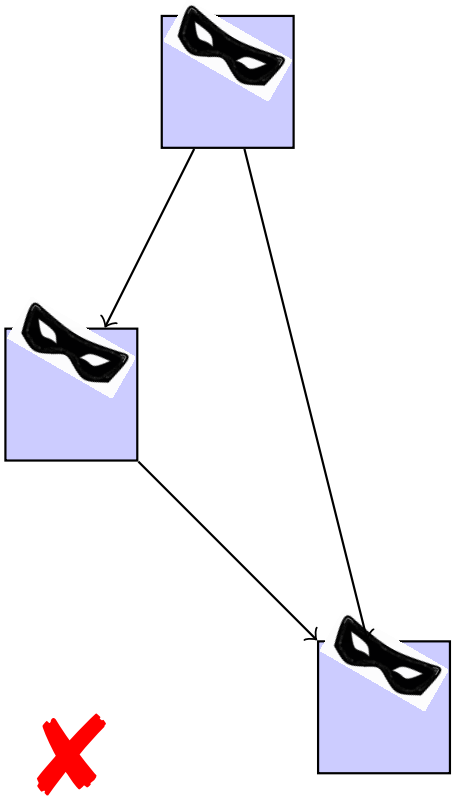

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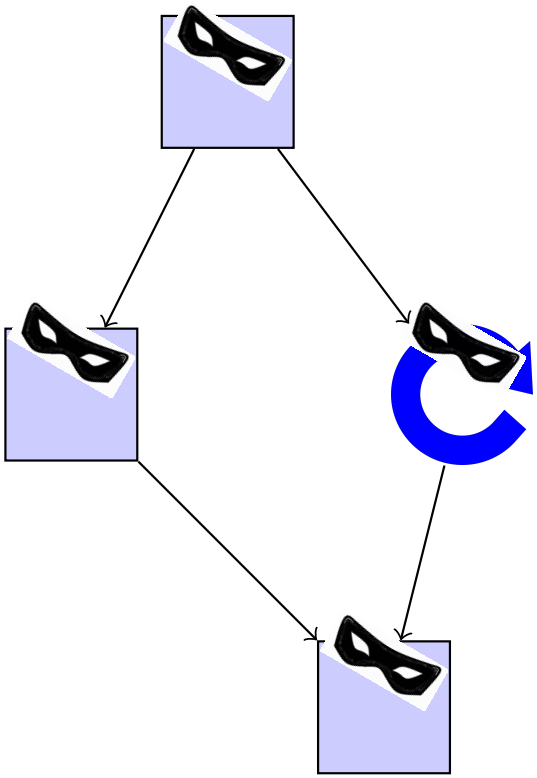

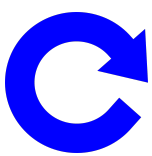

A refresh algorithm takes as input a sharing $(x_i)_{i\geq 0}$ of x and returns a new sharing $(x'_i)_{i\geq 0}$ of x such that $(x_i)_{i\geq 1}$ and $(x'_i)_{i\geq 1}$ are mutually independent.

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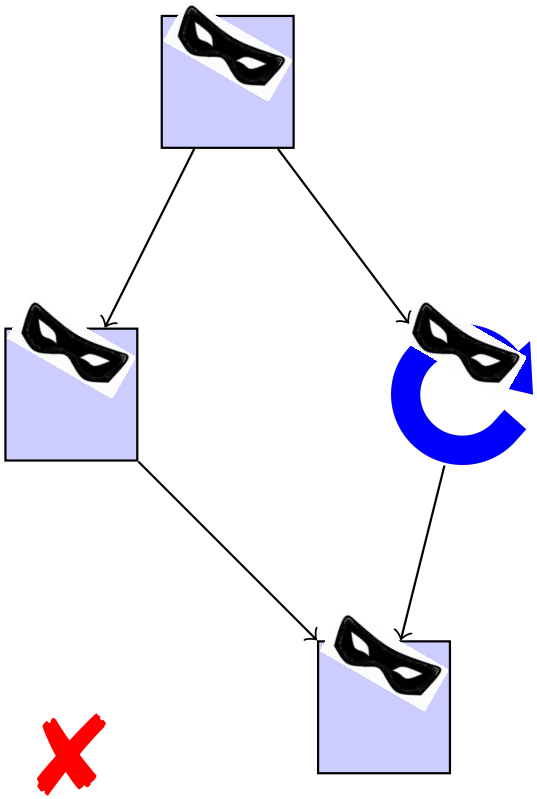

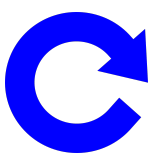

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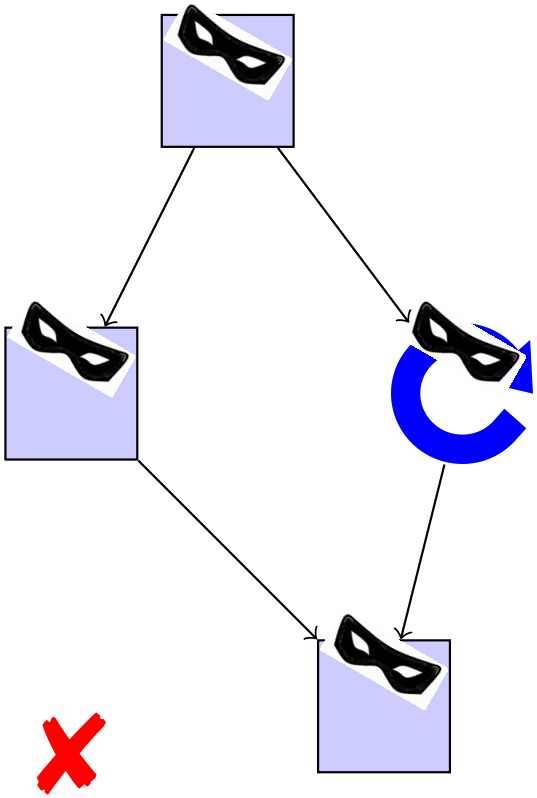

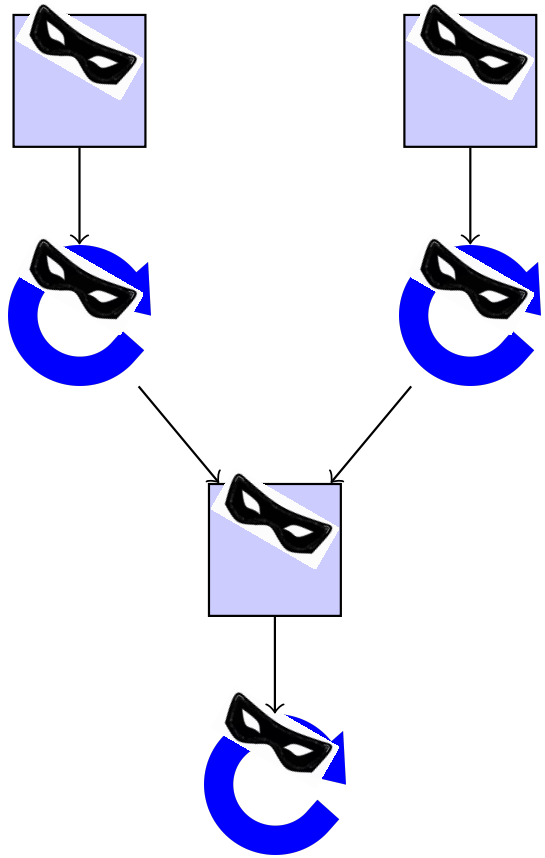

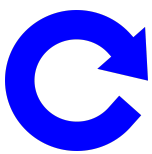

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Security properties in the t-probing model

if t is fixed: show that any set of t intermediate variables is independent from the secret

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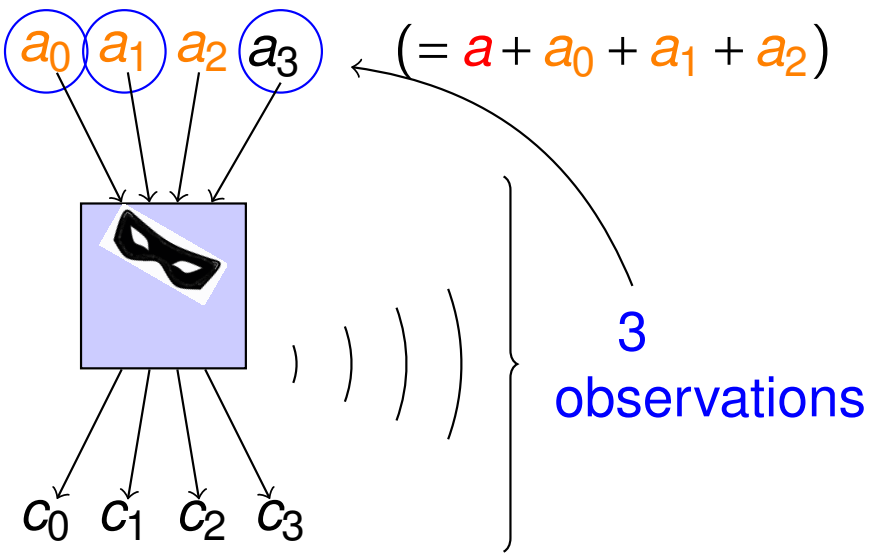
if t is not fixed: show that any set of t intermediate variables can be simulated with at most t shares of each input



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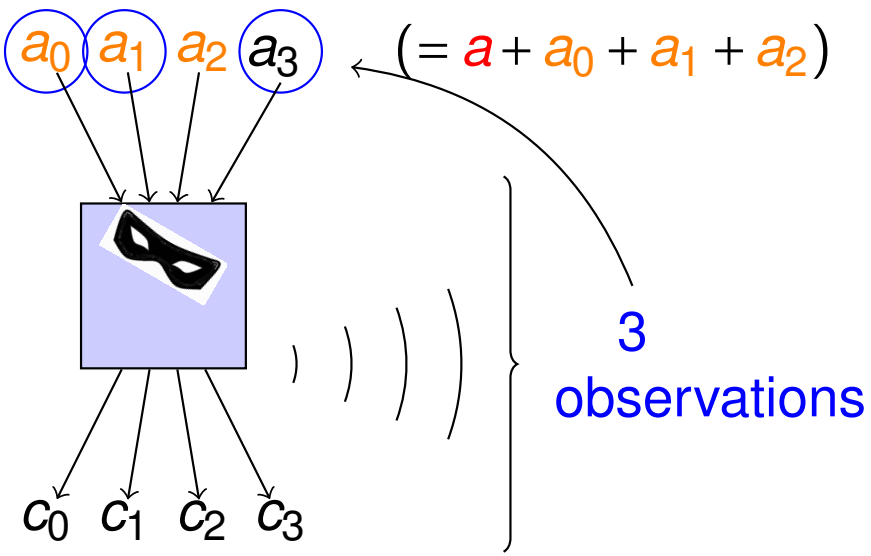

function Linear-function-t$(a_0, ..., a_i, ...a_t)$:

for $i = 0$ to t

$c_i \leftarrow f(a_i)$

return $(c_0, ..., c_i, ..., c_t)$

➜ straightforward for linear functions

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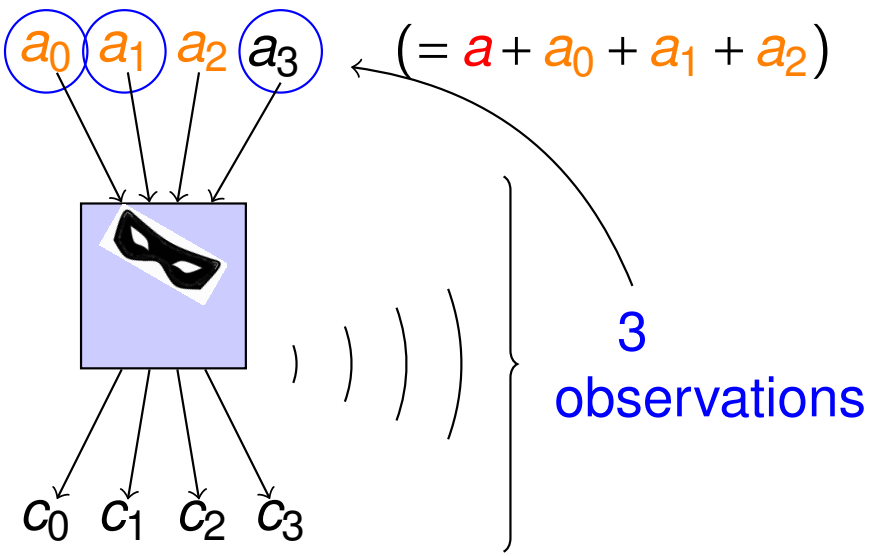

