CryptoExperts

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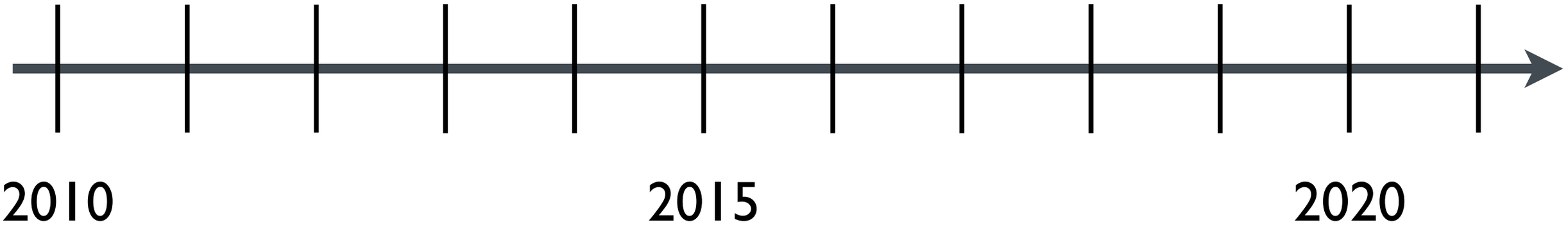
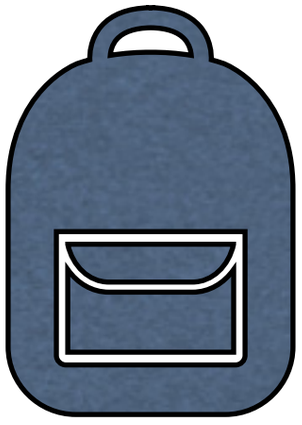
# On the road to building formally verified side-channel countermeasures

CrossFyre 2021

December 2, 2021


2010
2015
2020

# First Steps: 2010



- Engineering school
- Some lectures in cryptography
- 1 internship at Thales in crypto

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- Engineering school
- Some lectures in cryptography
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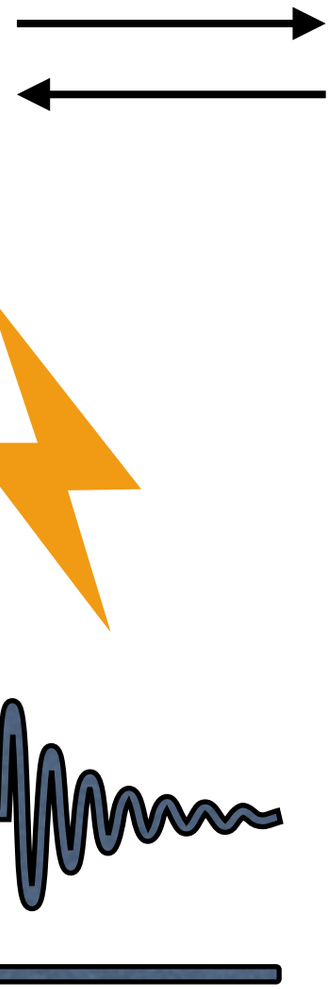
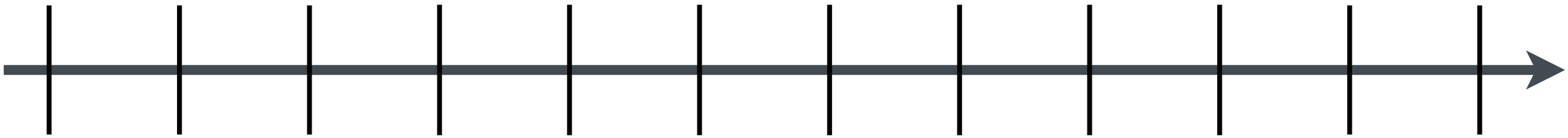
# Side-Channel Attacks

inputs / outputs

Power consumption

$$\approx \left|\left|_i \left(f(v_i) + \eta\right)\right.\right.$$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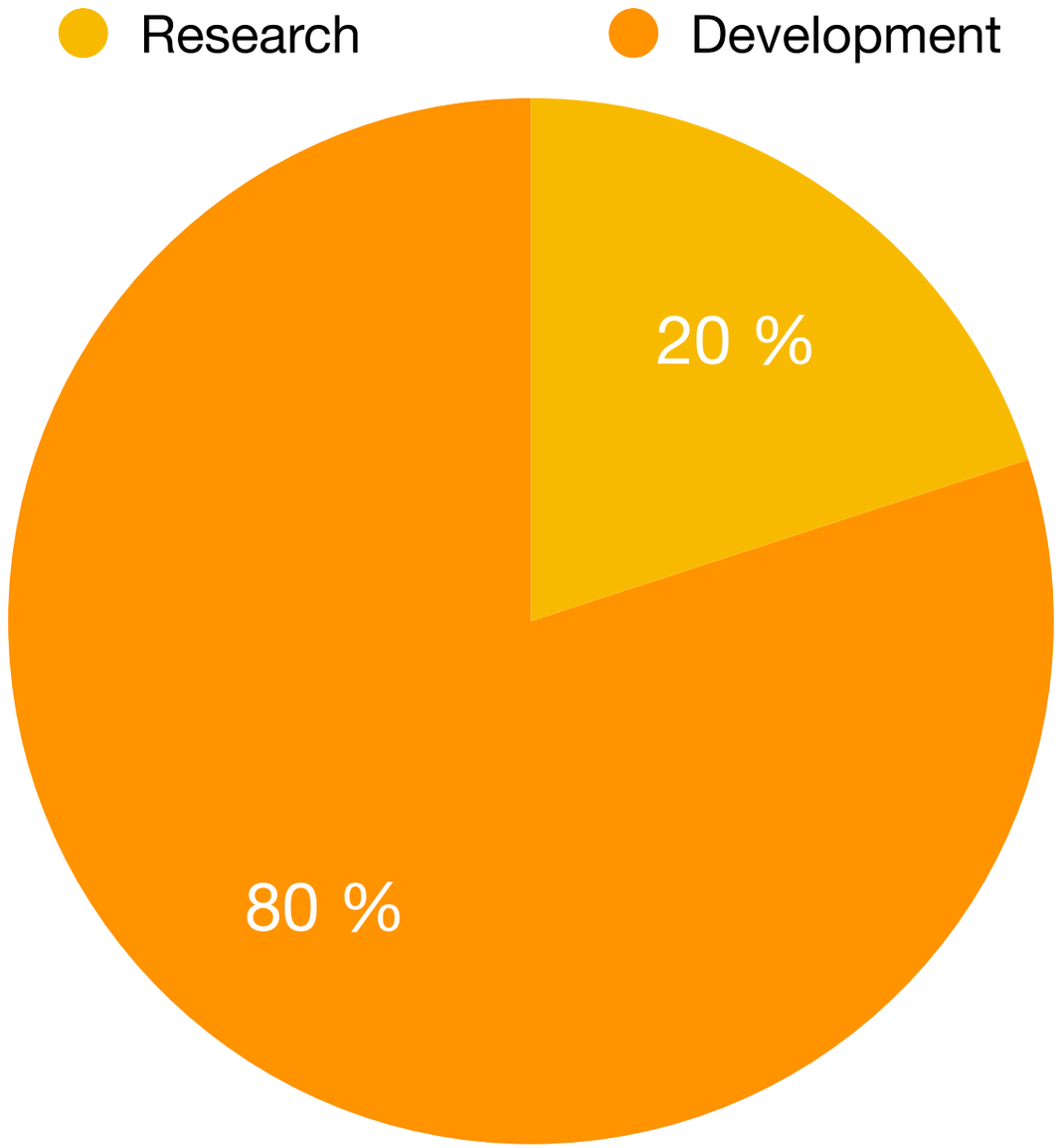
# First Steps: 2011

- Engineering school
- Some lectures in cryptography
- 2 internships at Thales in crypto

- First working experience as an engineer
- No PhD thesis
- Some research in crypto

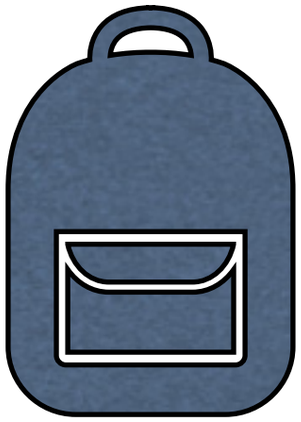
# First Working Experience

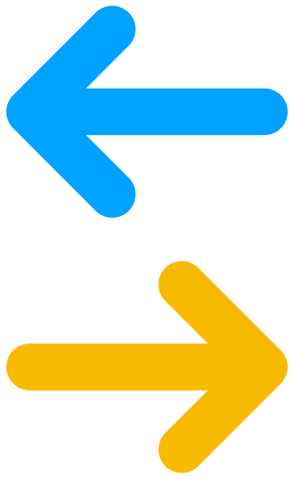


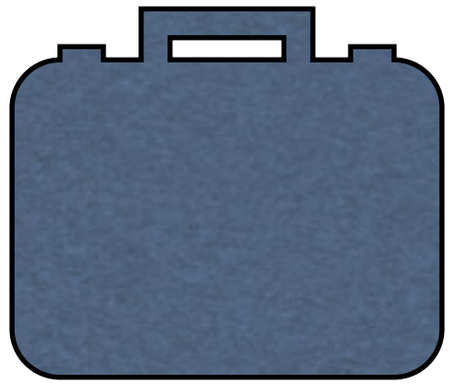

Oberthur
Technologies
Grenoble INP
ENSIMAG
2010
2015
2020

# First Steps: 2012

- Second working experience as an engineer
- PhD thesis in crypto
- Some research in crypto







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Oberthur Technologies

Grenoble INP ENSIMAG

PhD thesis

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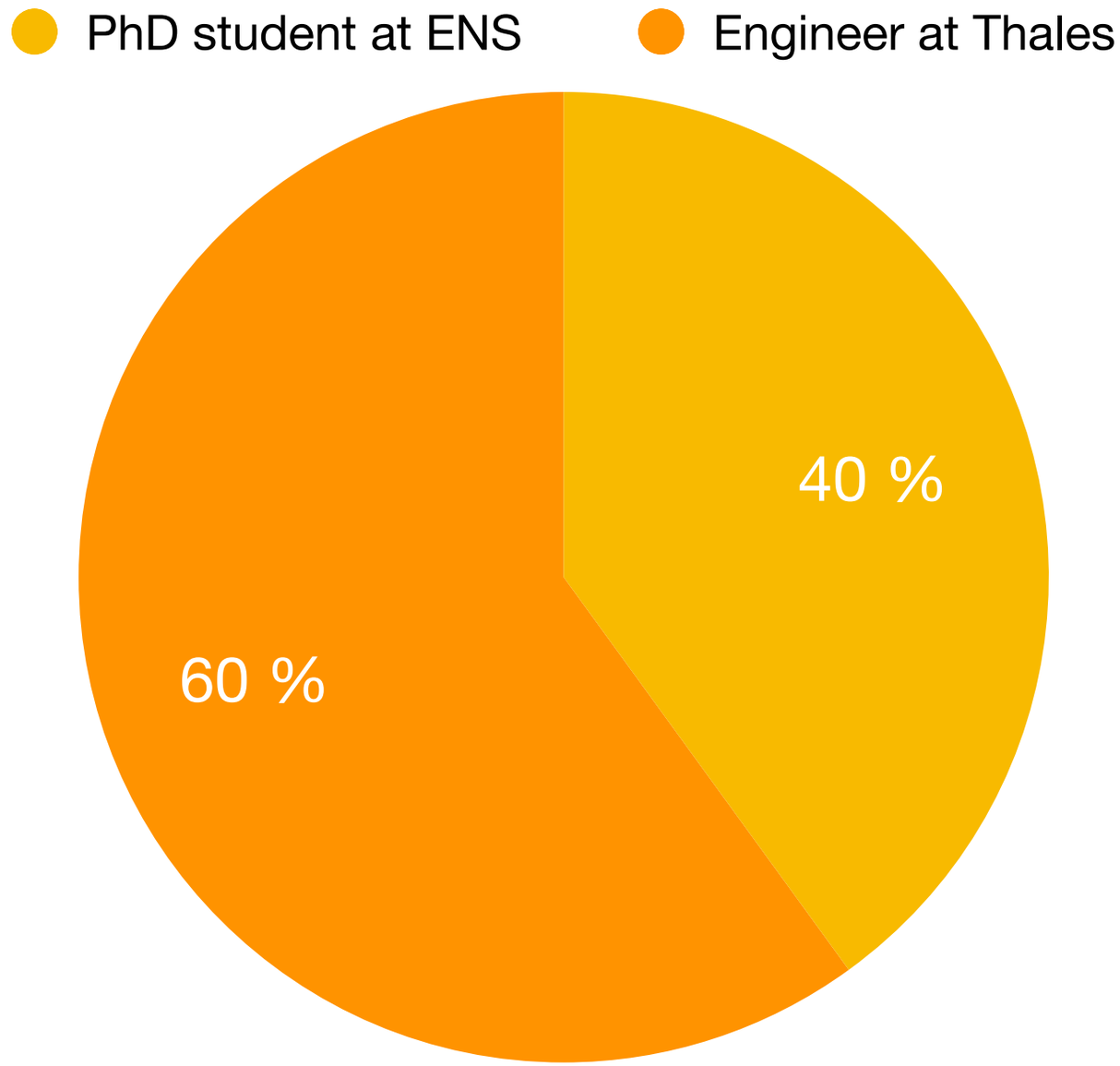
# First Steps: 2012



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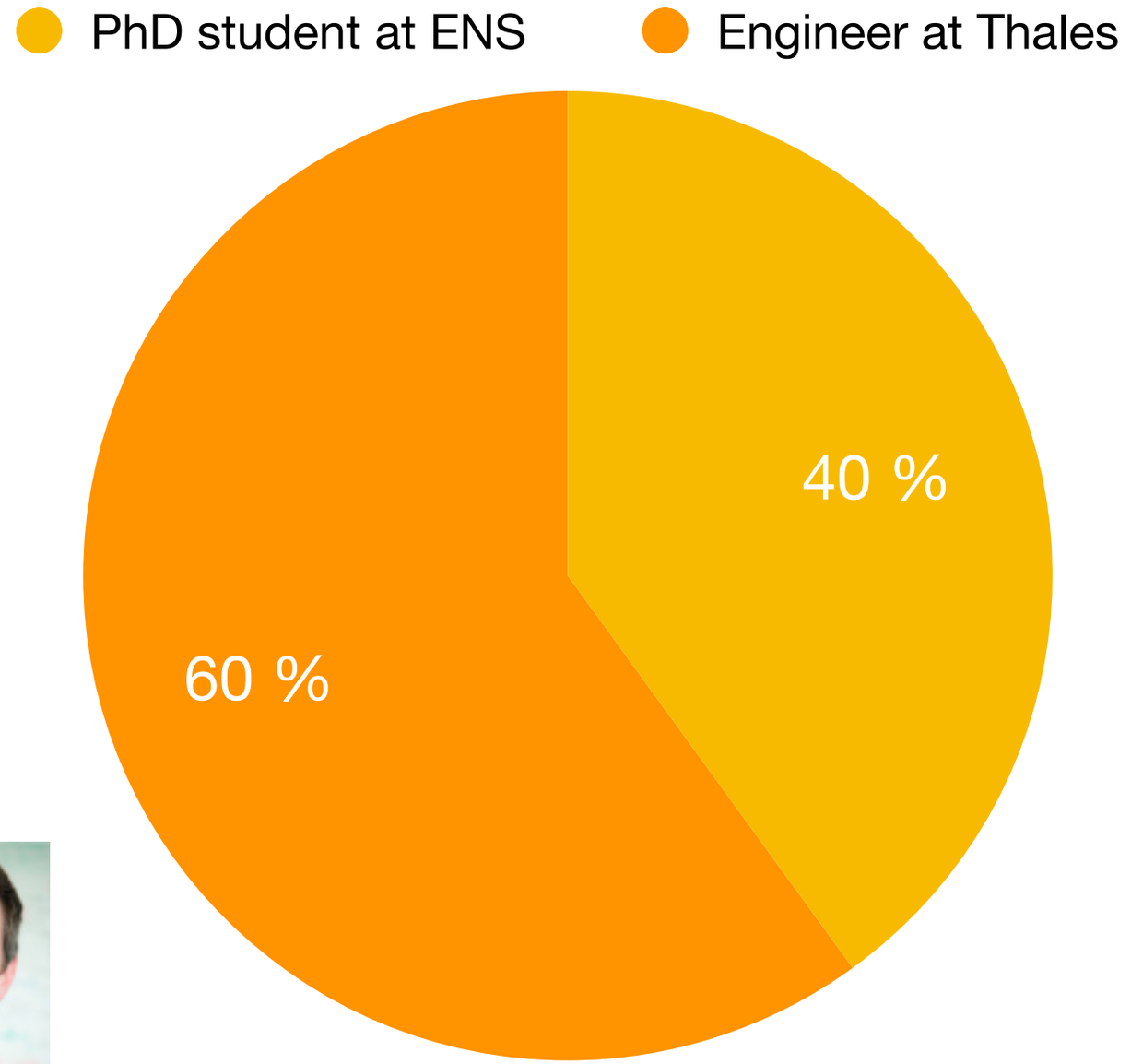




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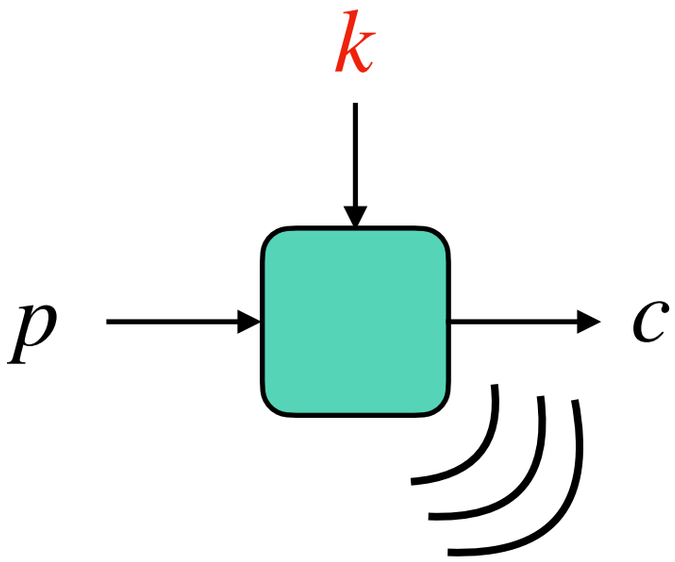
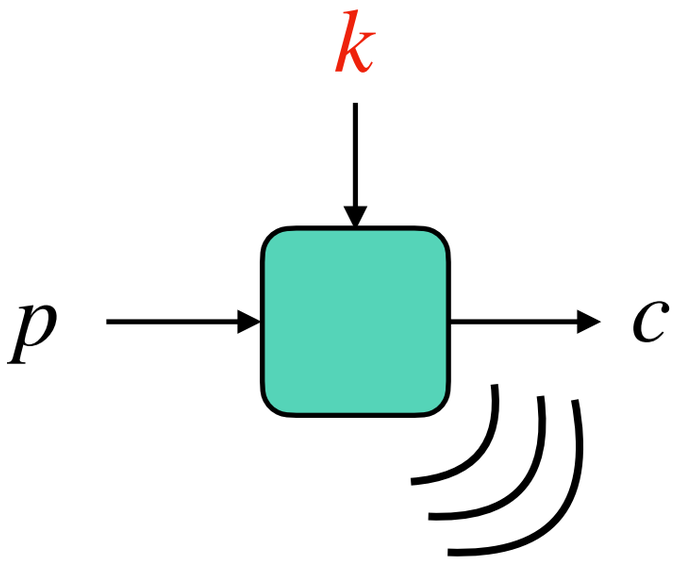
# Side-Channel Countermeasures




Problem: the leakage is key-dependent

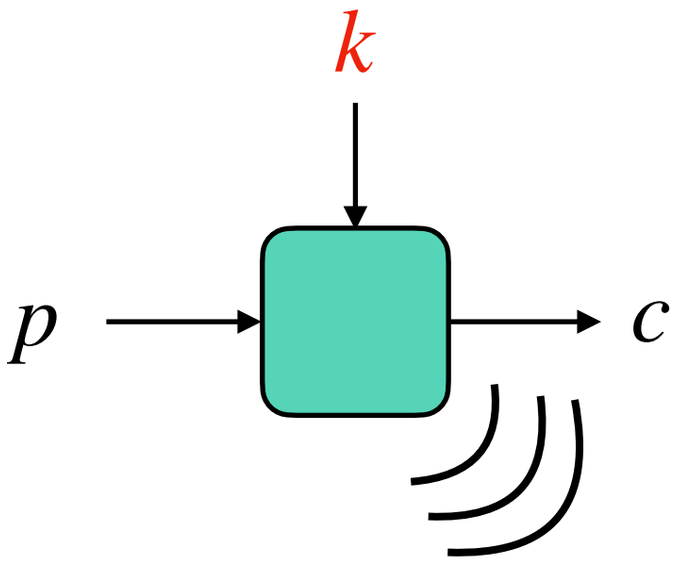
# Side-Channel Countermeasures




Problem: the leakage is key-dependent

## Solution 1: Fresh Re-Keying (regularly change the key)

# Side-Channel Countermeasures

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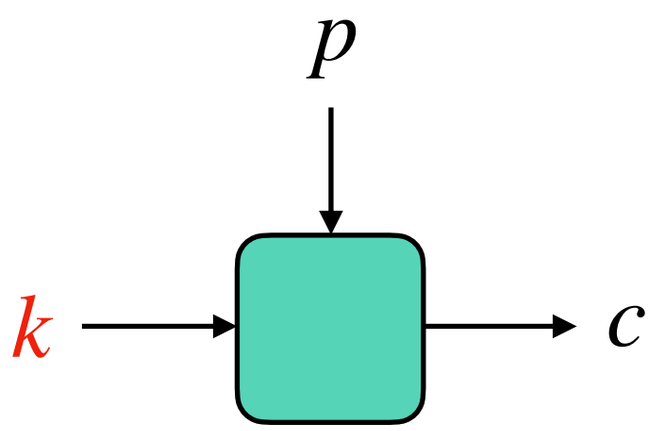

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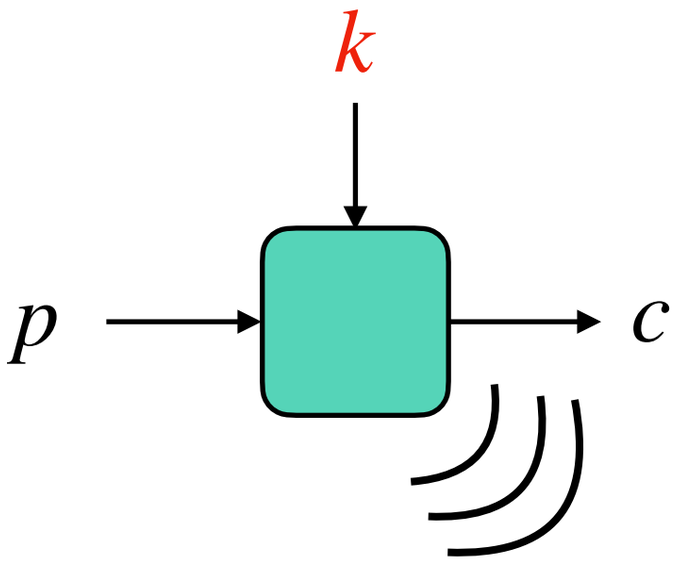


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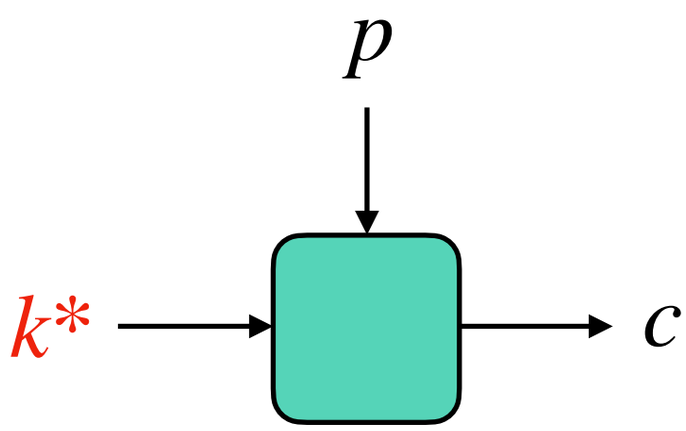

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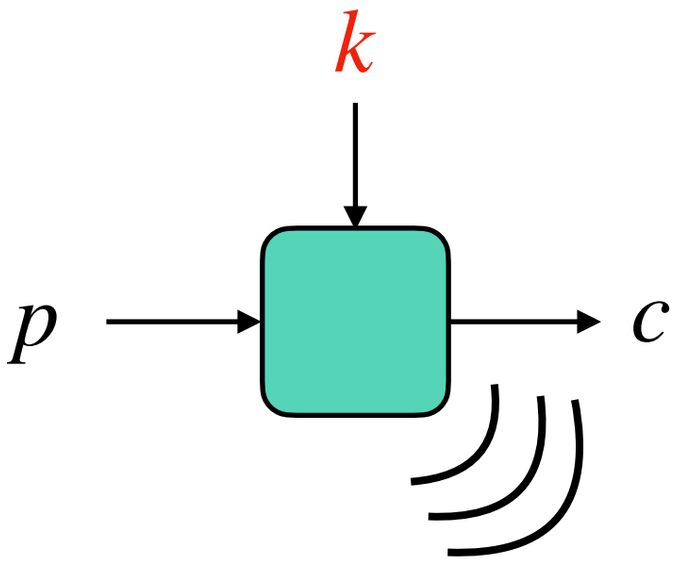


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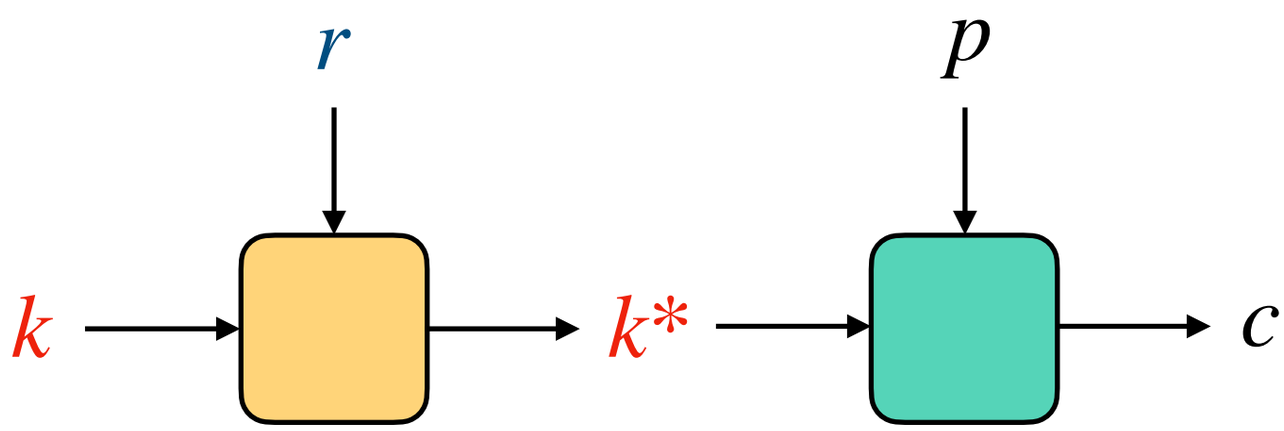

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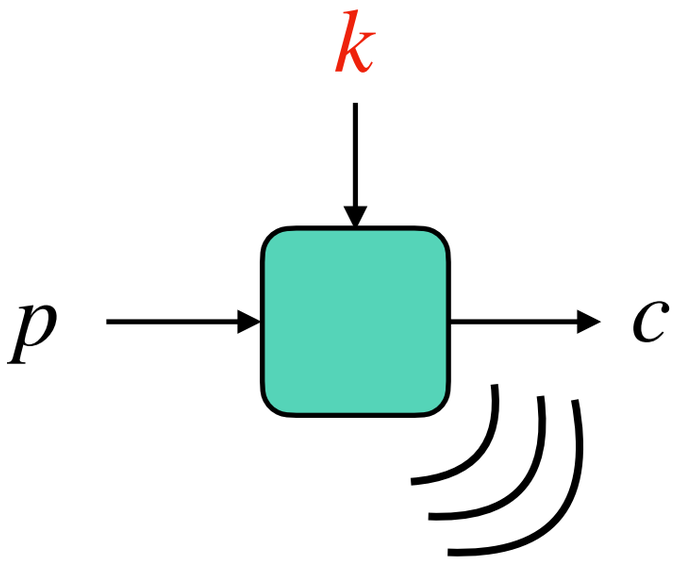
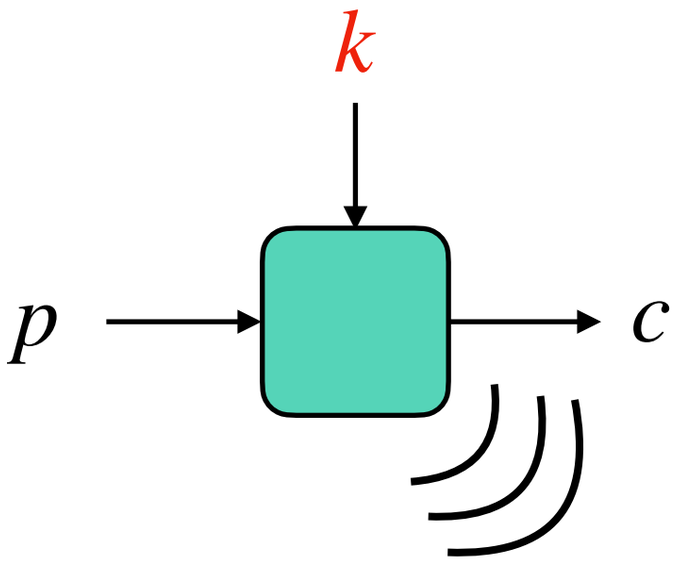