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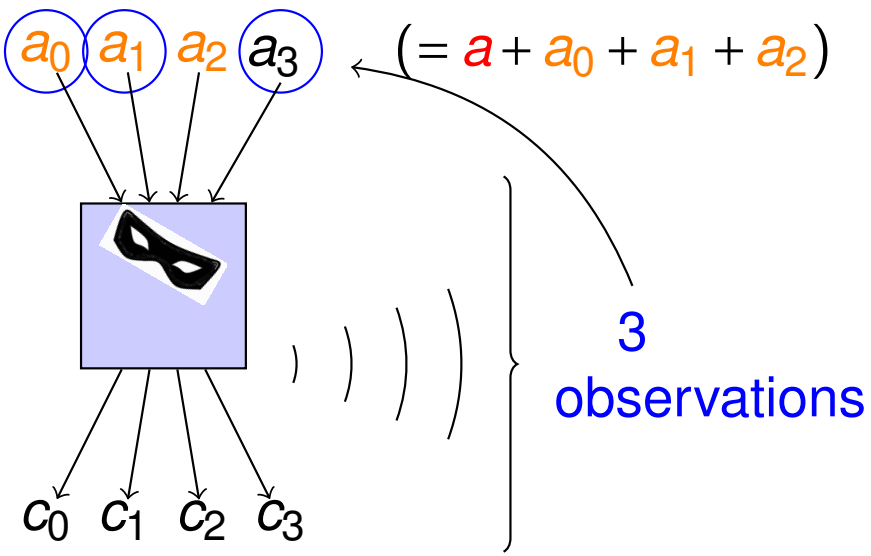

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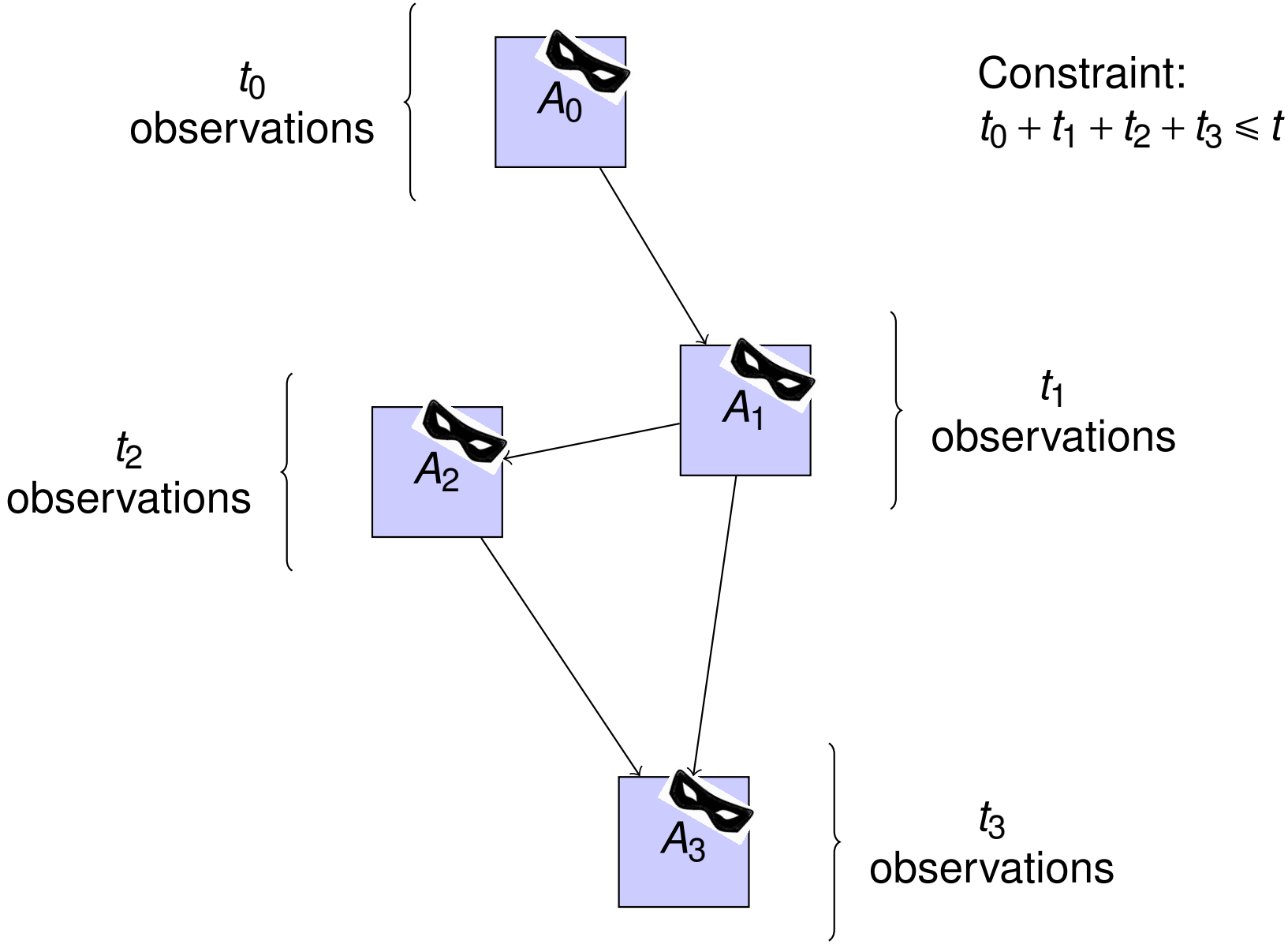
➜ straightforward for linear functions

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

Current Issues



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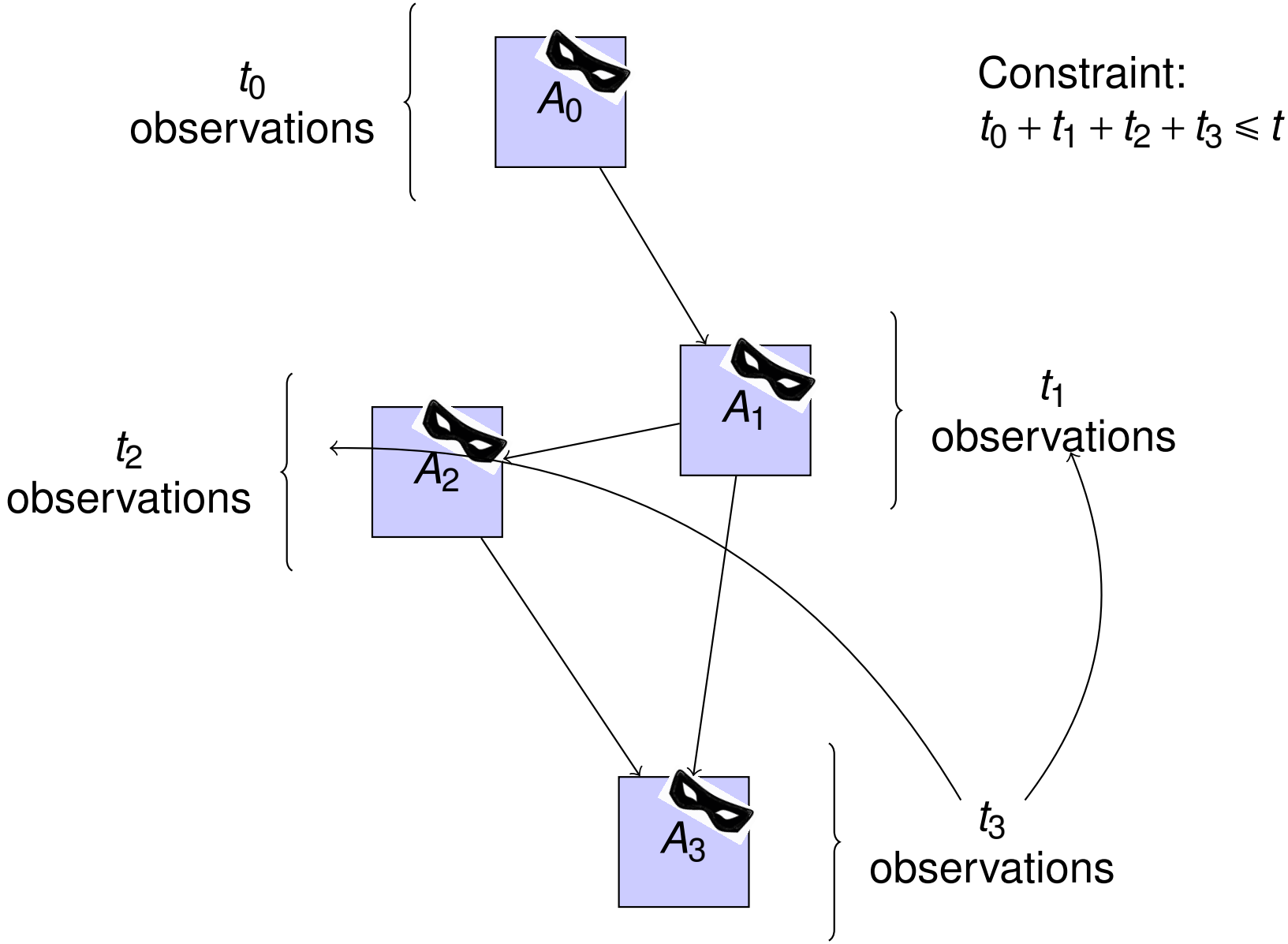

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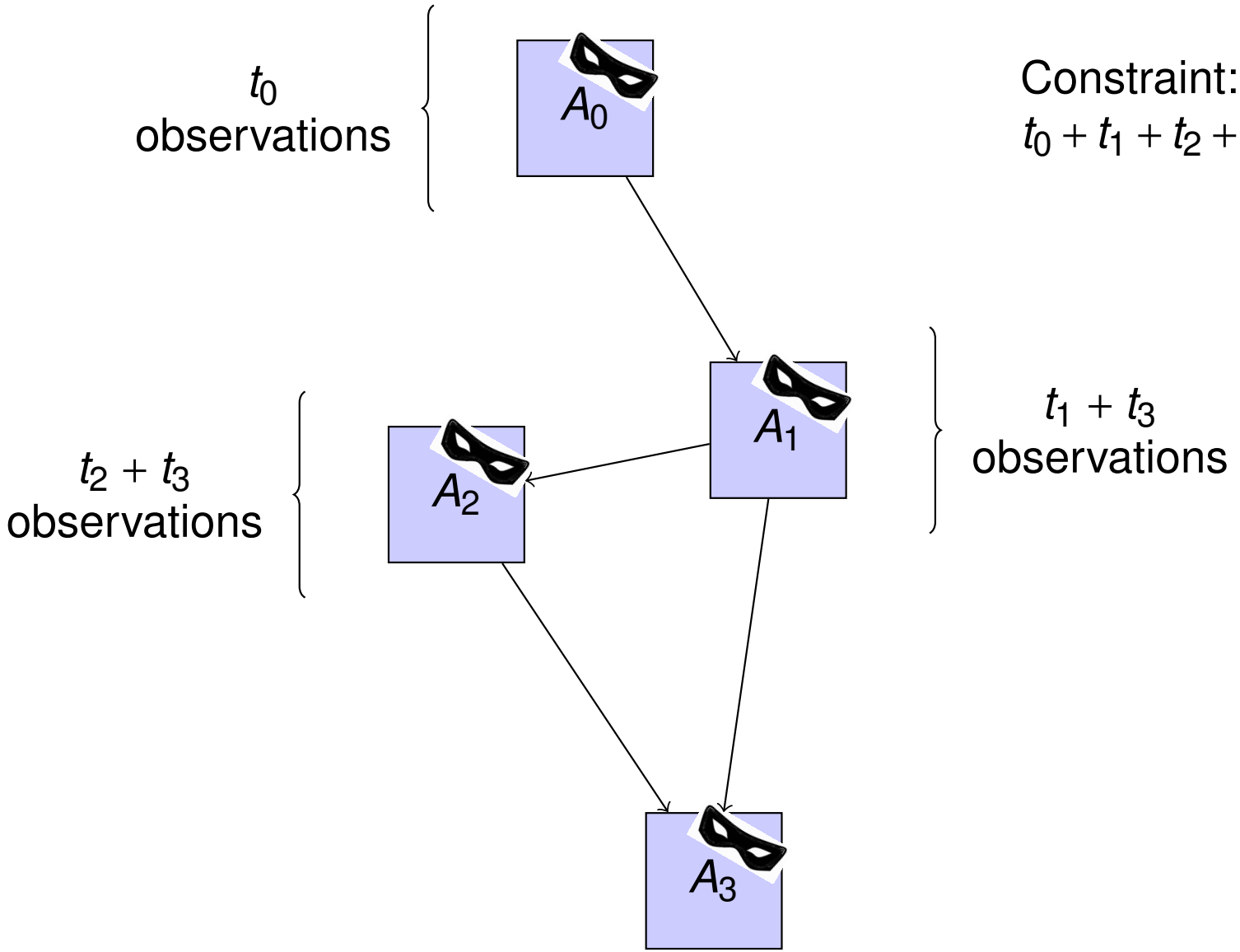

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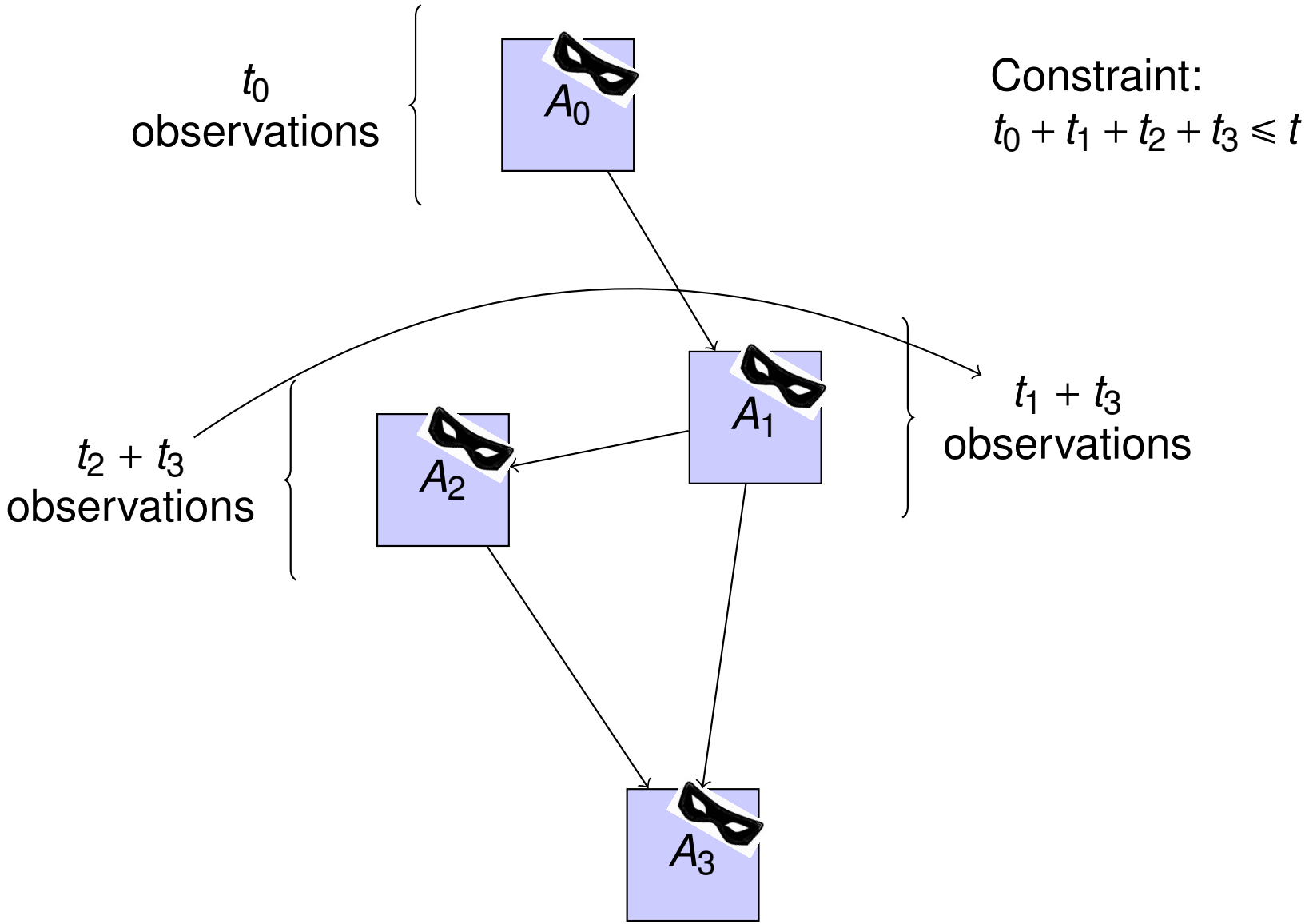

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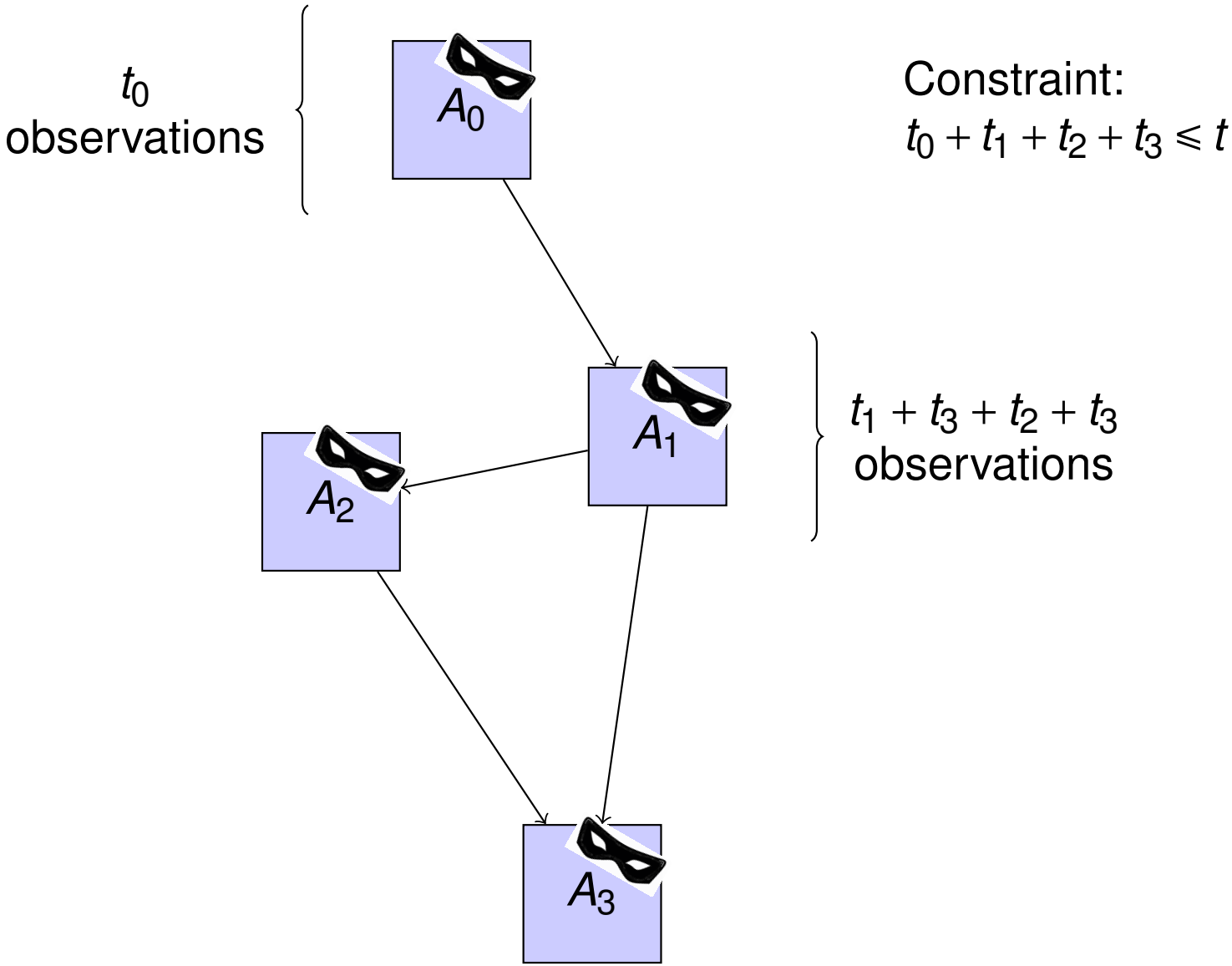

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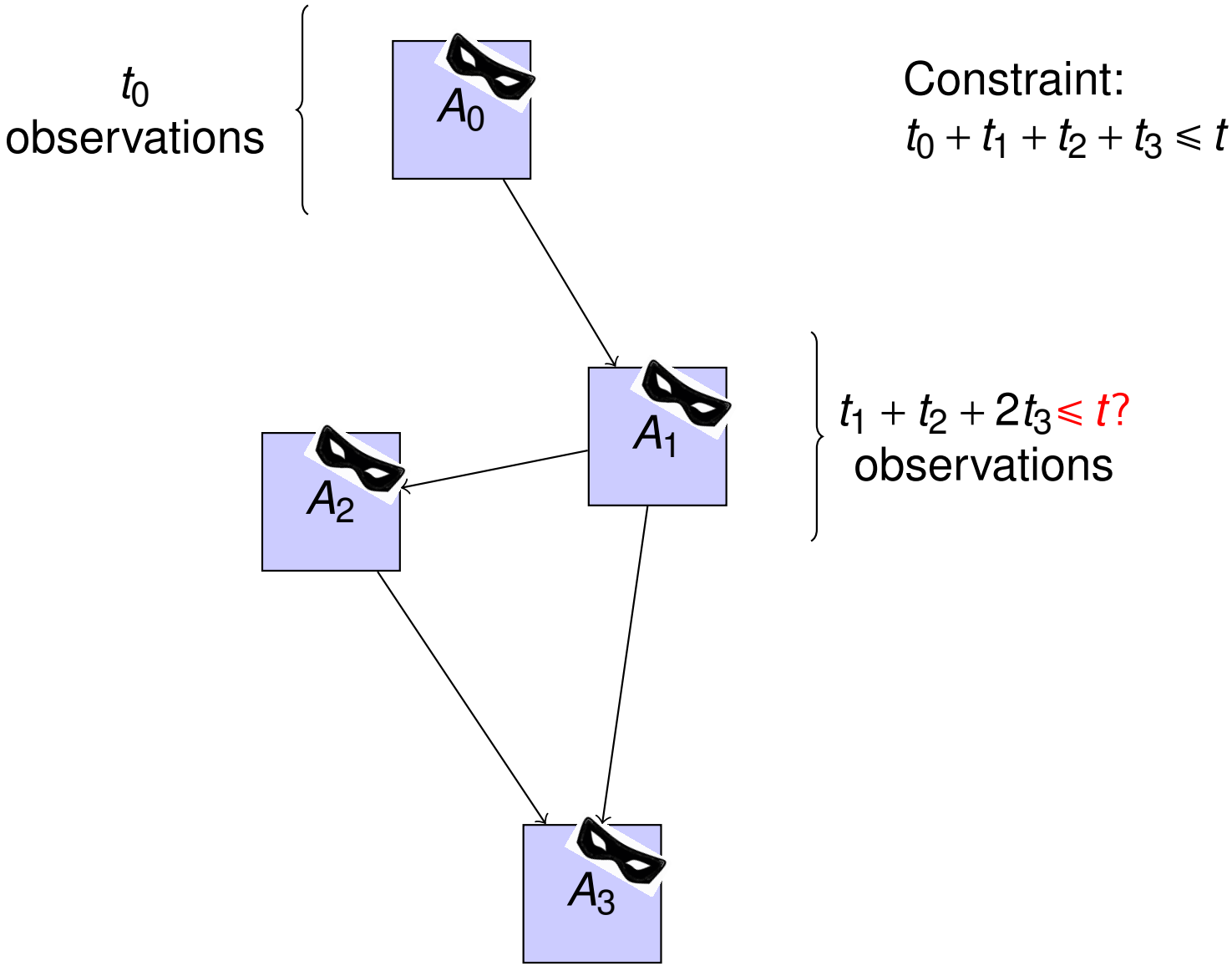