Problem: the leakage is key-dependent

First research idea:
*Discussion with a researcher at the conference CARDIS'12*

> Further developed with my supervisors and then published at CHES'13

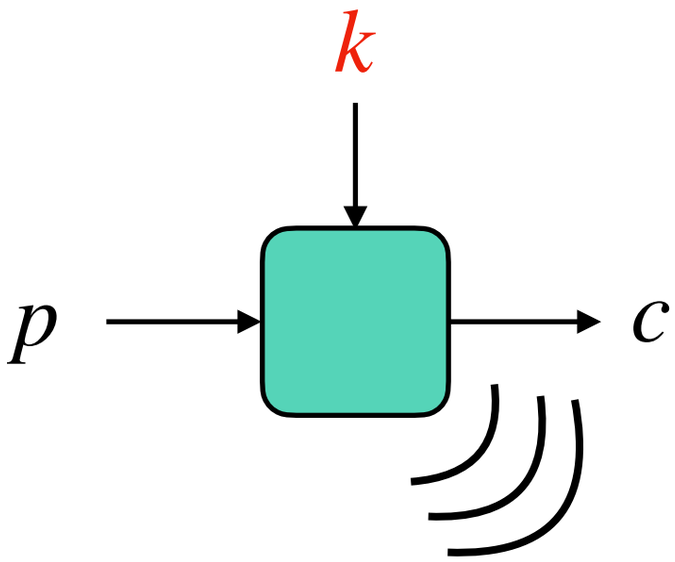
# Side-Channel Countermeasures




Problem: the leakage is key-dependent

## Solution 2: Masking (make the leakage random)

# Side-Channel Countermeasures

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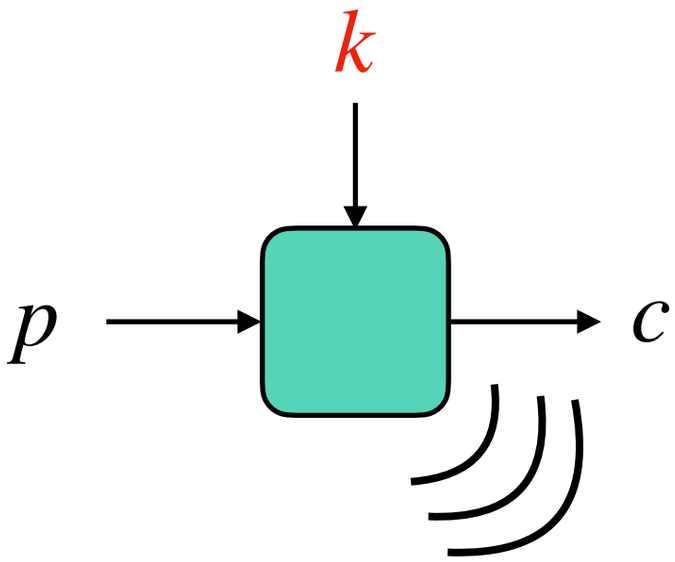
for each sensitive value $v \leftarrow f(p, k)$

# Side-Channel Countermeasures

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for each sensitive value $v \leftarrow f(p, k)$

$$v_1 \leftarrow \$ \qquad v_2 \leftarrow \$ \qquad \cdots \qquad v_{n-1} \leftarrow \$$$

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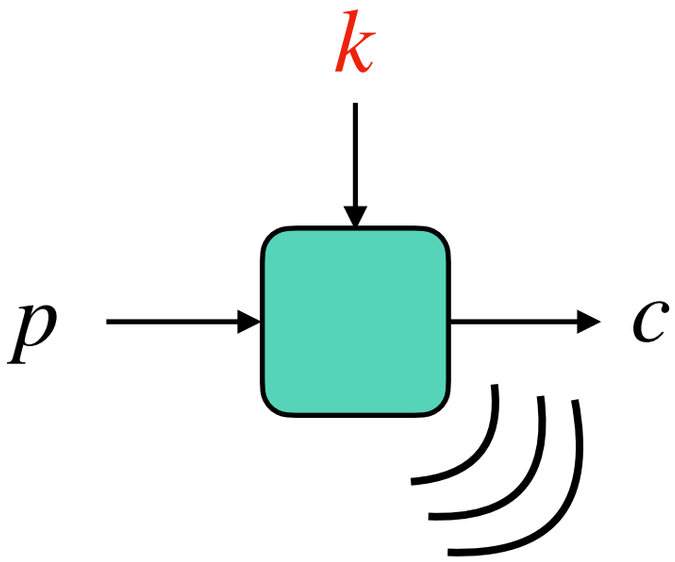


Problem: the leakage is key-dependent

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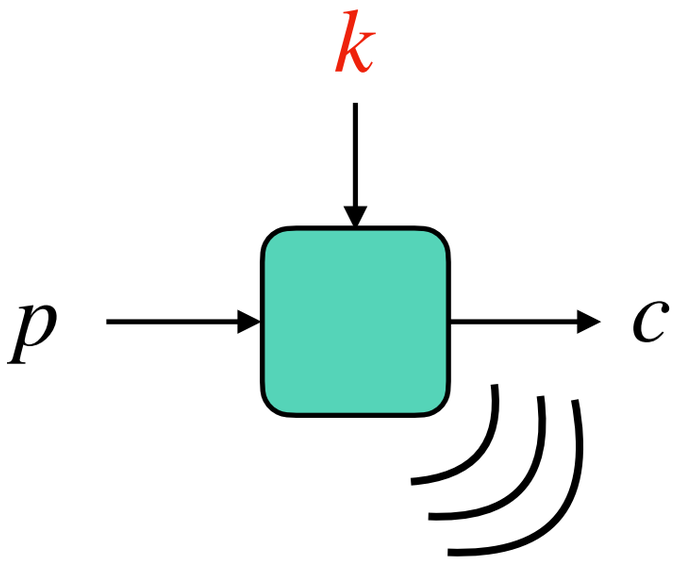
for each sensitive value $v \leftarrow f(p, k)$

$$v_0 \leftarrow v \oplus \left( \bigoplus_{i=1}^{n-1} v_i \right) \qquad v_1 \leftarrow \$ \qquad v_2 \leftarrow \$ \qquad \cdots \qquad v_{n-1} \leftarrow \$$$

# Side-Channel Countermeasures




Problem: the leakage is key-dependent

Research ideas from:

- my supervisors
- collaborative projects
- discussion with other researchers (seminars, conferences)

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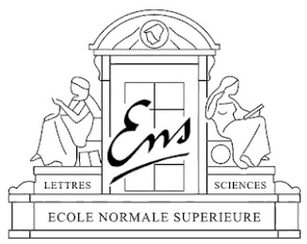
*Summer 2014*

PhD thesis

2010

2015

2020

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# Mid-PhD thesis

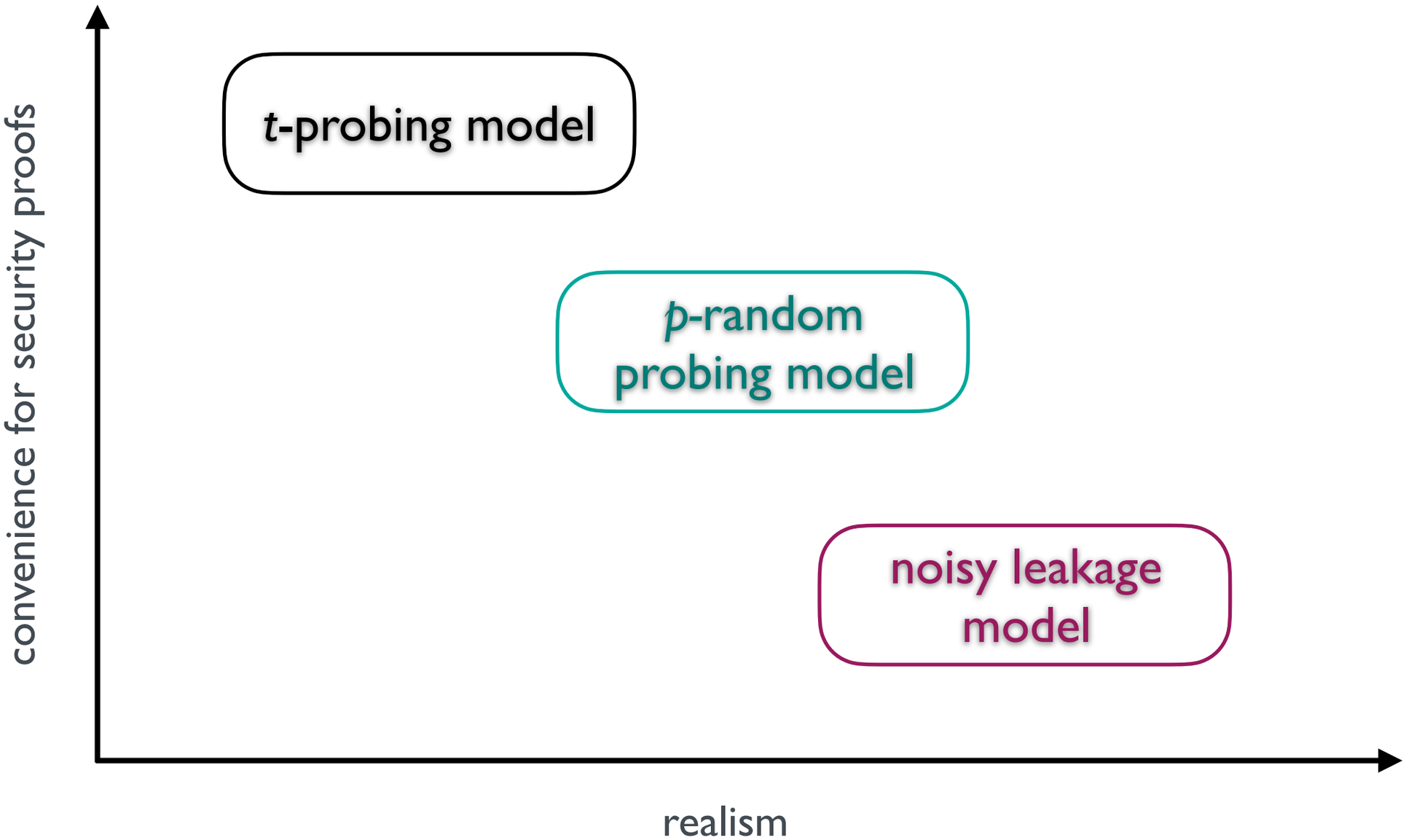
# Mid-PhD thesis

IMDEA+ team: Gilles Barthe, François Dupressoir, Benjamin Grégoire and Pierre-Yves Strub

# How to Use Formal Methods for Masking?

# First Step: How to Prove the Security of the Masked Implementations?

# Leakage Models



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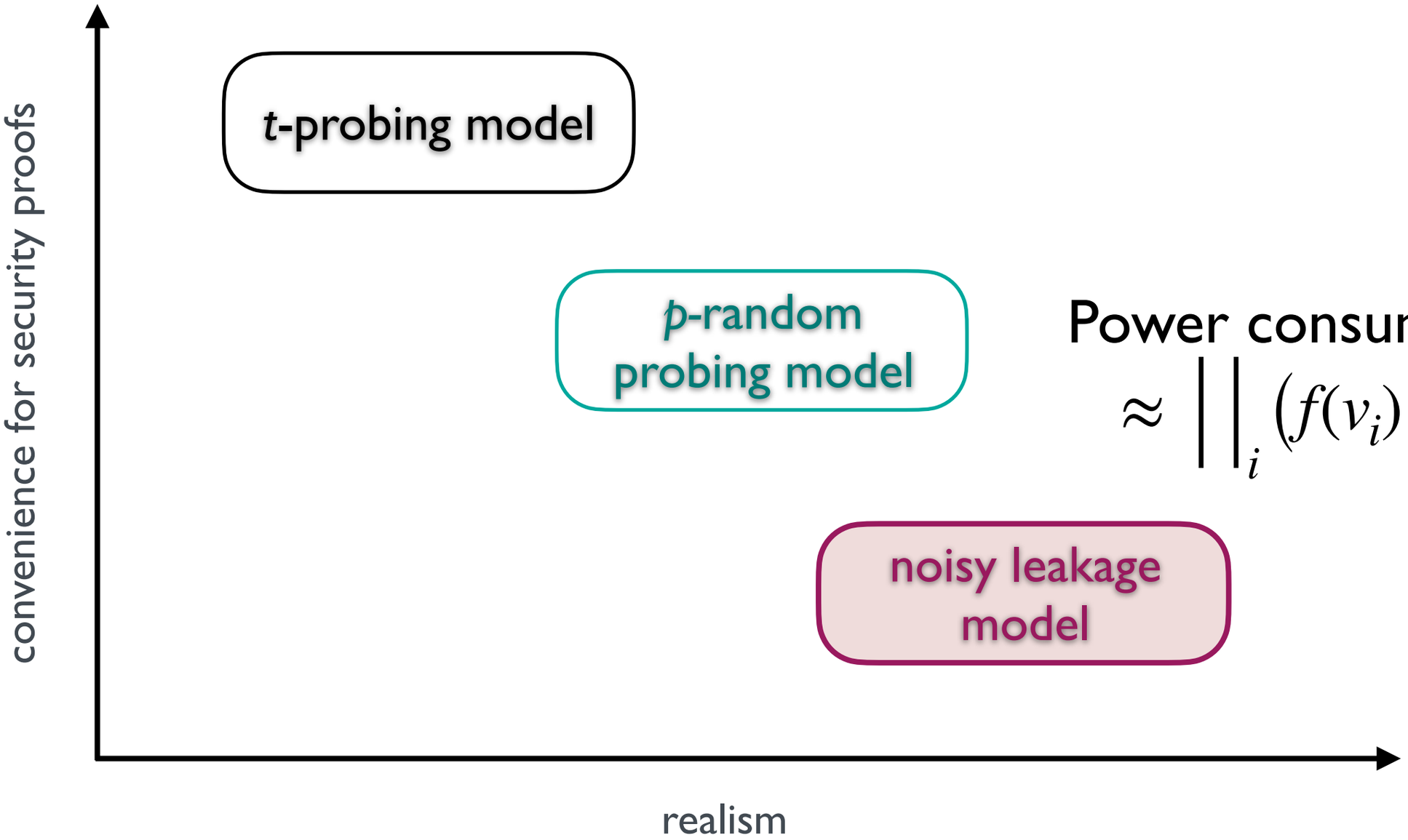
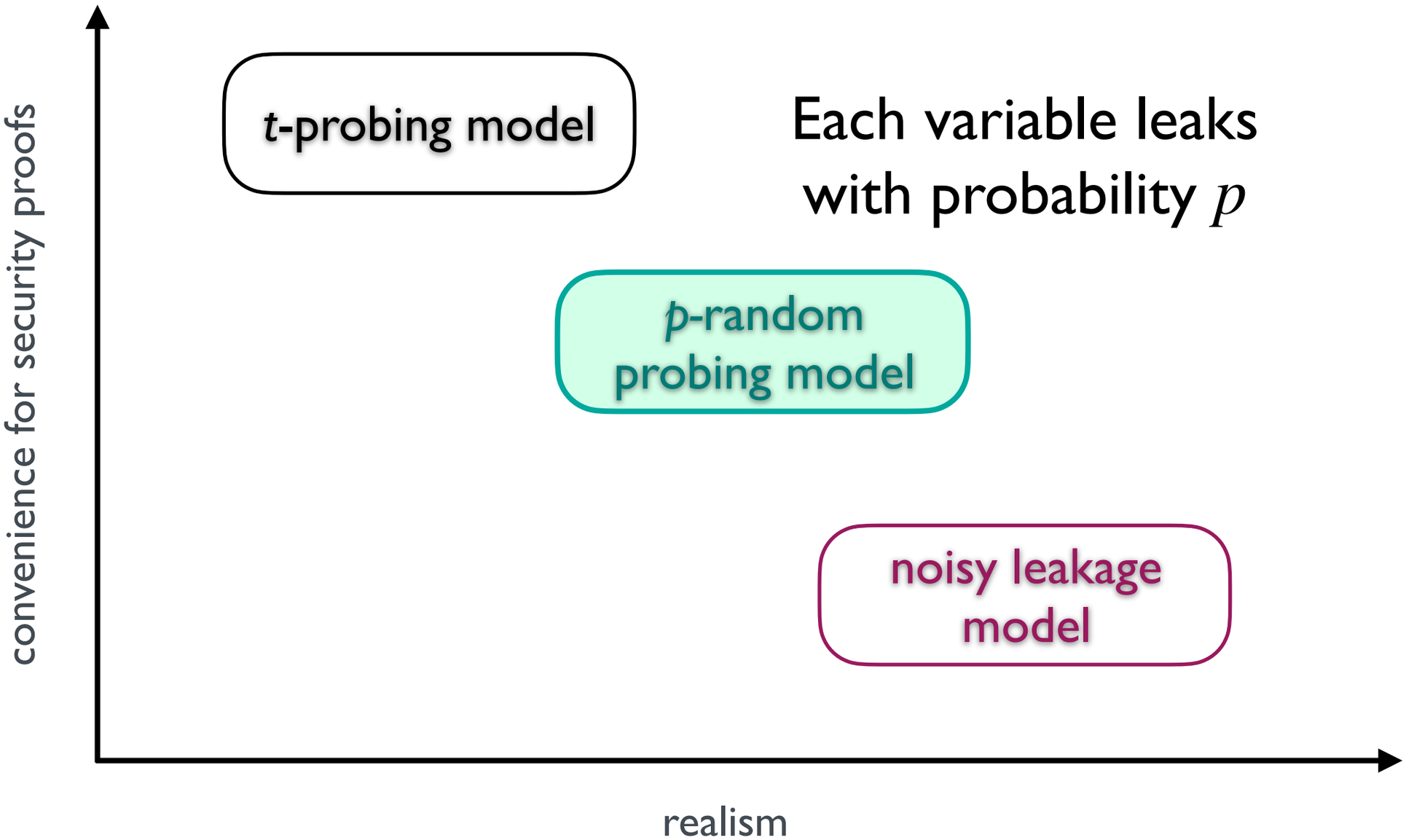



Power consumption

$$\approx \left|\left|_i \left(f(v_i) + \eta\right)\right.\right.$$

# Leakage Models



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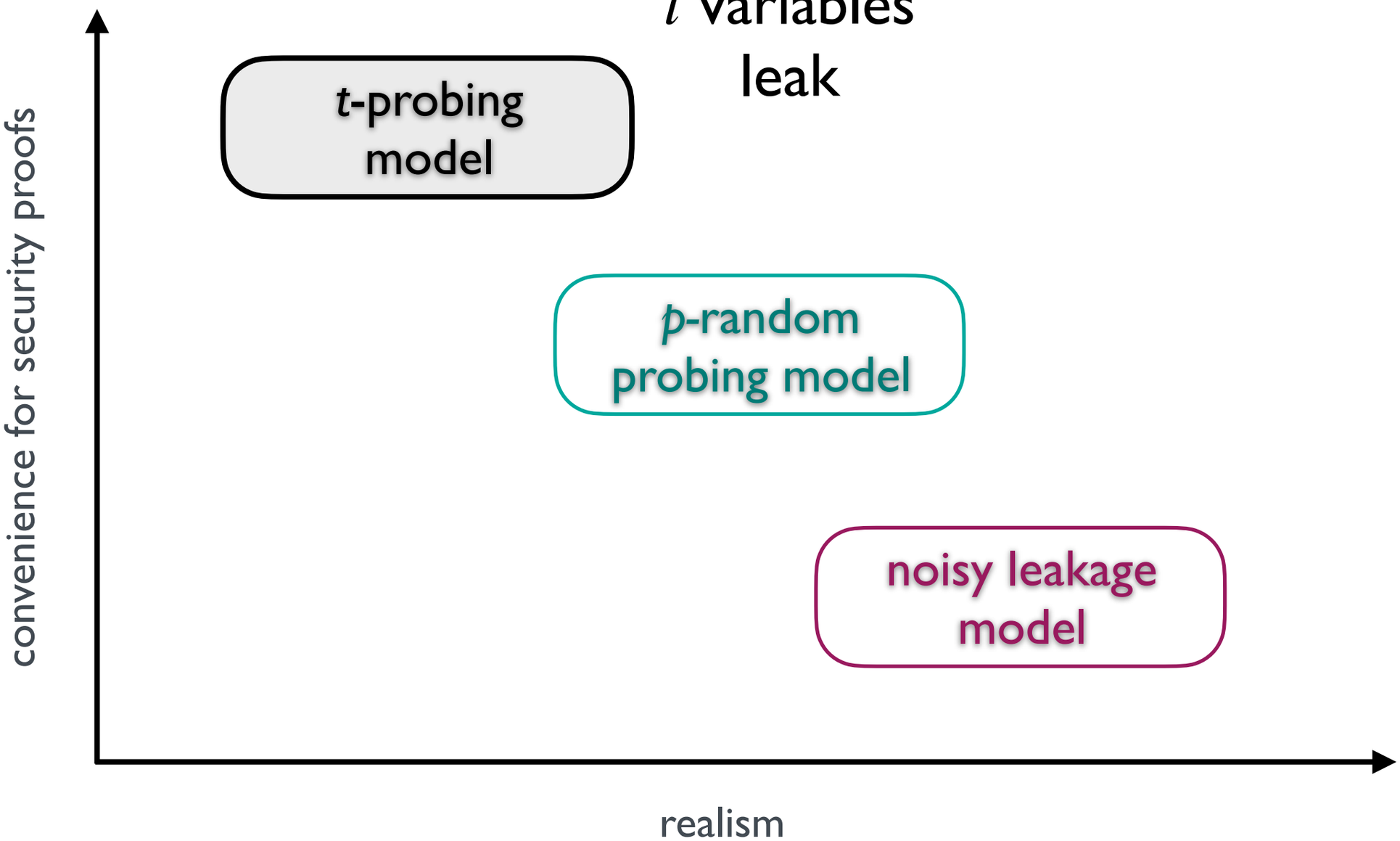
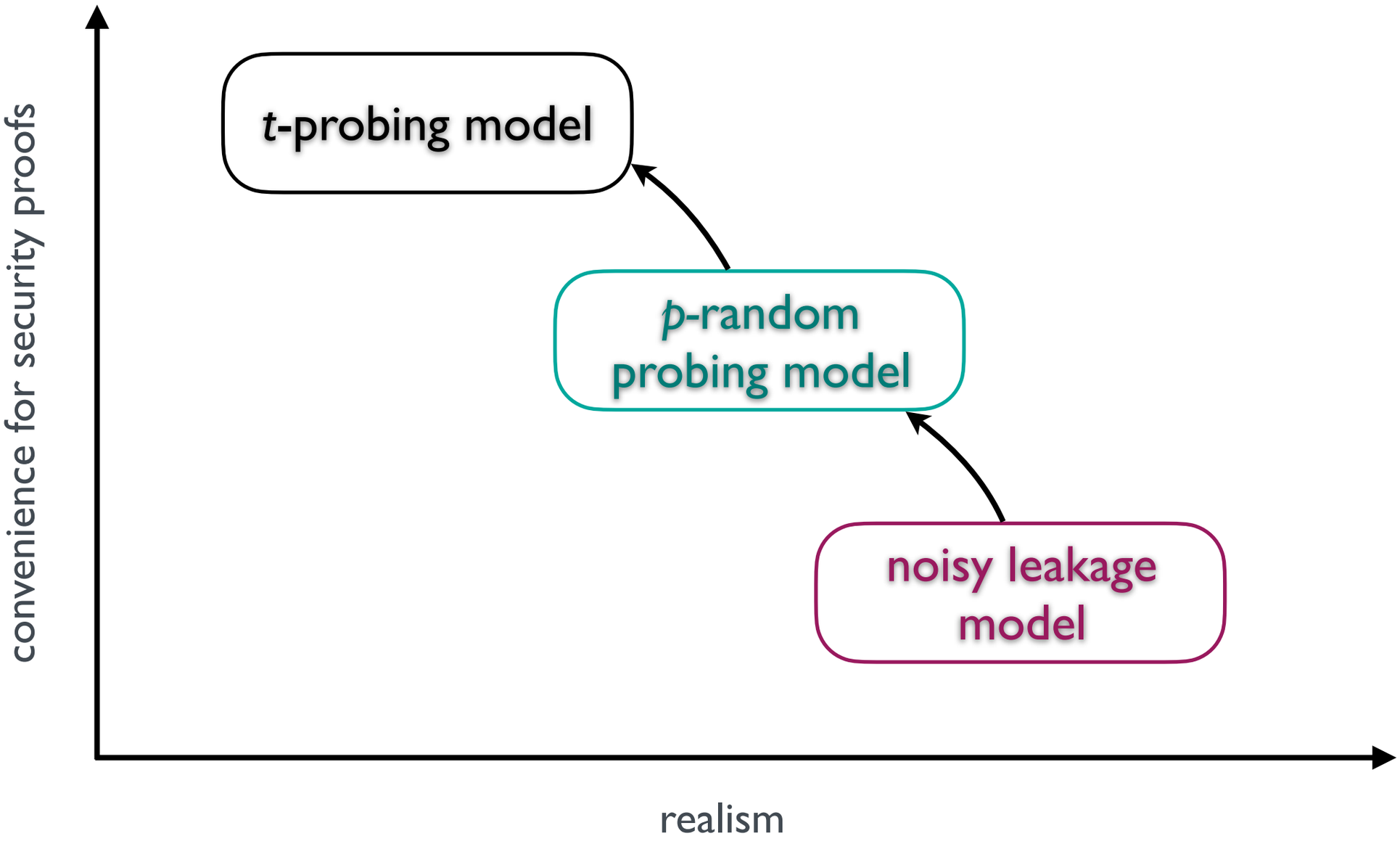


# Leakage Models




**[EC:DDF14]** *Unifying Leakage Models: From Probing Attacks to Noisy Leakage*. Alexandre Duc, Stefan Dziembowski, Sebastian Faust. Eurocrypt 2014

# Probing Security [ISW03]

Attacker model: adversary gets the exact values of $t$ intermediate variables

Security: any set of *at most* $t$ intermediate variables must be independent of the secrets

# Proof in the Probing Model

- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret

2 shares

function example$(a_0, a_1, b_0, b_1)$

$r \leftarrow \$$

$u \leftarrow a_0 \cdot b_0$

$c_0 \leftarrow u \oplus r$

$v \leftarrow a_1 \cdot b_1$

$x \leftarrow a_0 \cdot b_1$

$w \leftarrow v \oplus x$

$y \leftarrow w \oplus r$

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return $(c_0, c_1)$

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1-probing secure?

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# Proof in the Probing Model

- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret

Independent from secrets?

$$w = v \oplus x$$

$$w = a_1 \cdot b_1 \oplus a_0 \cdot b_1$$

$$w = a \cdot b_1$$

function example$(a_0, a_1, b_0, b_1)$

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# Proof in the Probing Model

- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret

3 shares

function example$(a_0, a_1, a_2, b_0, b_1, b_2)$

$r_{00}, r_{01}, r_{02}, r_{12} \leftarrow \$$
$t \leftarrow a_0 \cdot b_0$
$c_0 \leftarrow t \oplus r_{00}$
$t \leftarrow a_0 \cdot b_1$
$t \leftarrow t \oplus r_{01}$
$c_0 \leftarrow c_0 \oplus t$
$t \leftarrow a_0 \cdot b_2$
$t \leftarrow t \oplus r_{02}$
$c_0 \leftarrow c_0 \oplus t$
$t \leftarrow a_1 \cdot b_0$
$c_1 \leftarrow t \oplus r_{01}$
$t \leftarrow a_1 \cdot b_1$
$c_1 \leftarrow c_1 \oplus t$
$\ldots$

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- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret

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33 intermediate variables

$\binom{33}{2} = 528$ couples to verify

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3 shares

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$\binom{n}{t}$ tuples to verify

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# With Formal Methods

Formally verify security in the probing model with EasyCrypt

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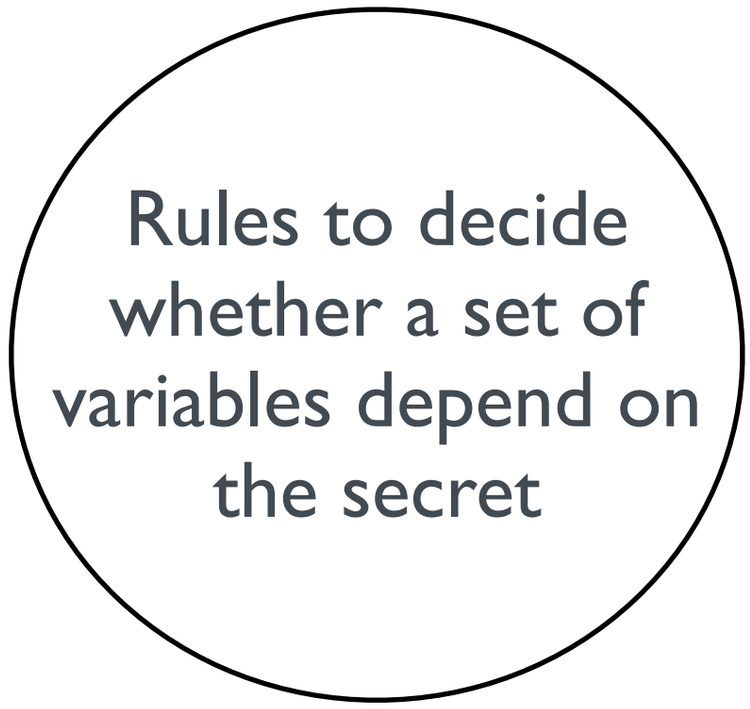
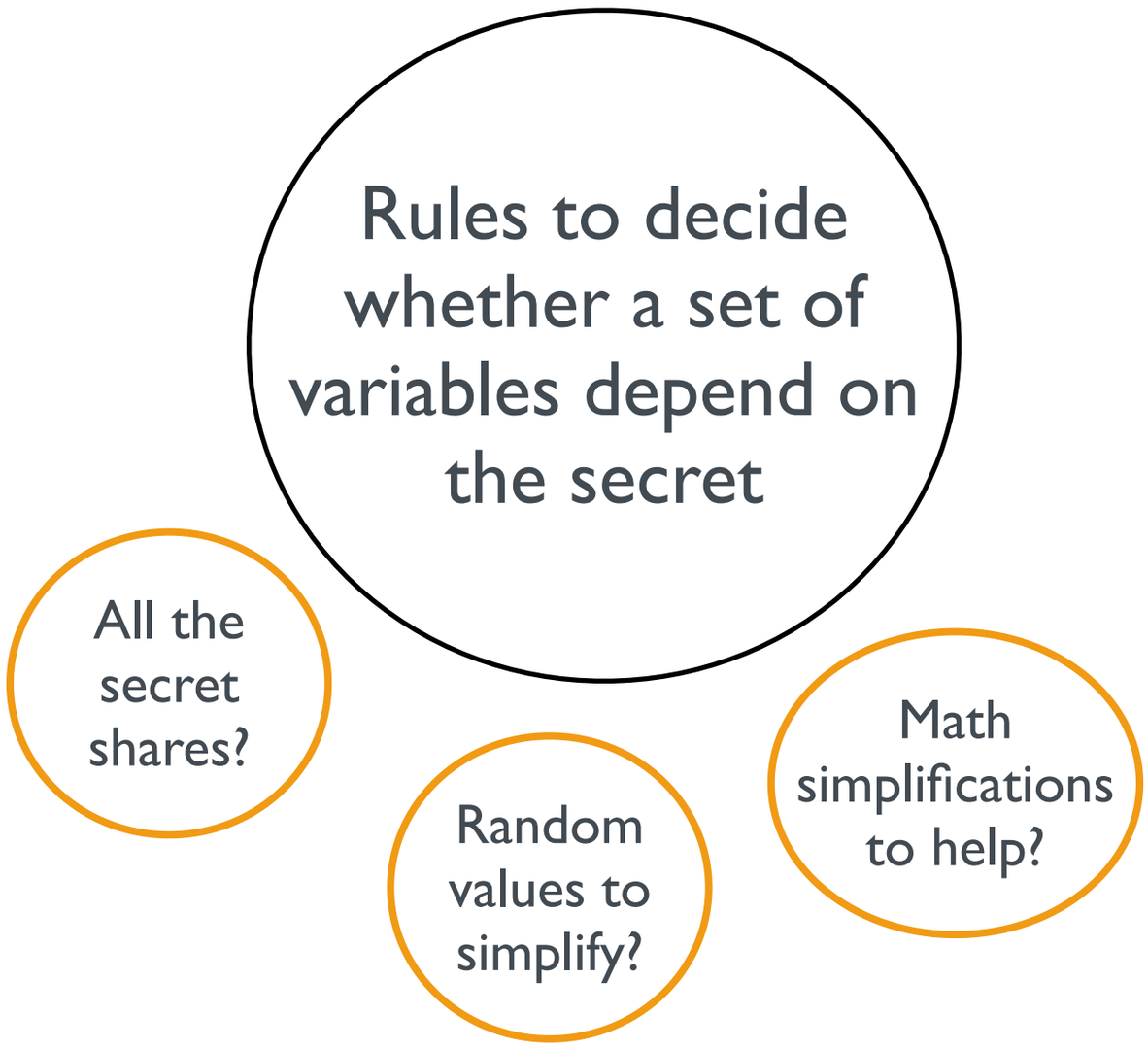