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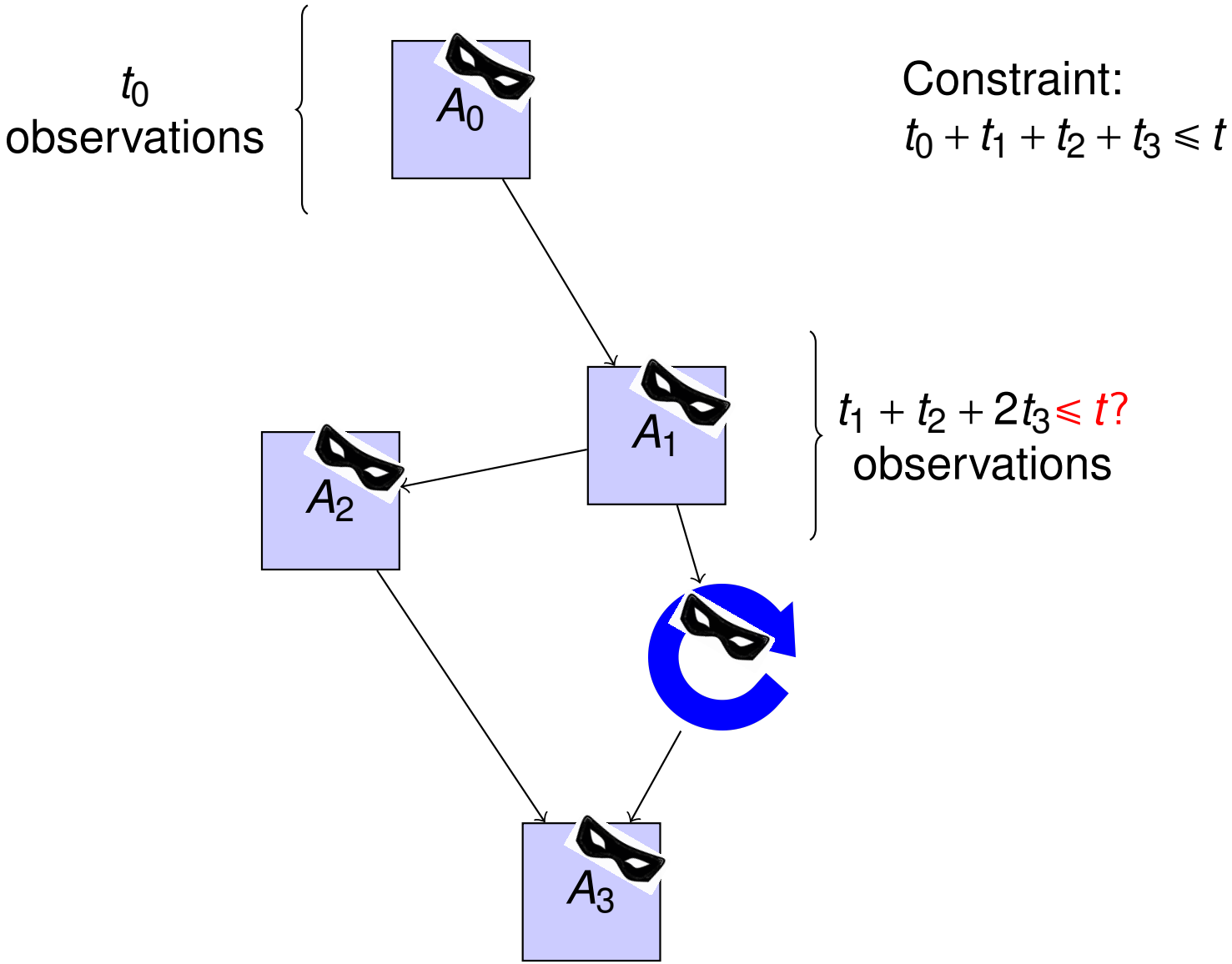

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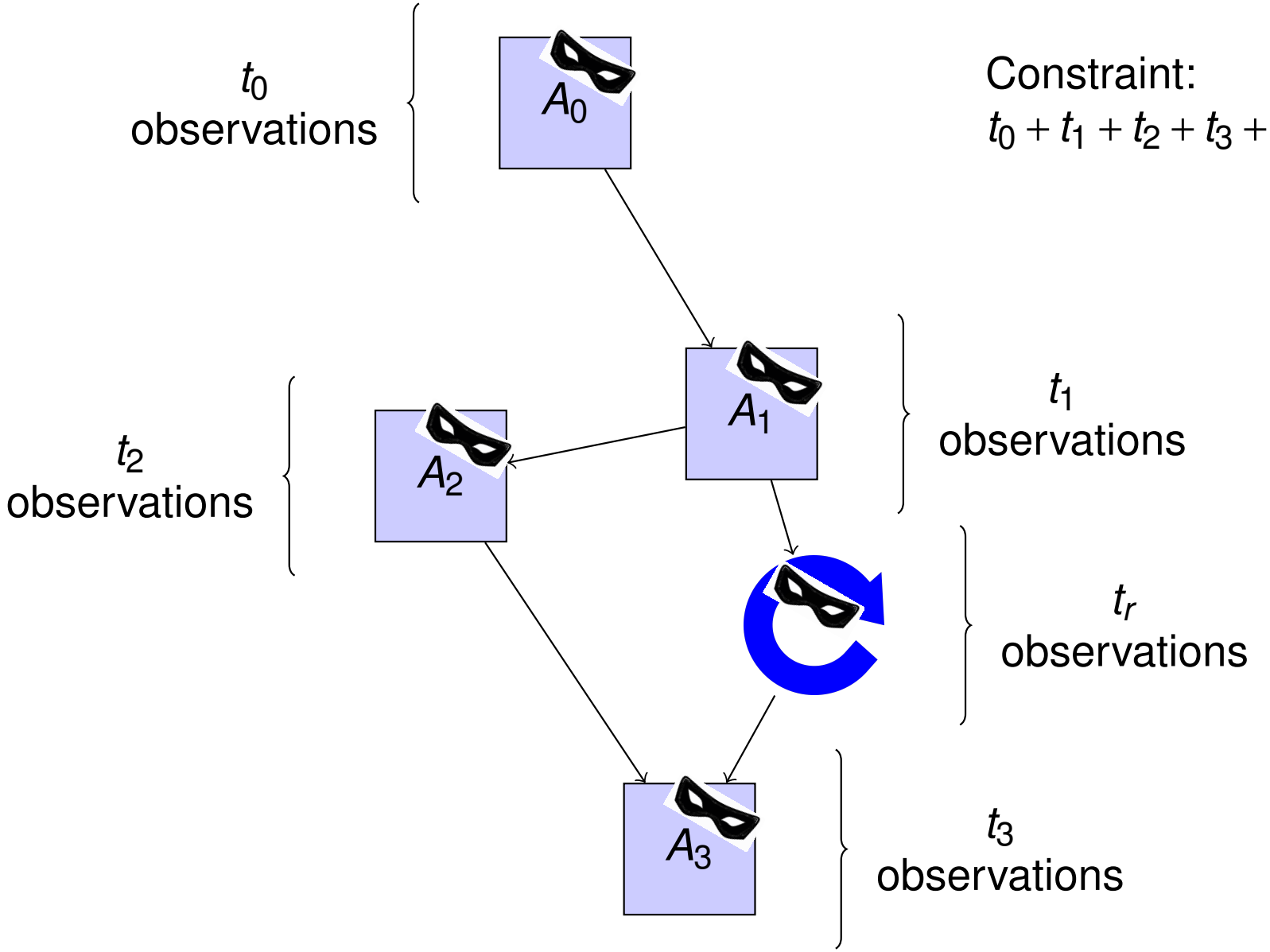

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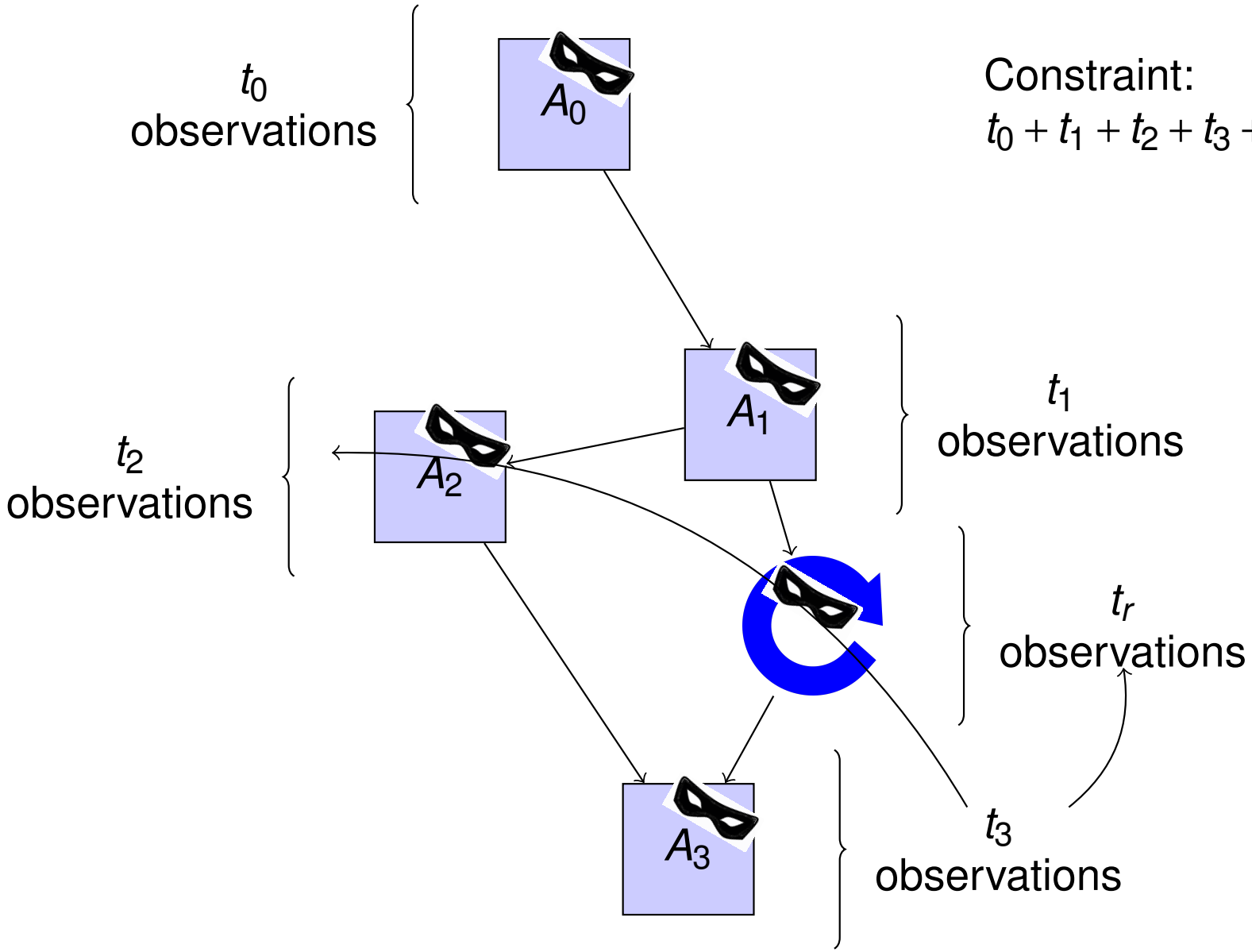

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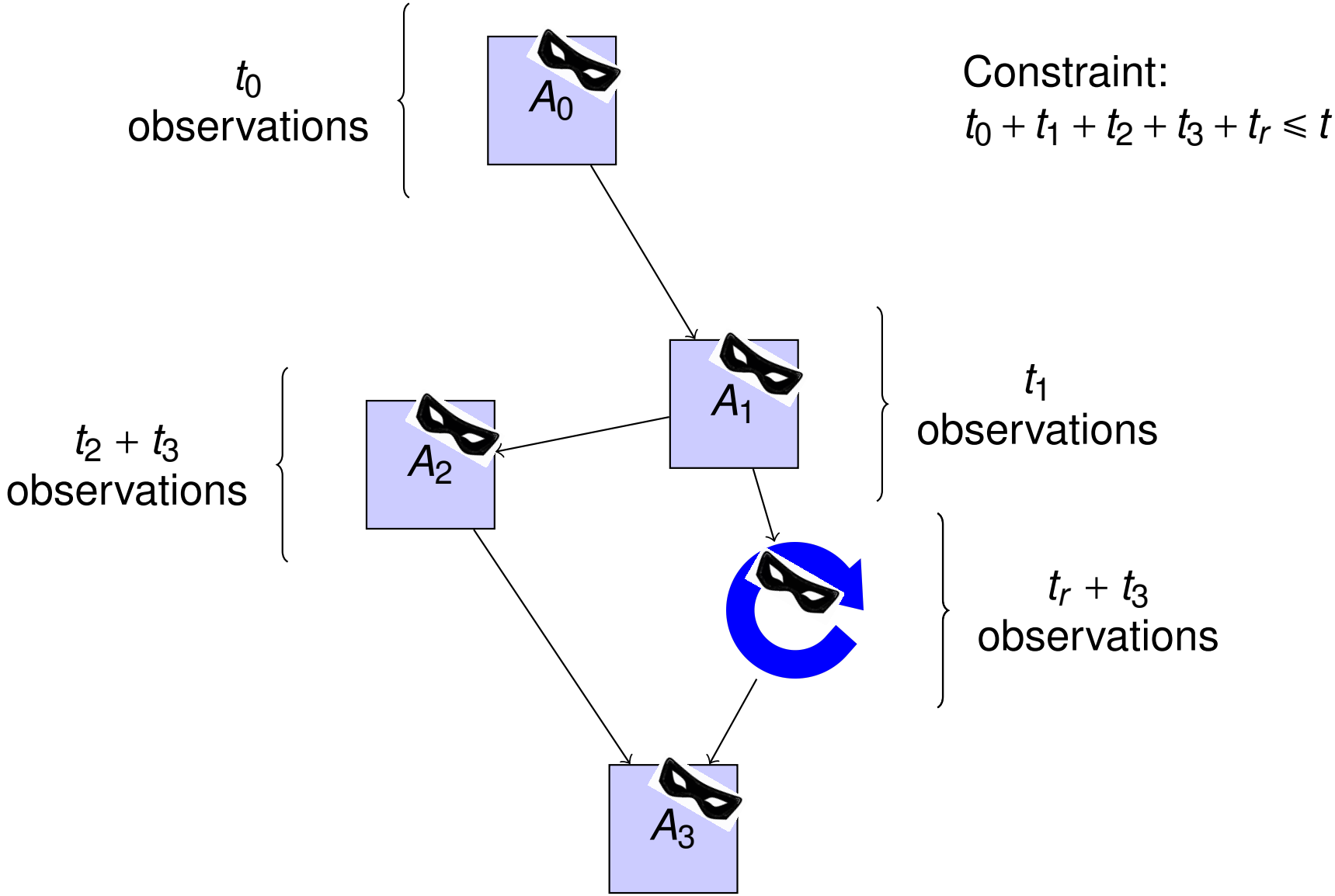