# With Formal Methods

Formally verify security in the probing model with EasyCrypt



# With Formal Methods

Formally verify security in the probing model with EasyCrypt

Rules to decide whether a set of variables depend on the secret

All the secret shares?

Random values to simplify?

Math simplifications to help?

Instead of verifying all the sets of $t$ variables
=> verifying bigger sets

# With Formal Methods

maskVerif

# With Formal Methods

Security order $t$

function example$(a_0, a_1, a_2, b_0, b_1, b_2)$

$r_{00}, r_{01}, r_{02}, r_{12} \leftarrow \$$
$t \leftarrow a_0 \cdot b_0$
$c_0 \leftarrow t \oplus r_{00}$
$t \leftarrow a_0 \cdot b_1$
$t \leftarrow t \oplus r_{01}$
$c_0 \leftarrow c_0 \oplus t$
$t \leftarrow a_0 \cdot b_2$
$t \leftarrow t \oplus r_{02}$
$c_0 \leftarrow c_0 \oplus t$
$t \leftarrow a_1 \cdot b_0$
$c_1 \leftarrow t \oplus r_{01}$
$t \leftarrow a_1 \cdot b_1$
$c_1 \leftarrow c_1 \oplus t$
$\ldots$
return $(c_0, c_1, c_2)$

maskVerif

# With Formal Methods

Security order $t$

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$r_{00}, r_{01}, r_{02}, r_{12} \leftarrow \$$

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$t \leftarrow a_0 \cdot b_2$

$t \leftarrow t \oplus r_{02}$

$c_0 \leftarrow c_0 \oplus t$

$t \leftarrow a_1 \cdot b_0$

$c_1 \leftarrow t \oplus r_{01}$

$t \leftarrow a_1 \cdot b_1$

$c_1 \leftarrow c_1 \oplus t$

…

return $(c_0, c_1, c_2)$

maskVerif

Security proof or potential attacks

# With Formal Methods

Security order $t$

function example$(a_0, a_1, a_2, b_0, b_1, b_2)$

$r_{00}, r_{01}, r_{02}, r_{12} \leftarrow \$$
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$c_1 \leftarrow t \oplus r_{01}$
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$c_1 \leftarrow c_1 \oplus t$
...
return $(c_0, c_1, c_2)$

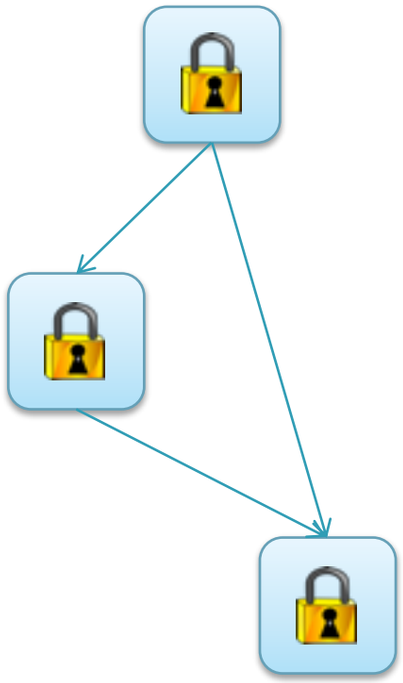
→ maskVerif →

Security proof or potential attacks

**[EC:BBDFGS15]** *Verified Proofs of Higher-Order Masking.* Gilles Barthe, Sonia Belaïd, François Dupressoir, Pierre-Alain Fouque, Benjamin Grégoire, and Pierre-Yves Strub. Eurocrypt 2015

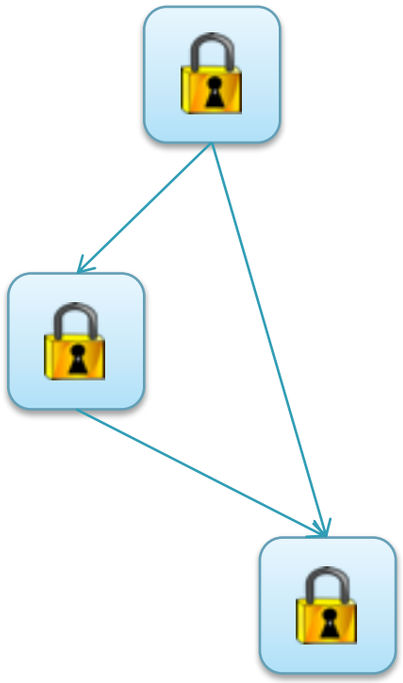
# New Ideas?

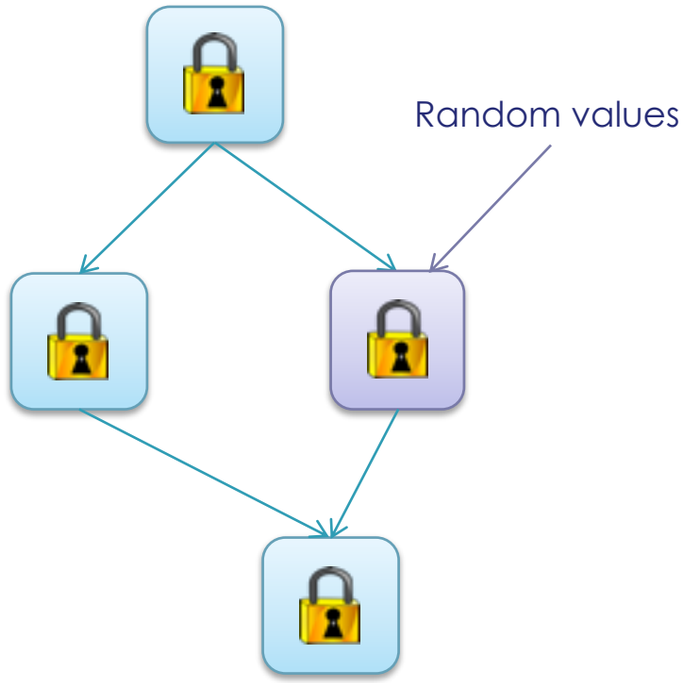
# Composition of gadgets



[1] Y. Ishai, A. Sahai, and D. Wagner. Private circuits: Securing hardware against probing attacks. CRYPTO 2003

# Composition of gadgets

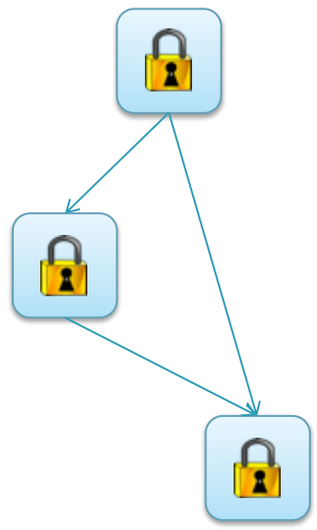





[1] Y. Ishai, A. Sahai, and D. Wagner. Private circuits: Securing hardware against probing attacks. CRYPTO 2003
[2] M. Rivain and E. Prouff. Provably secure higher-order masking of AES. CHES 2010

# Composition of gadgets

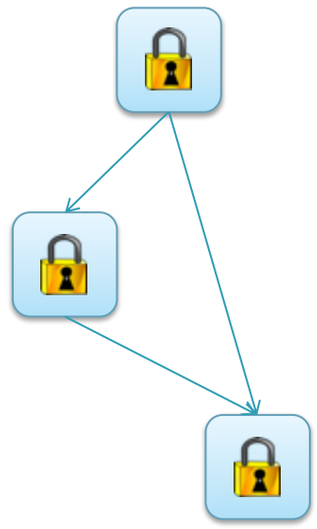
- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret
- How to reason on composition?



# Composition of gadgets

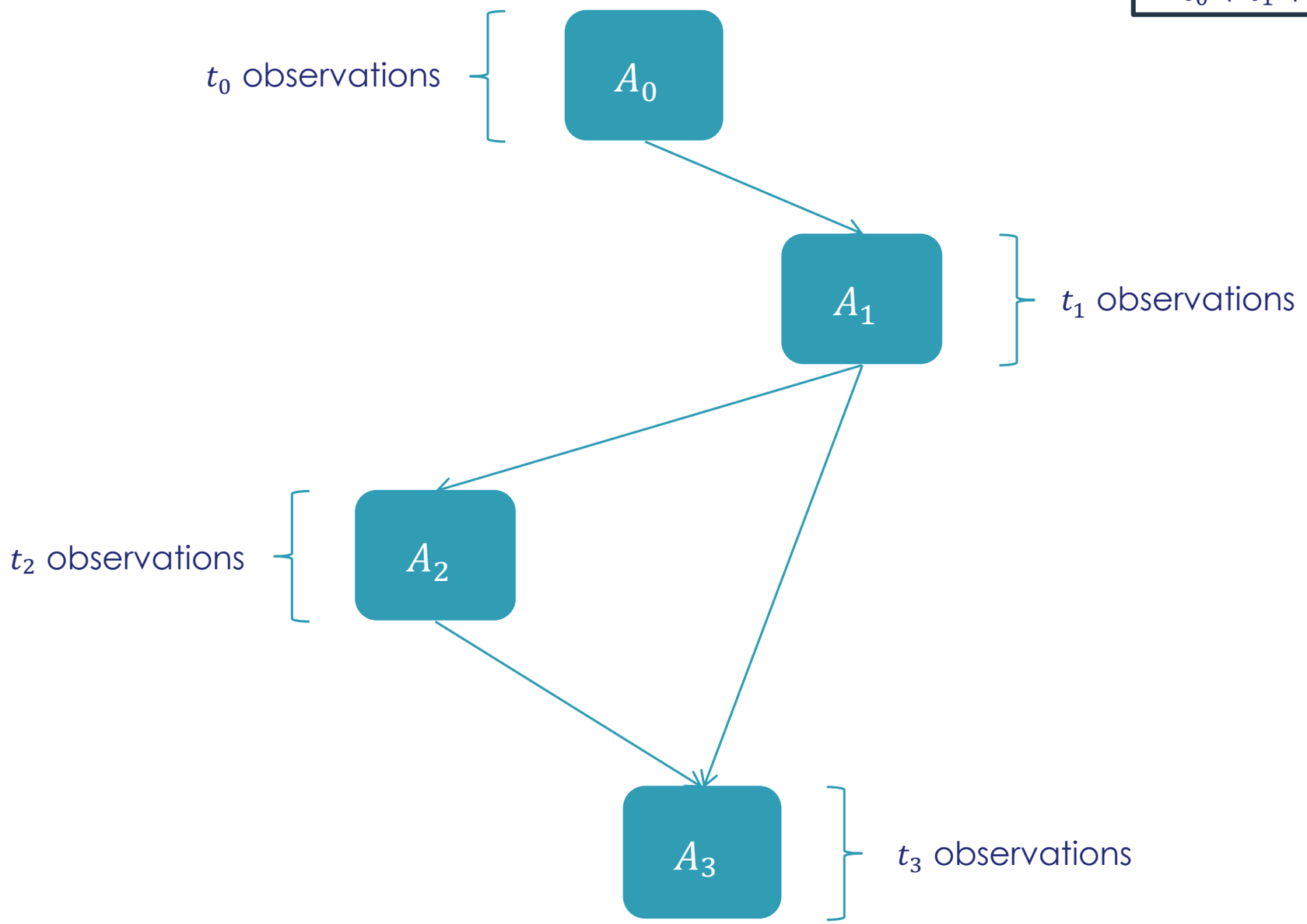
- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret
- How to reason on composition?
  - Stronger property: non-interference