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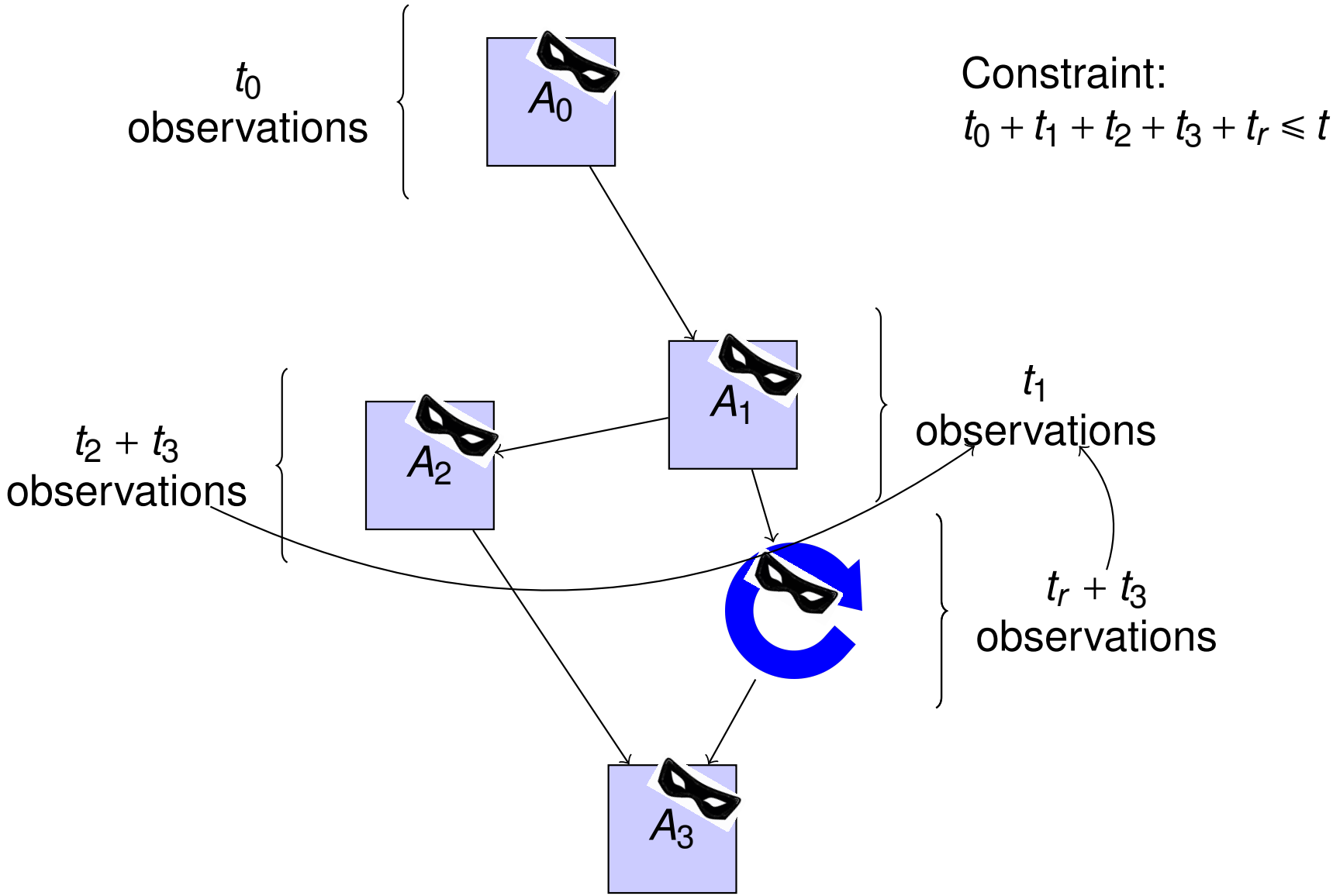

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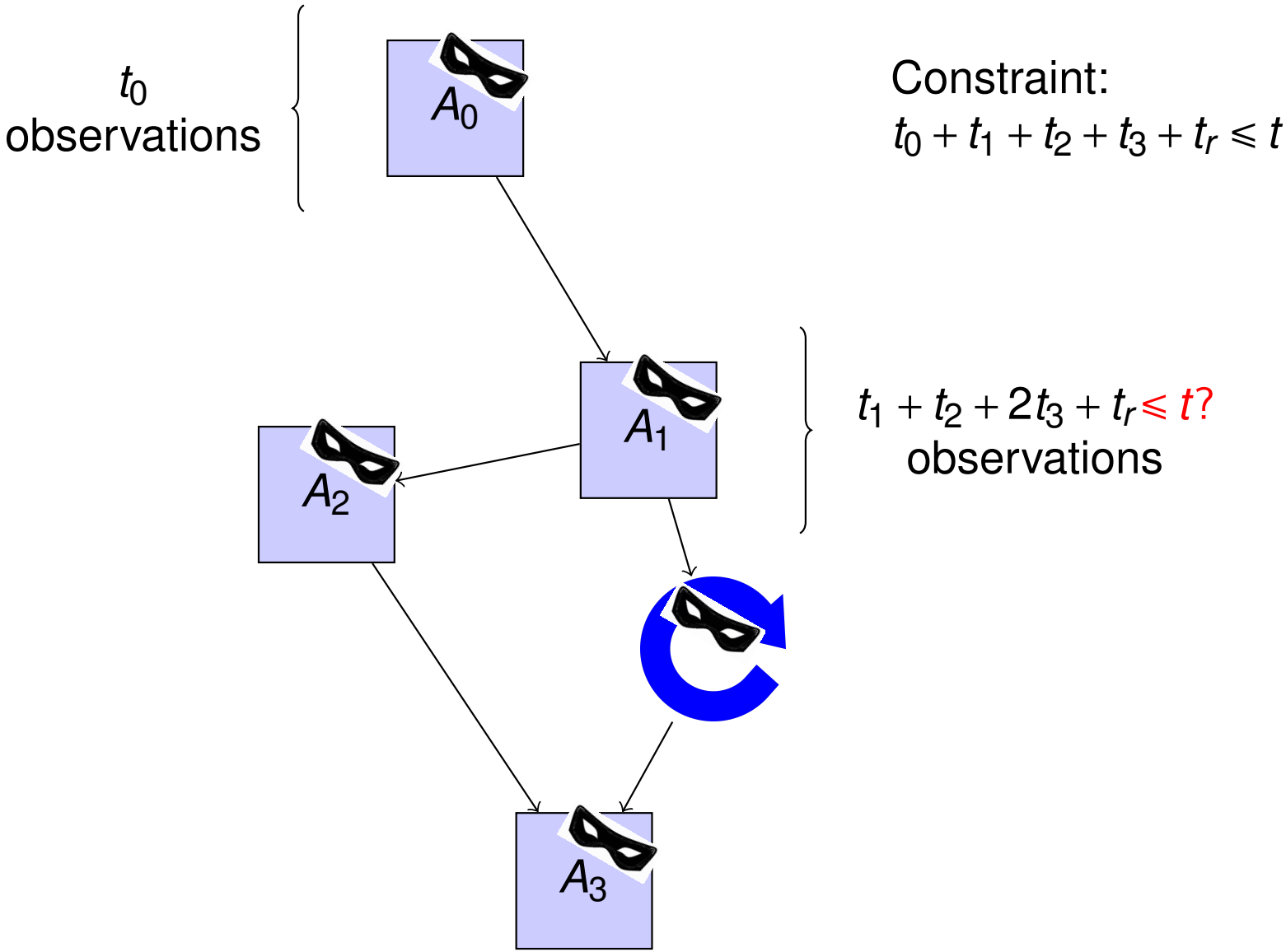


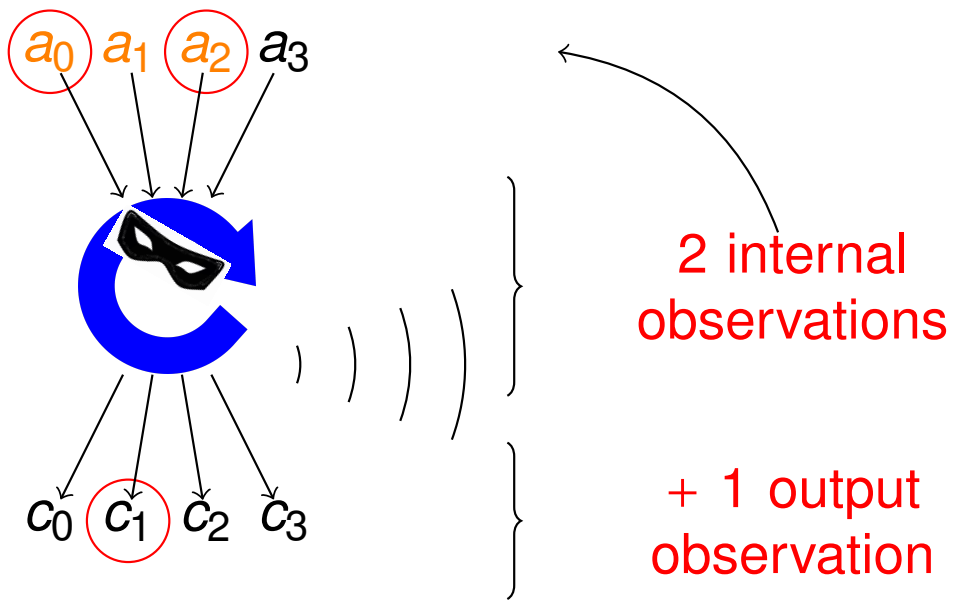
Stronger security property for Refresh

Strong Non-Interference in the t-probing model:

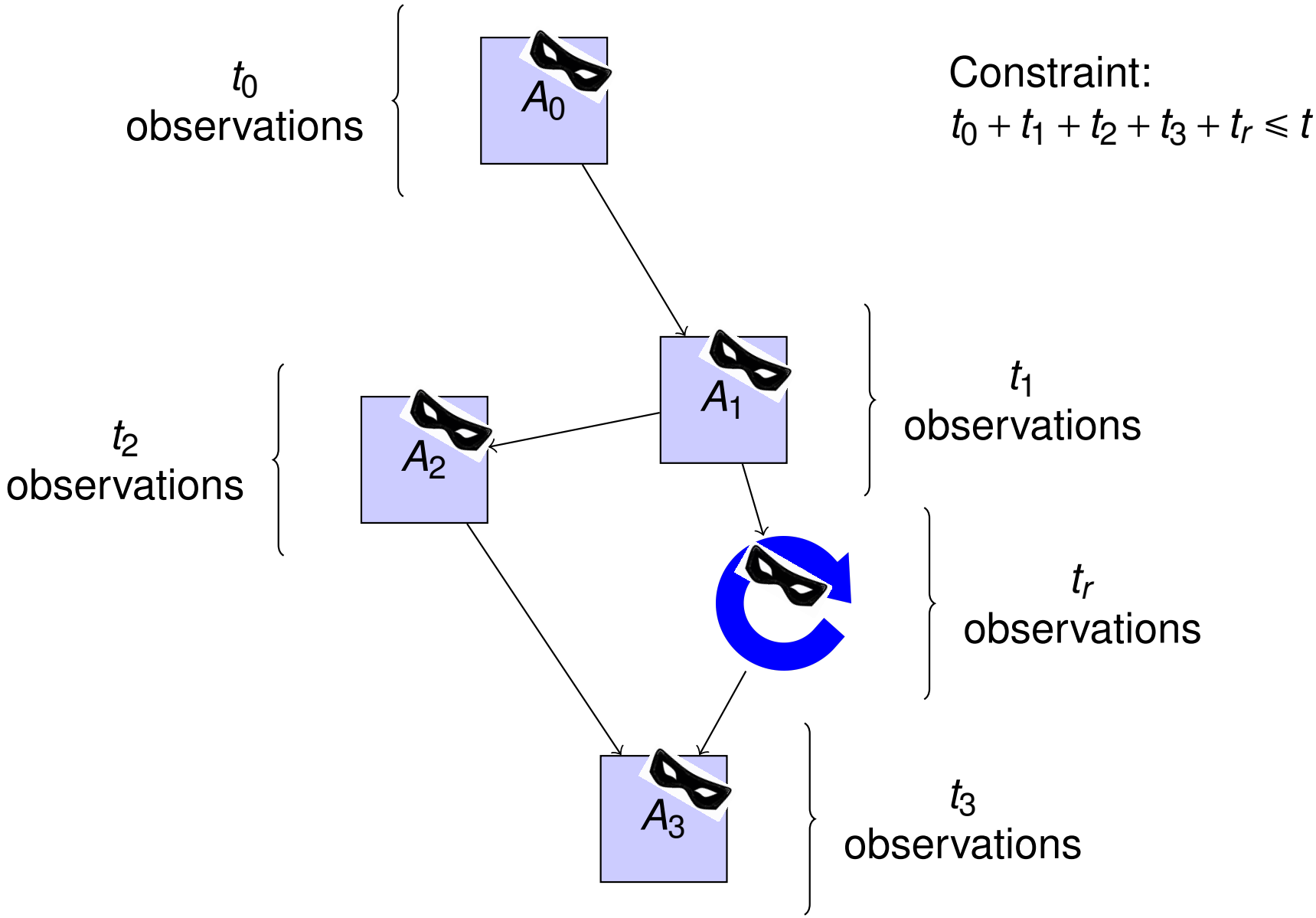
if t is not fixed: show that any set of t intermediate variables with