any set of *t* variables can be simulated with at most *t* input shares



# Composition of gadgets

$$t_0 + t_1 + t_2 + t_3 \leq t$$



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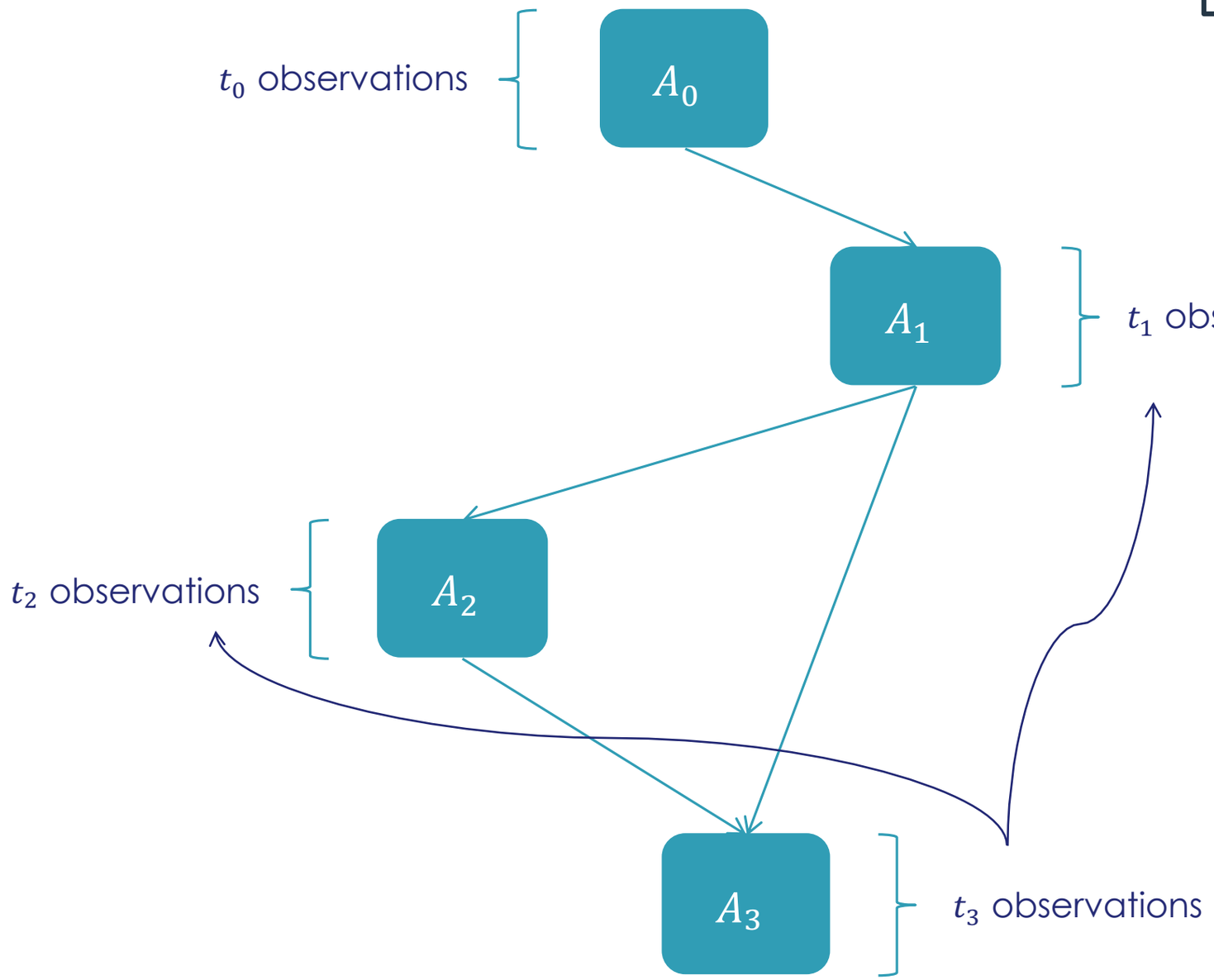

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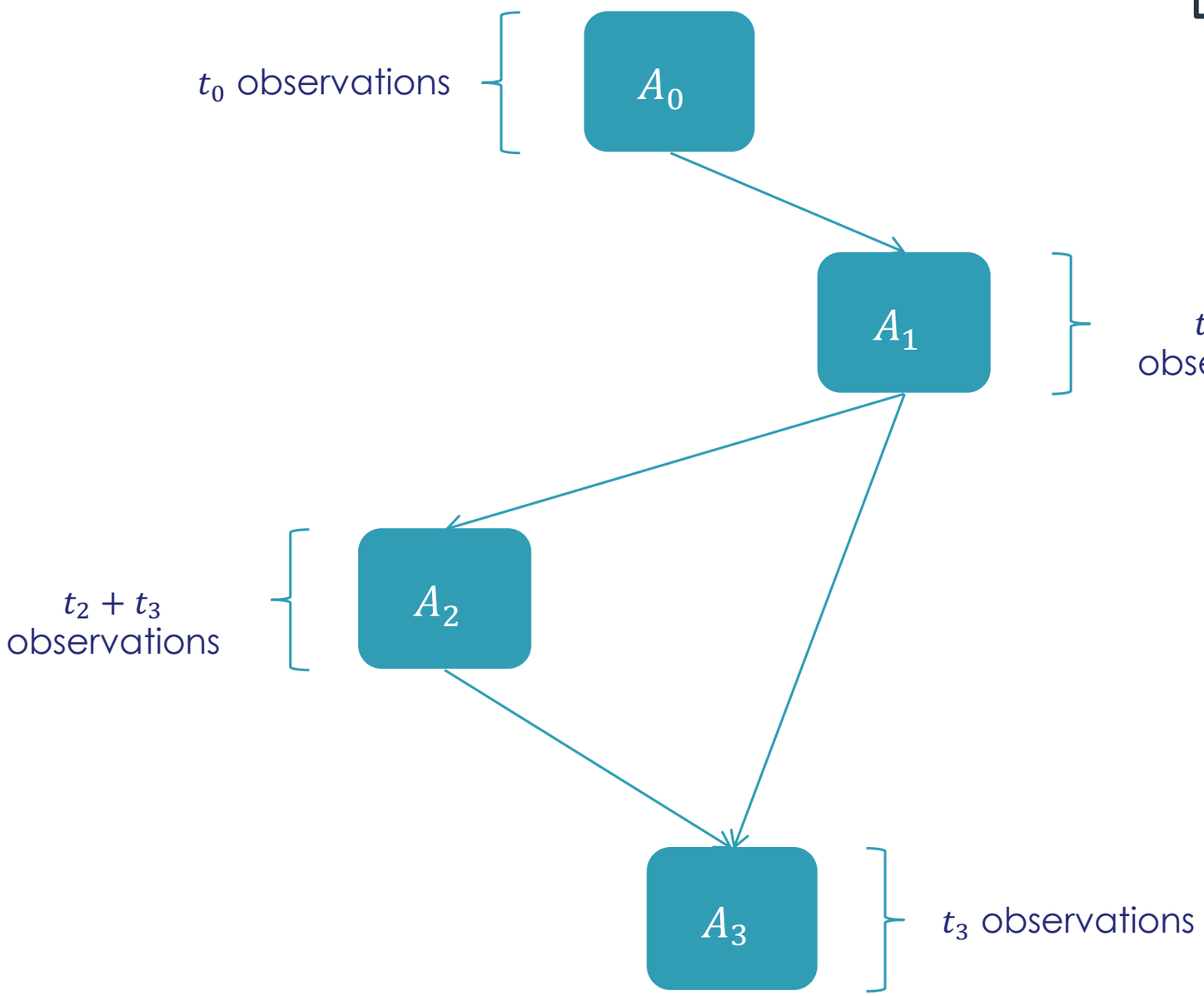

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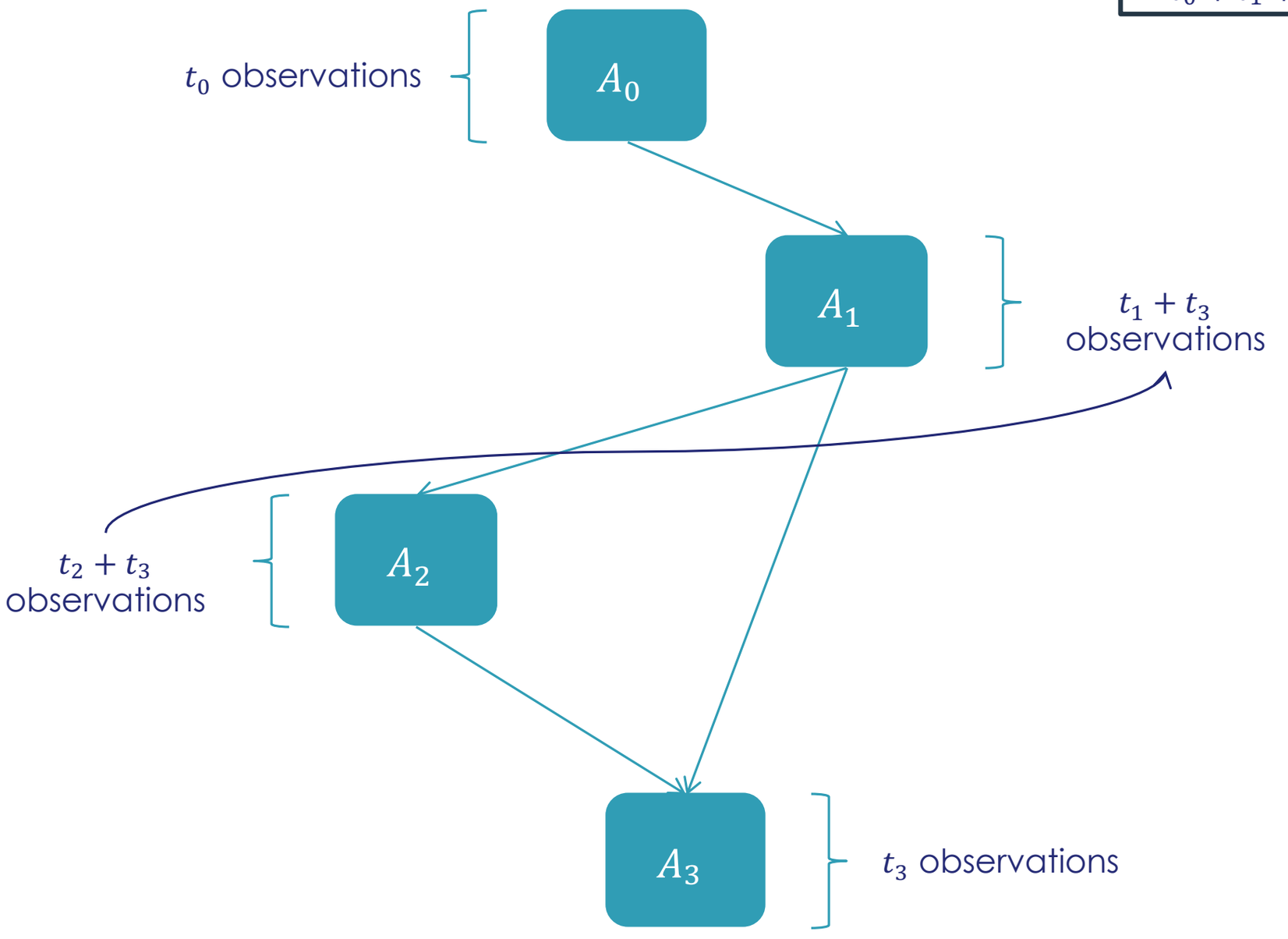
$$t_0 + t_1 + t_2 + t_3 \leq t$$



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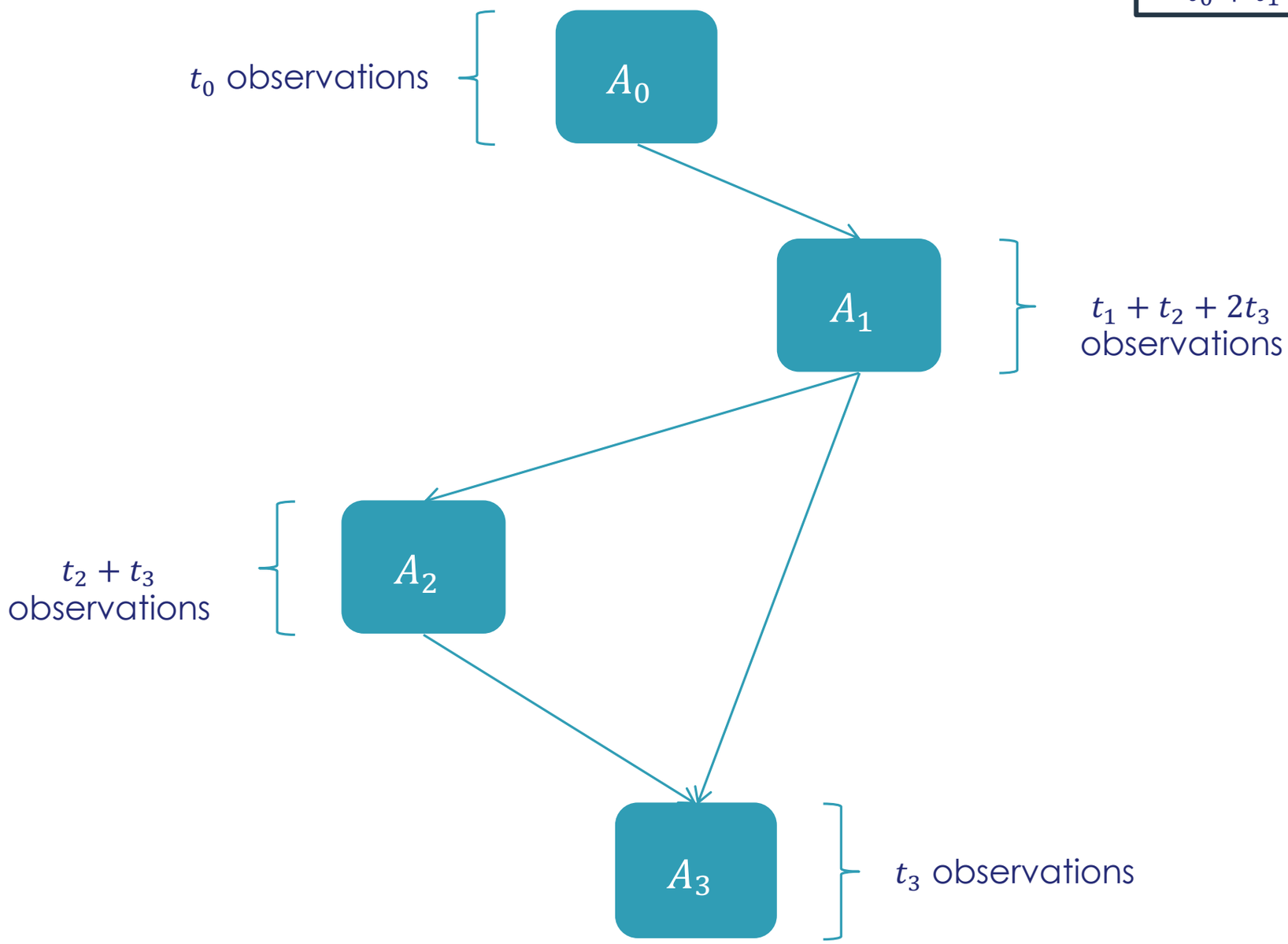
$$t_0 + t_1 + t_2 + t_3 \leq t$$



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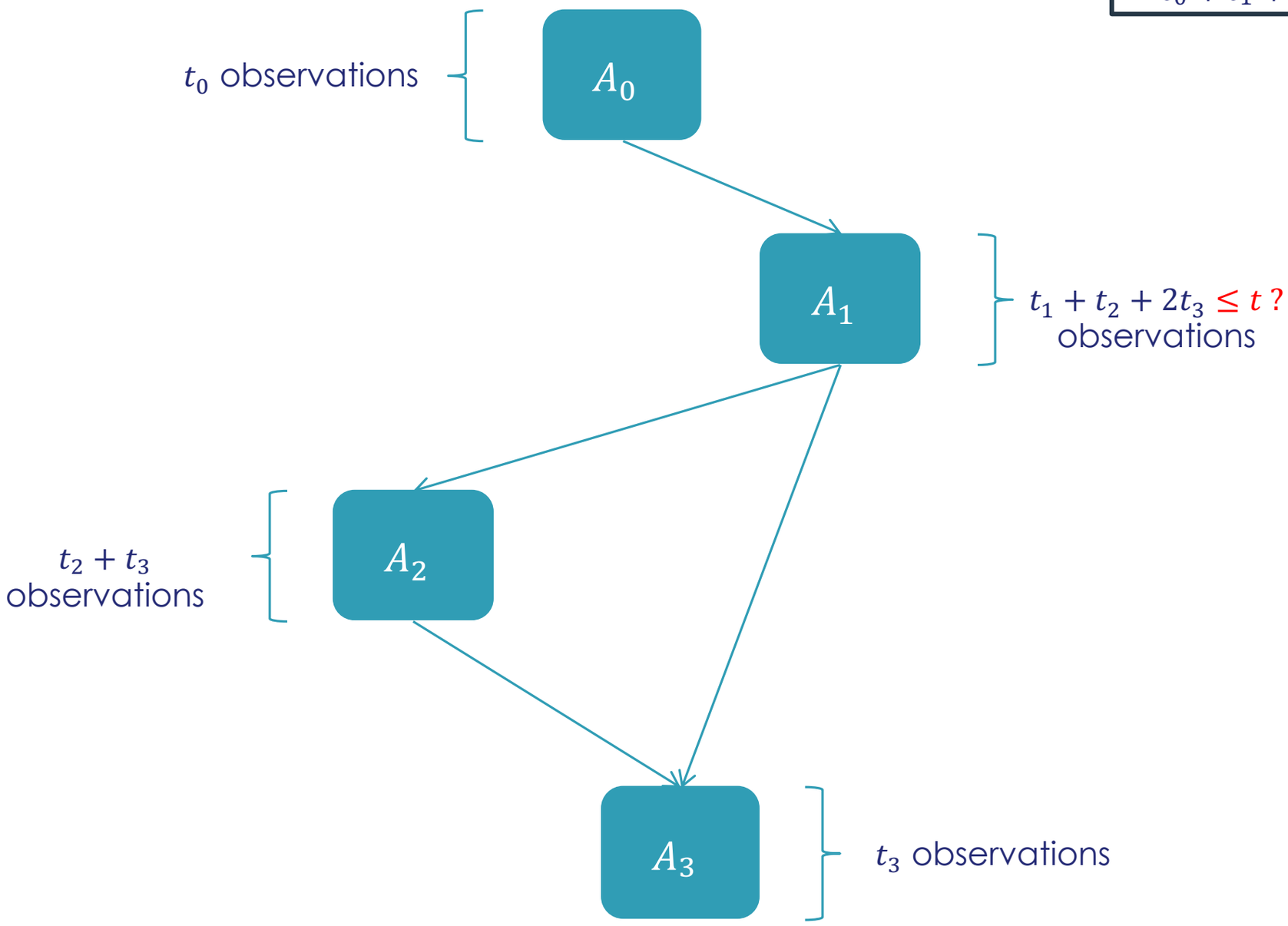
$t_0 + t_1 + t_2 + t_3 \leq t$



# Composition of gadgets

- Reminder: an implementation is *t*-probing secure iff any set of at most *t* variables is independent from the secret
- How to reason on composition?
  - Stronger property: non-interference

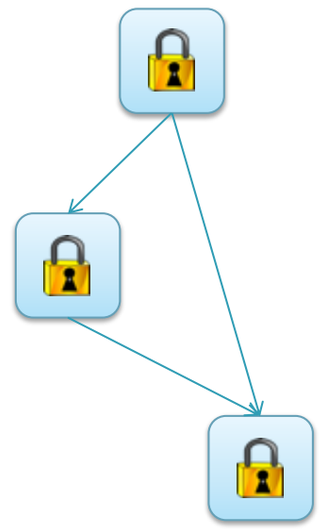
any set of $t$ variables can be simulated with at most $t$ input shares

  - **Stronger** property: strong non-interference

any set of

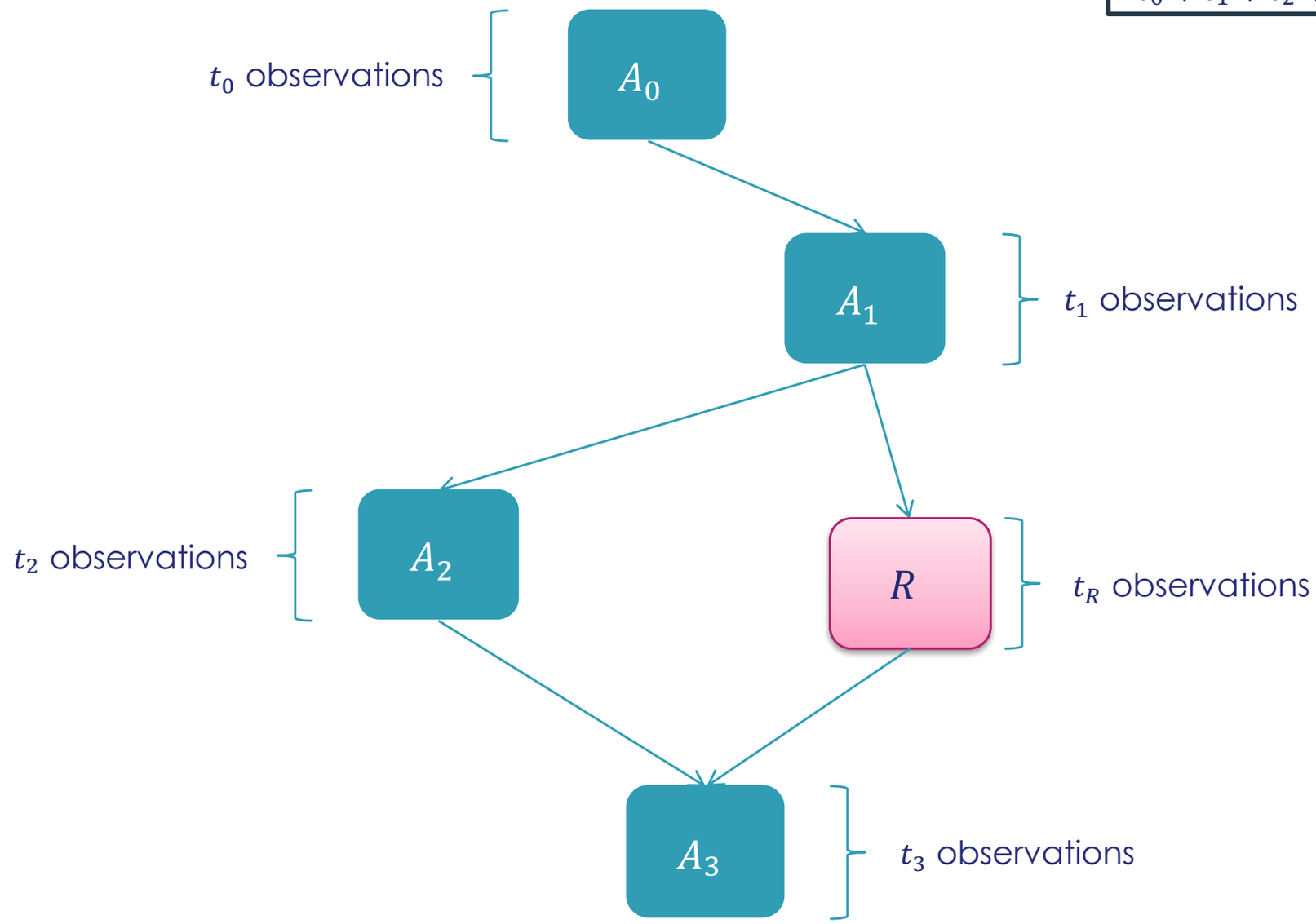
- $t_1$ internal variables
- $t_2$ output variables

can be simulated with at most $t_1$ input shares



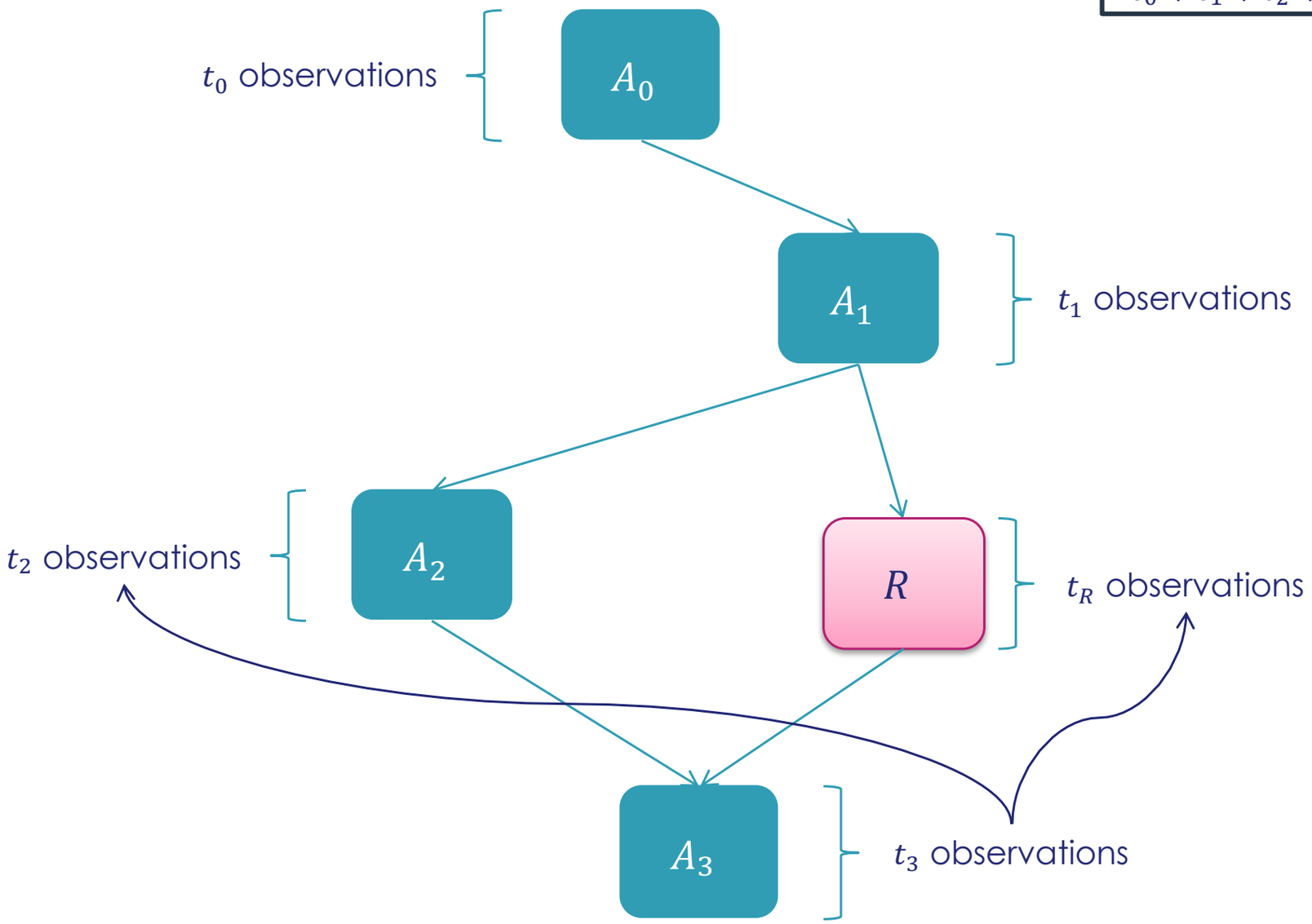
# Composition of gadgets

$$t_0 + t_1 + t_2 + t_3 + t_R \leq t$$



# Composition of gadgets

$$t_0 + t_1 + t_2 + t_3 + t_R \leq t$$



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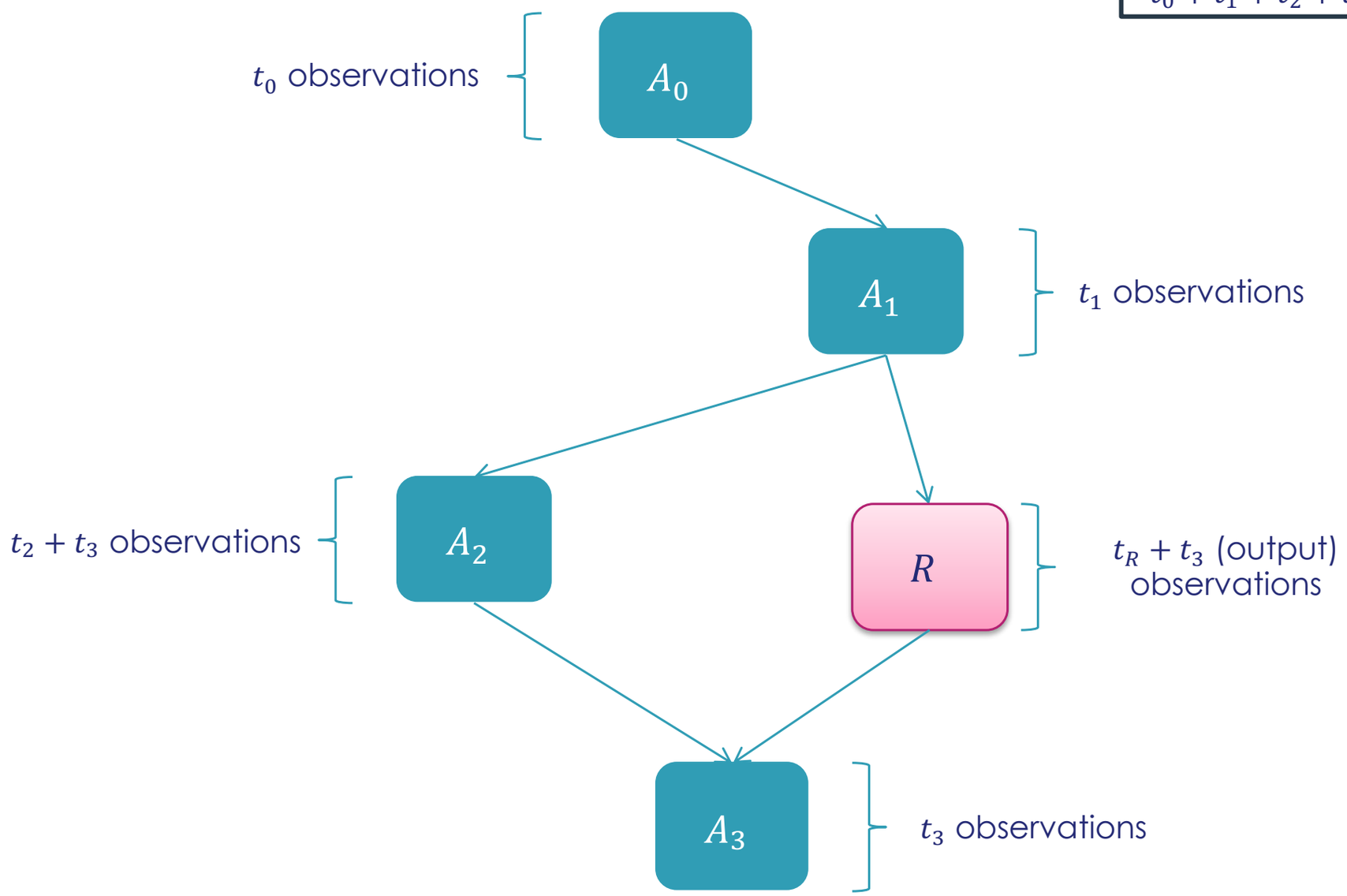