- 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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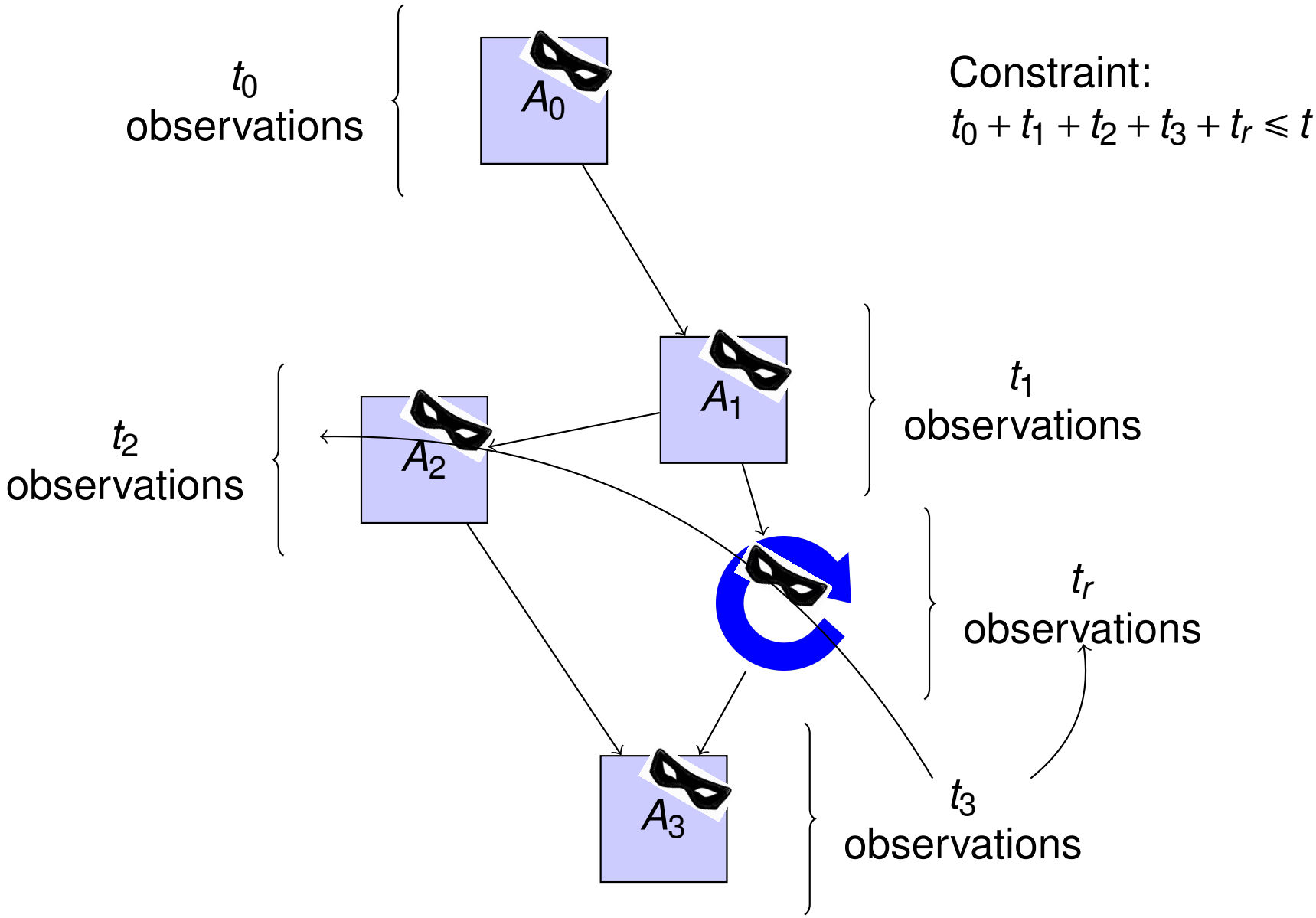

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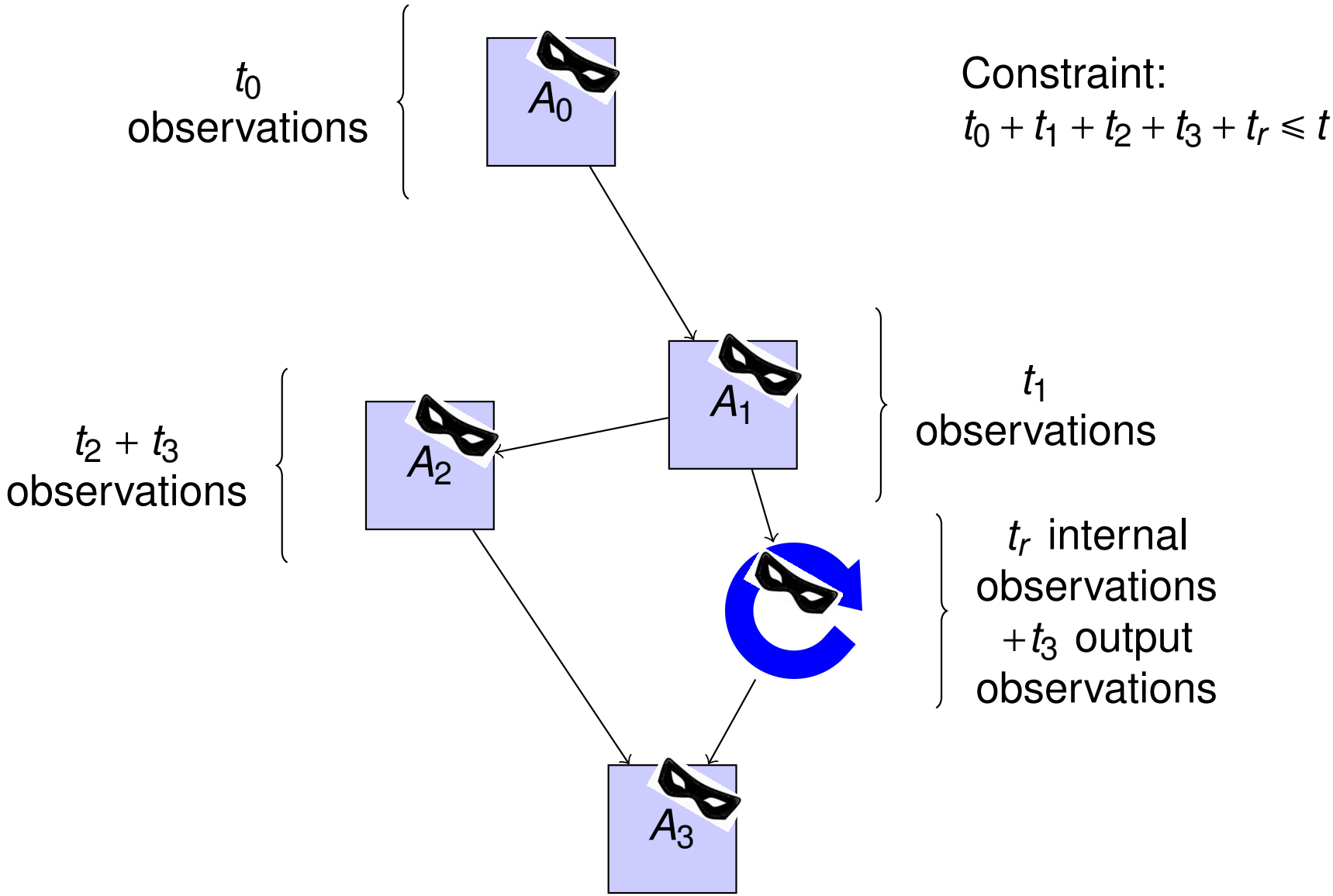

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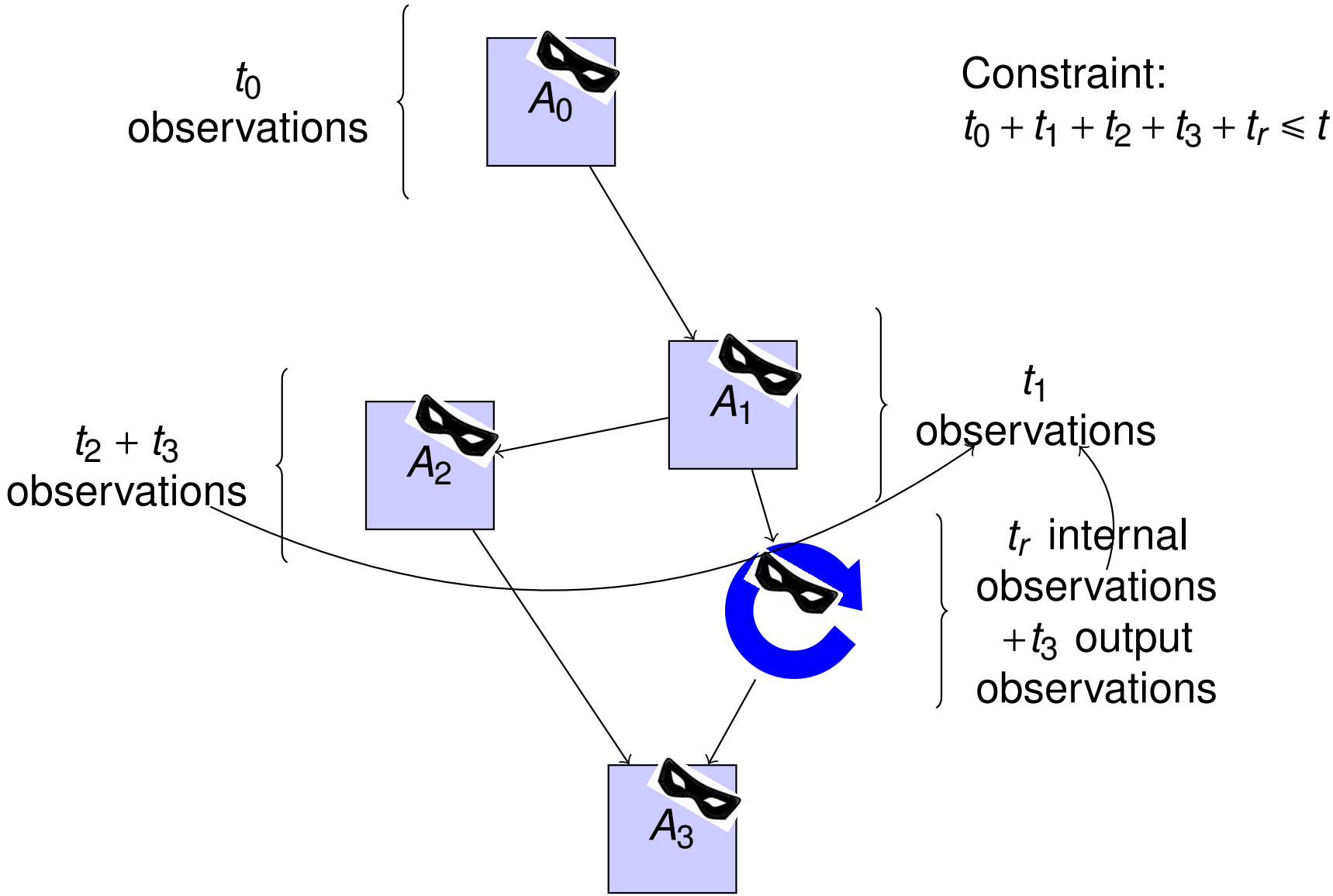

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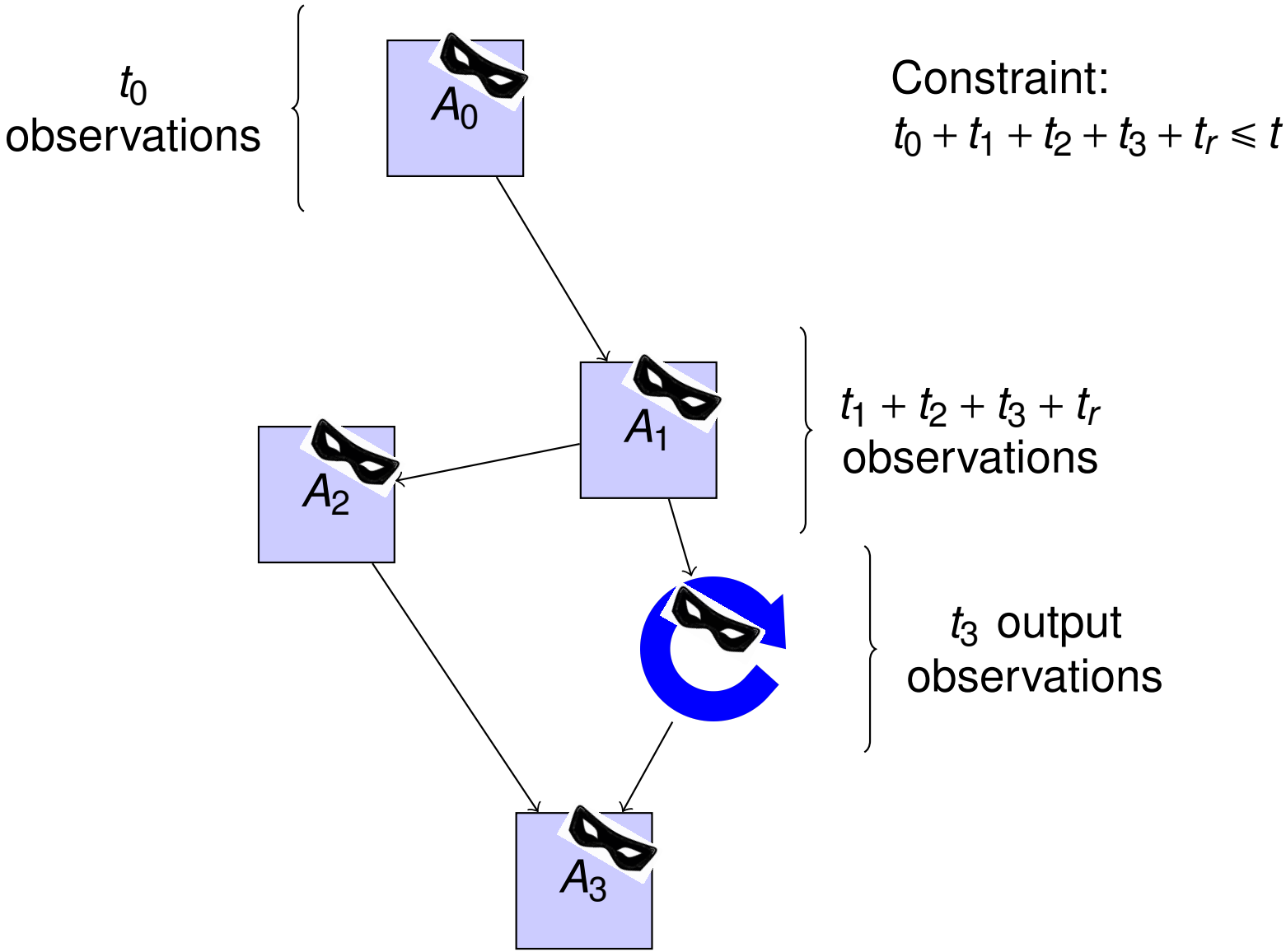

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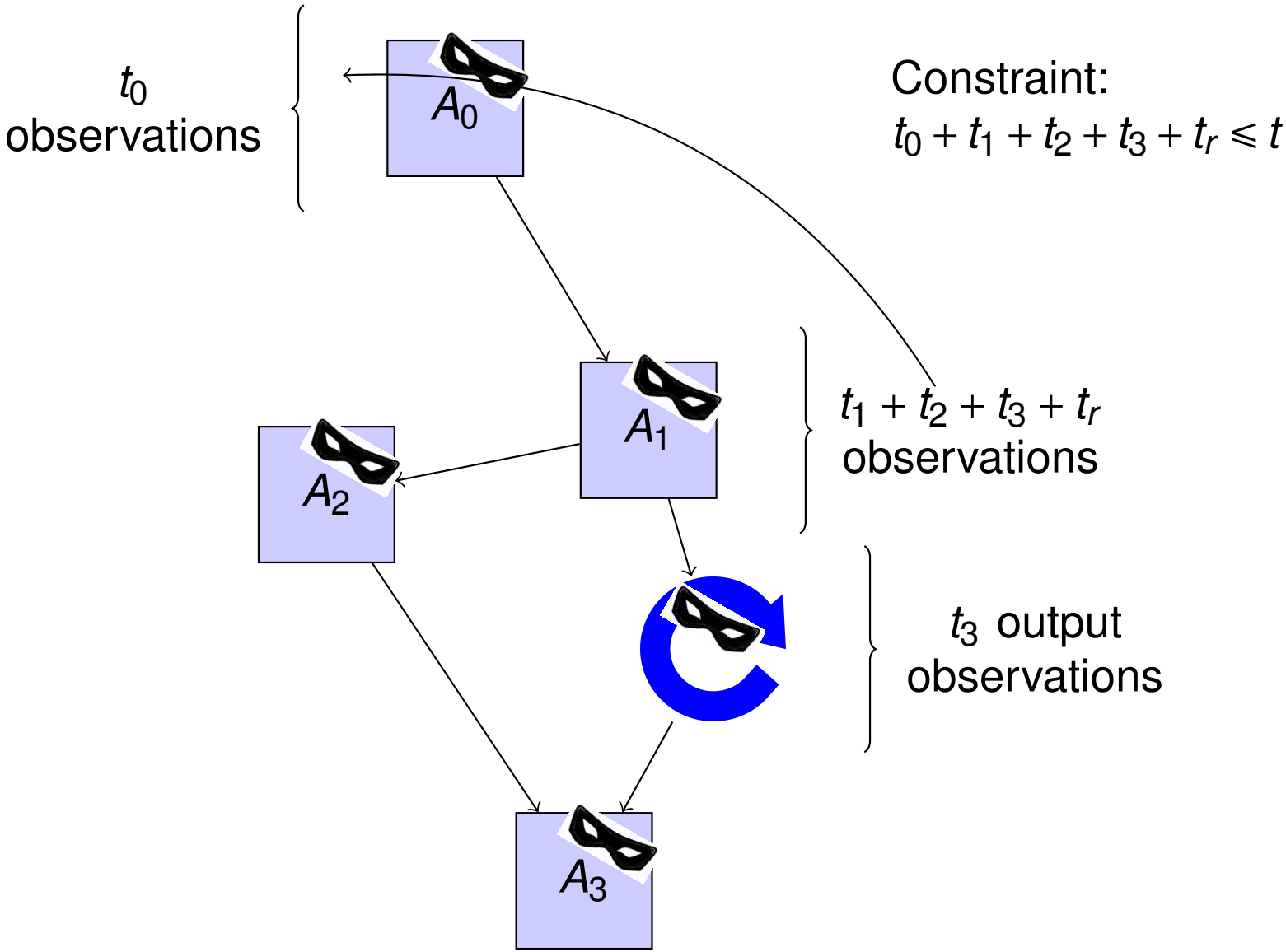

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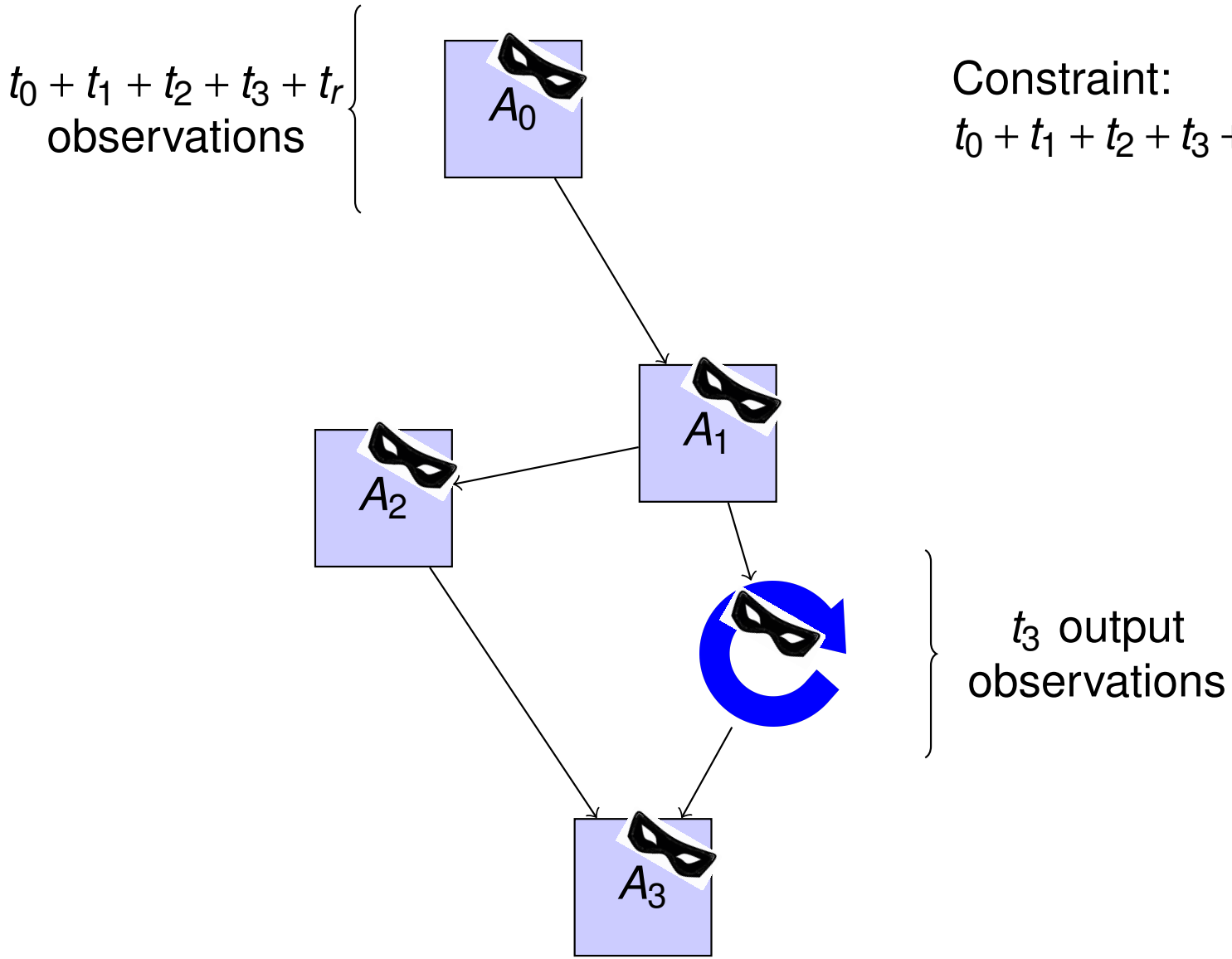

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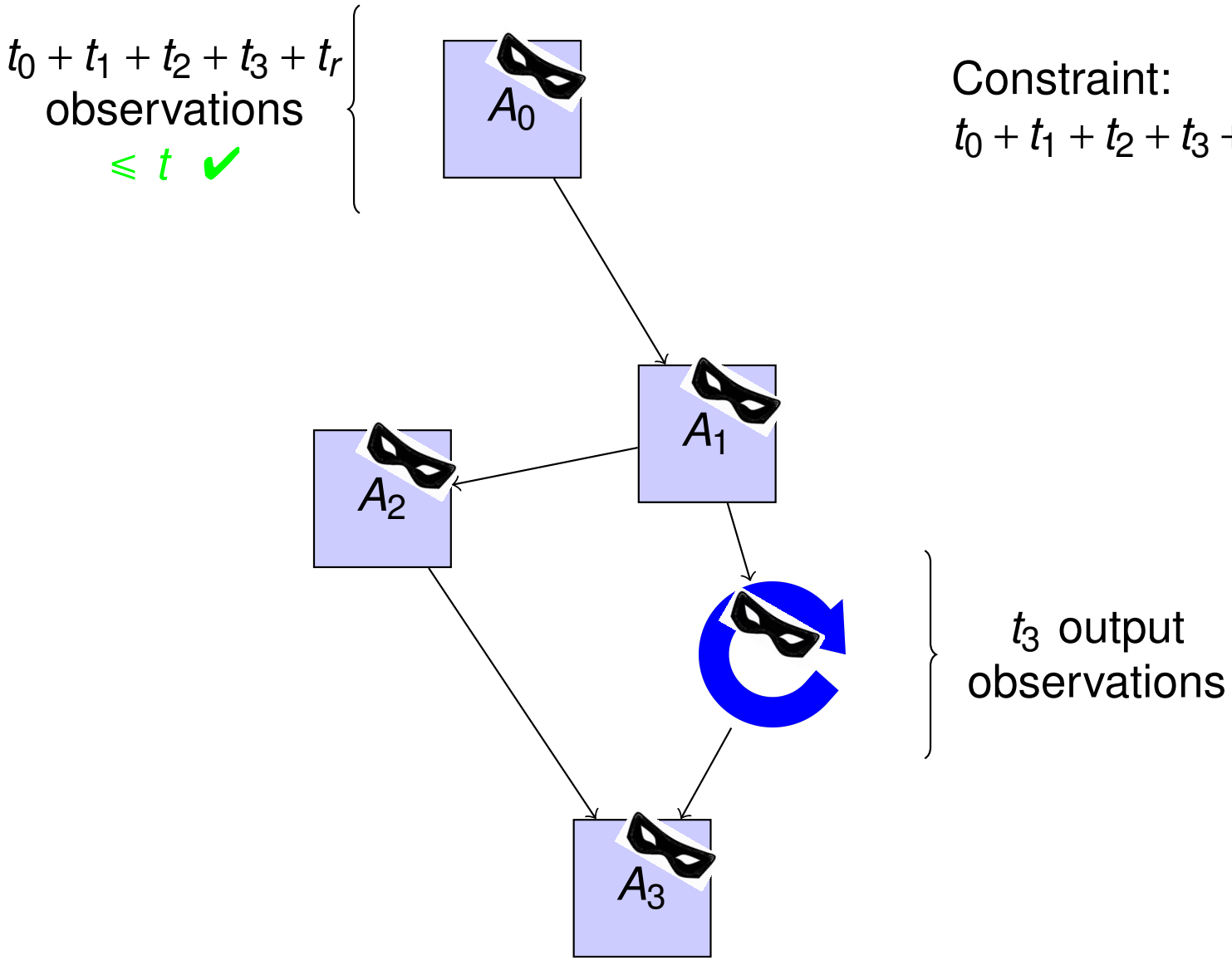
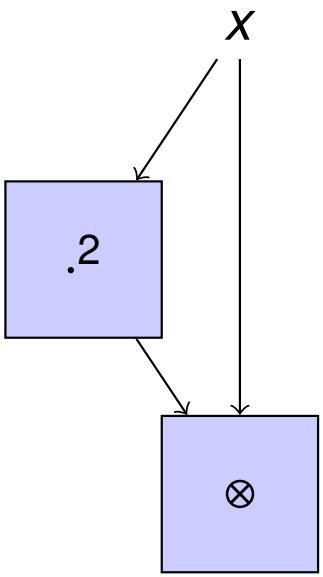


Secure Composition

Automatic tool for C-based algorithms

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



Secure Composition

Automatic tool for C-based algorithms

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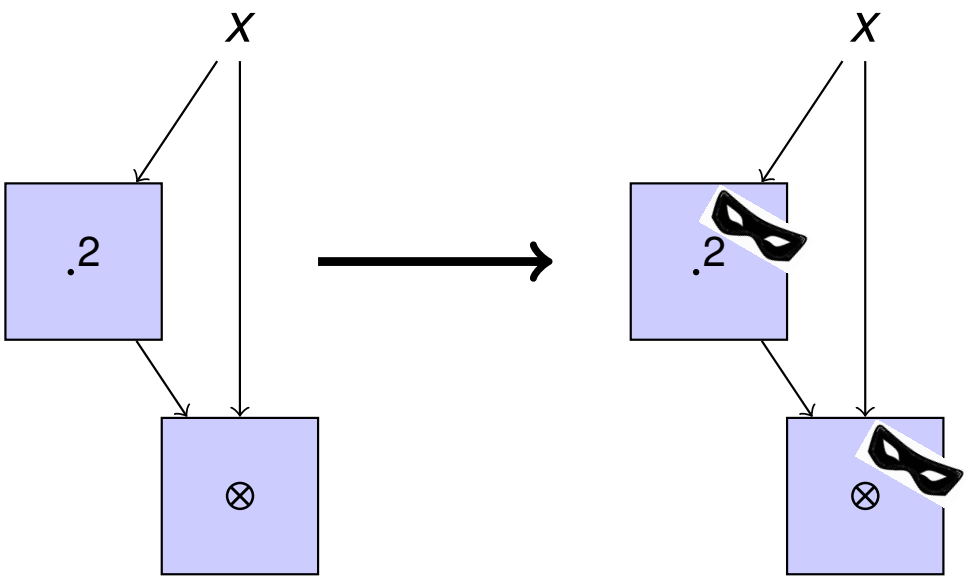

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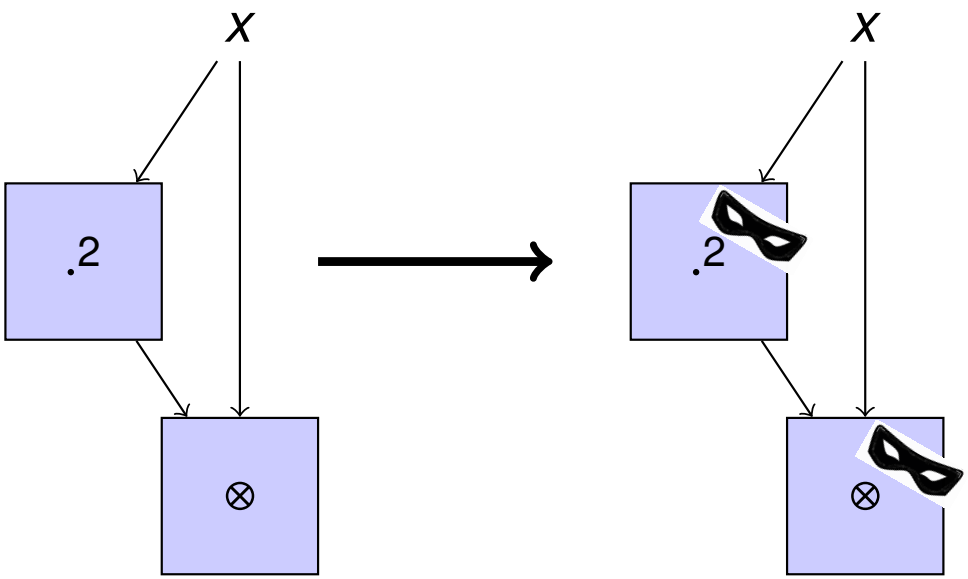

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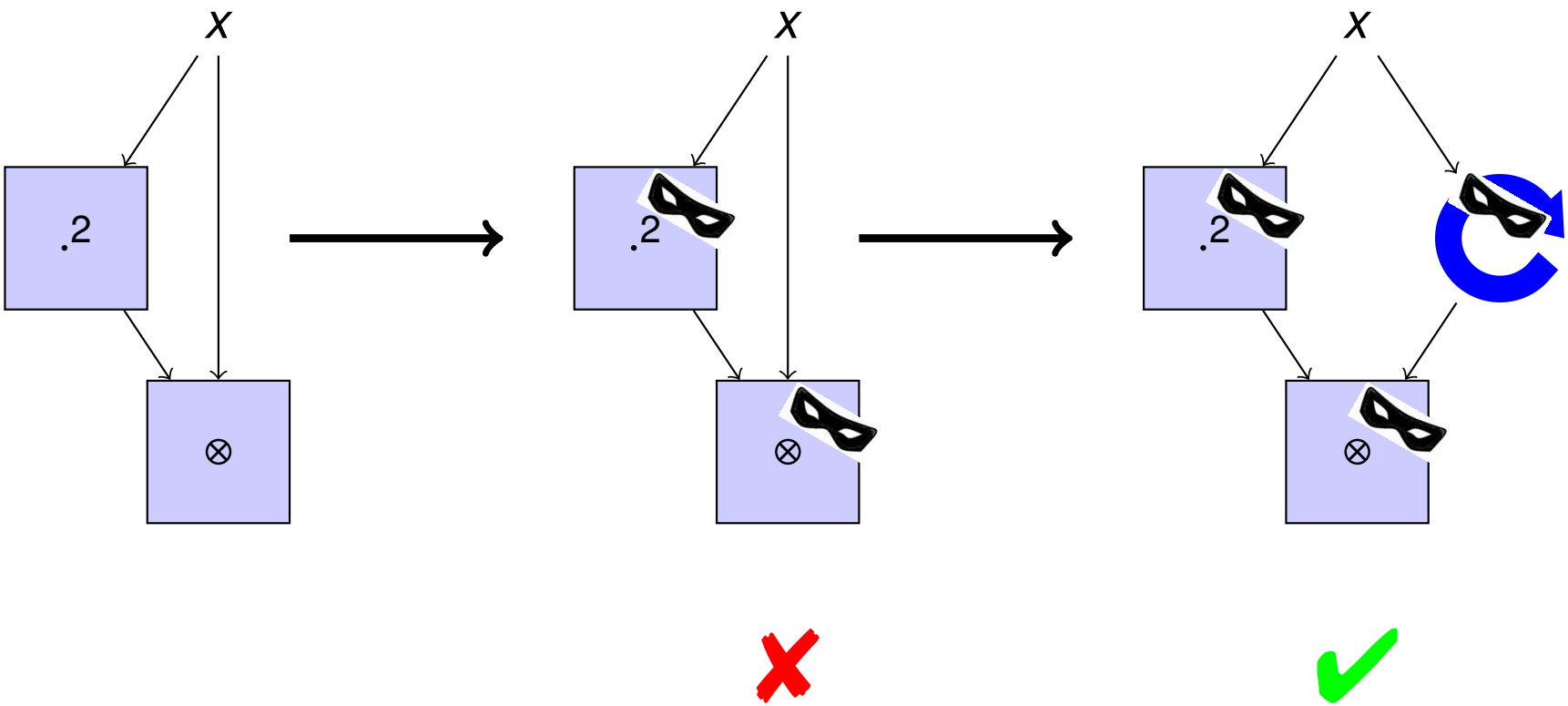

Some Results

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
Speck	61	6.22s	38Mo

[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 on Higher-Order Masking

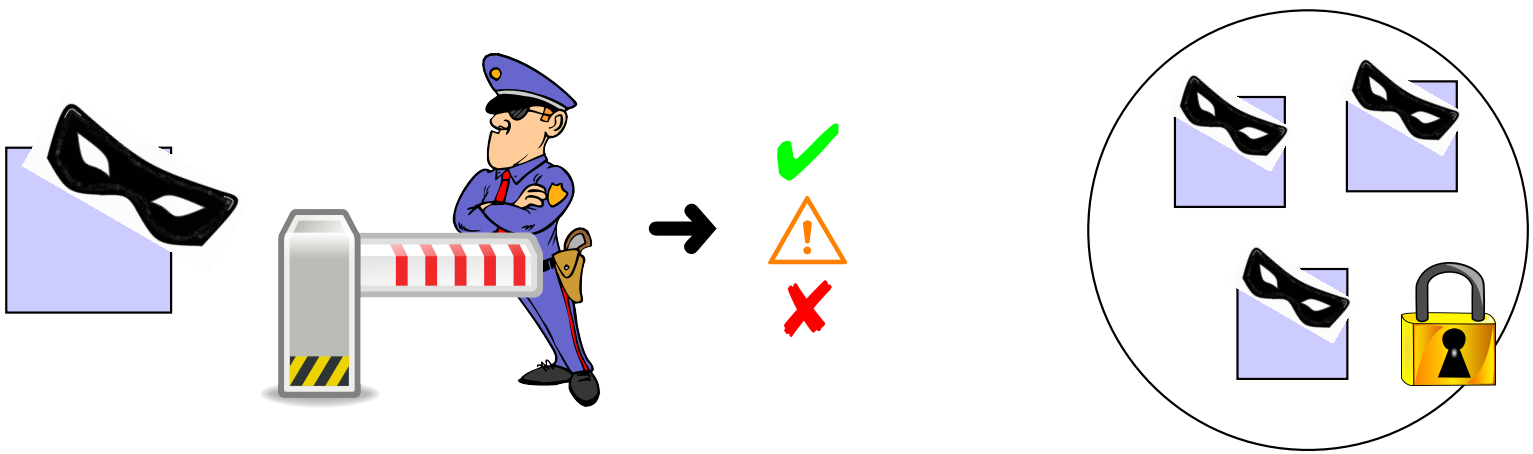
Summary

- ✔ 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

Cryptography: countermeasures against Power-Analysis Attacks



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

Publications


Sonia Belaïd, Luk Bettale, Emmanuelle Dottax, Laurie Genelle, and Franck Rondepierre.
Differential Power Analysis of HMAC SHA-2 in the Hamming weight model. SECRYPT 2013.


Michel Abdalla, Sonia Belaïd, and Pierre-Alain Fouque.
Leakage-resilient symmetric encryption via re-keying. CHES 2013.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Gilles Barthe, Sonia Belaïd, François Dupressoir, Pierre-Alain Fouque, Benjamin Grégoire, and Pierre-Yves Strub.
Verified proofs of higher-order masking. EUROCRYPT 2015.


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Masking and leakage-resilient primitives: One, the other(s) or both? Cryptography and Communications 2015.


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