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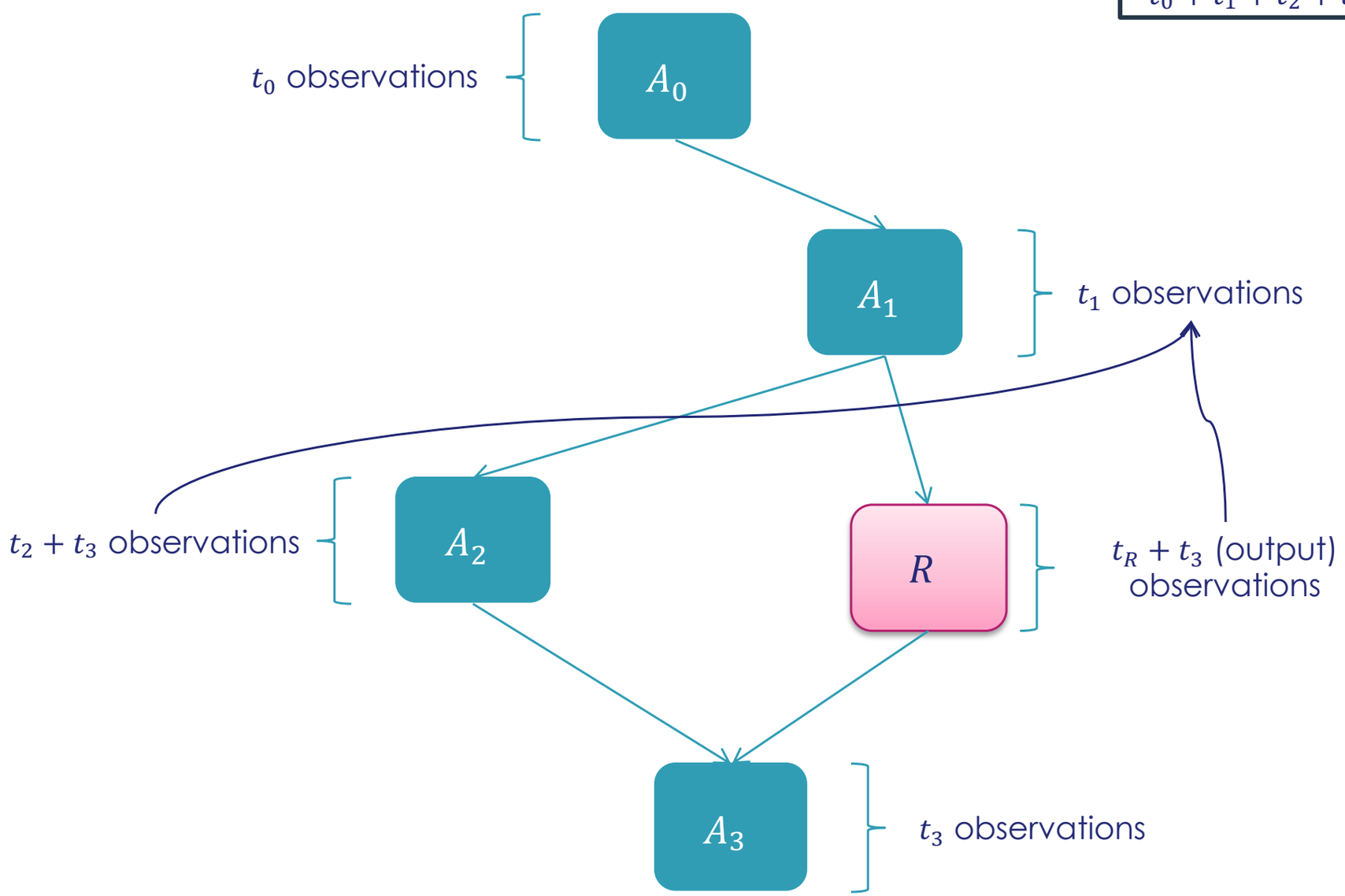

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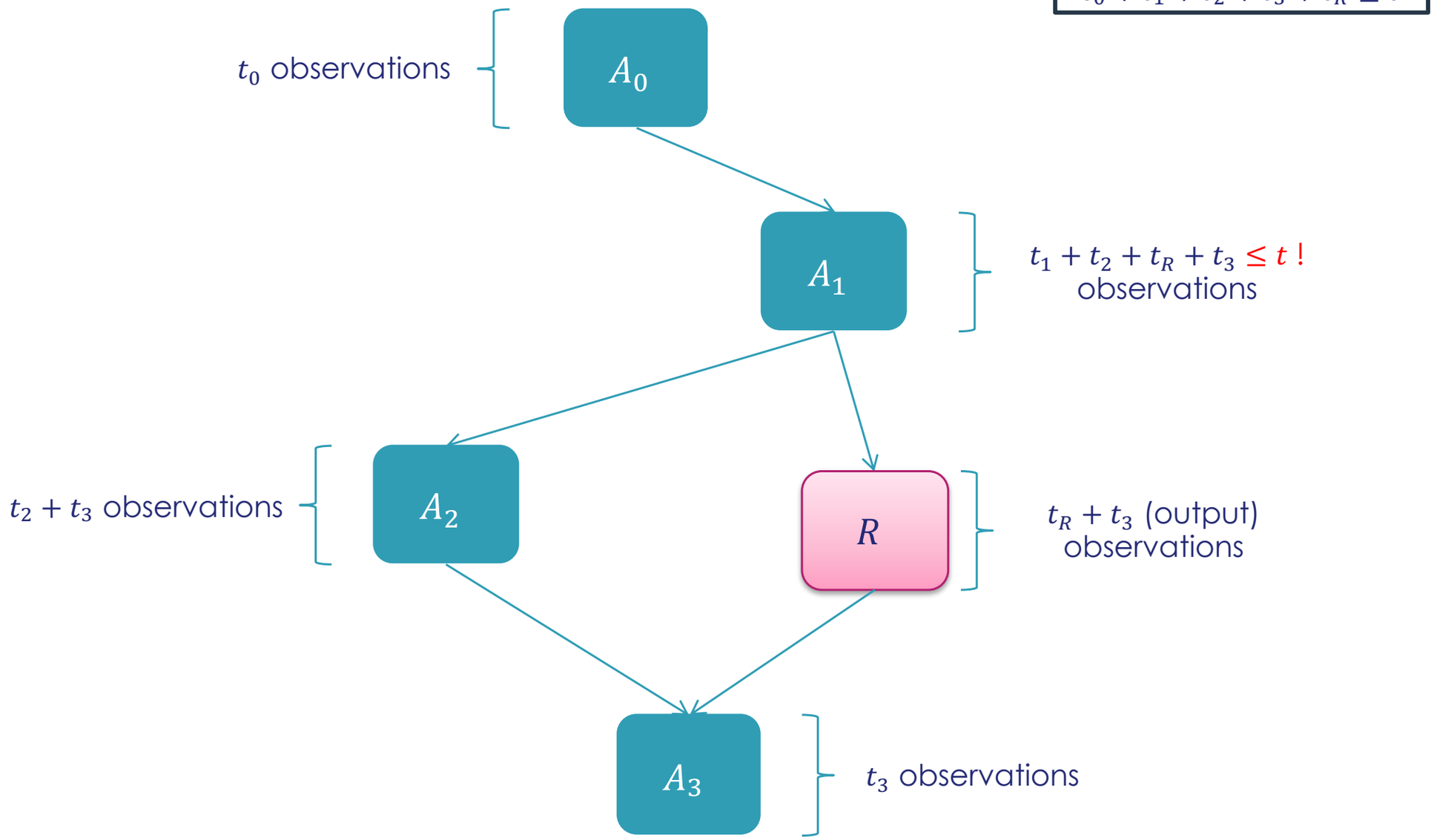

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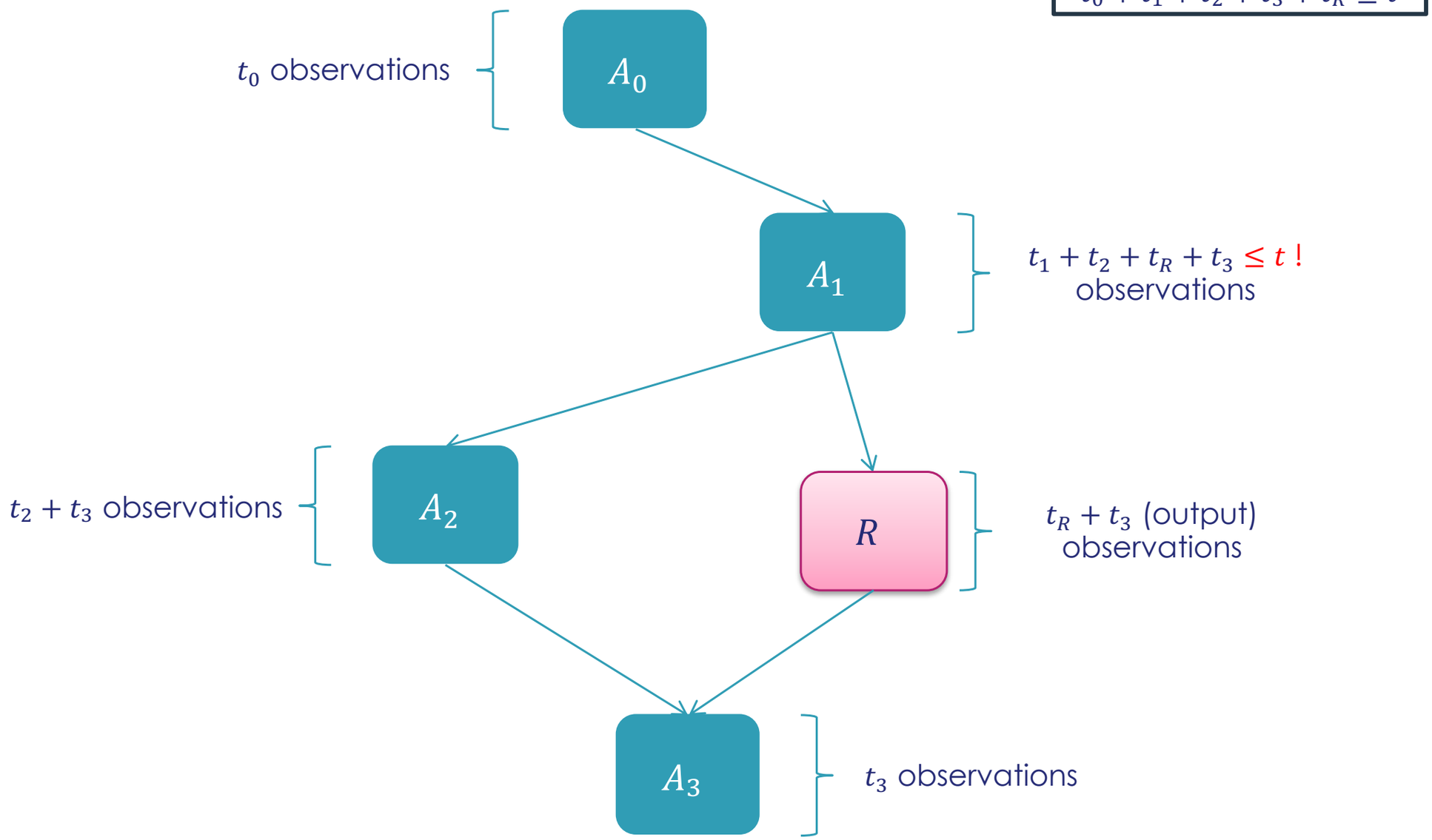
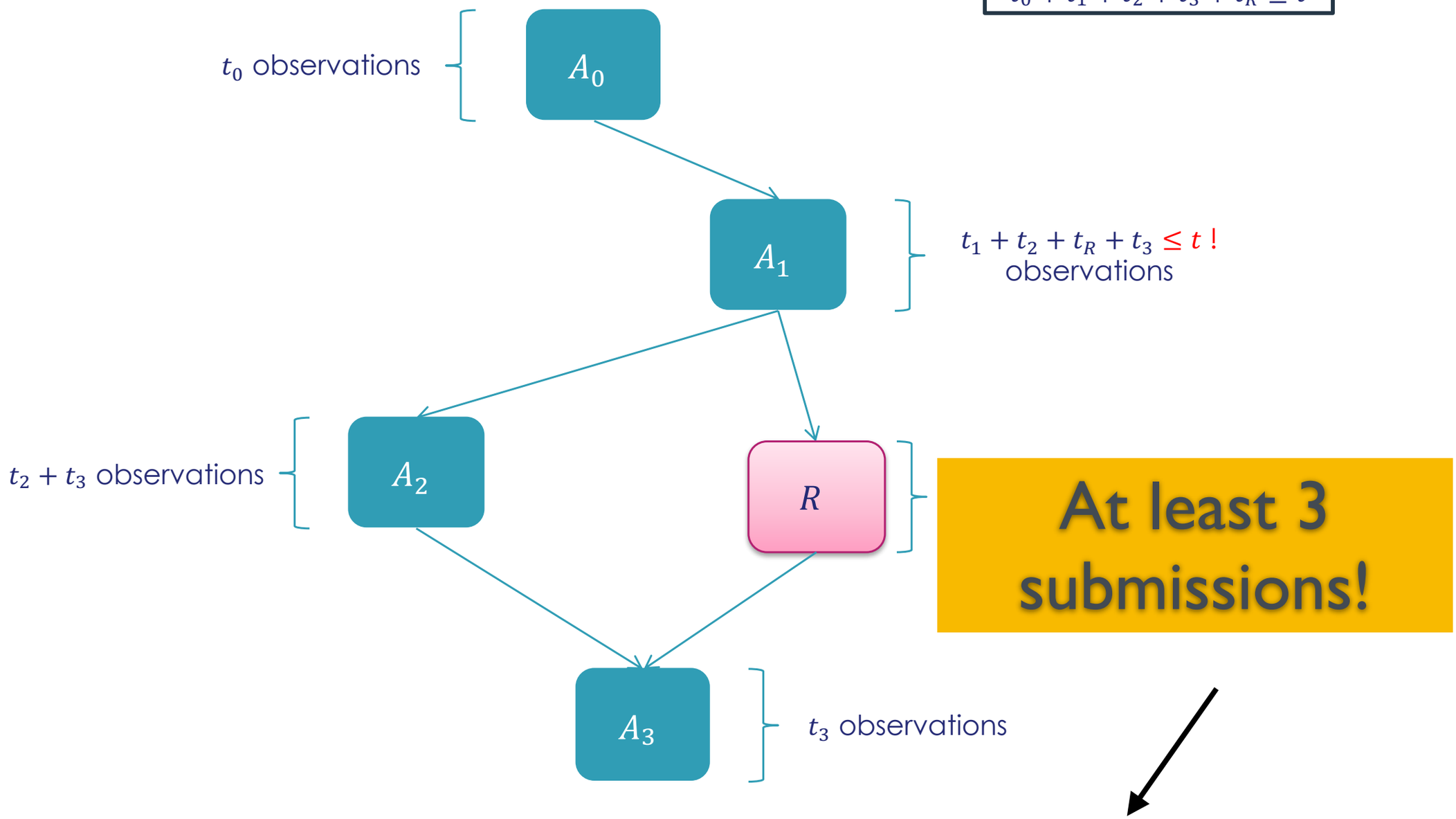



**[CCS:BBDFGS+16]** *Strong Non-Interference and Type-Directed Higher-Order Masking.* Gilles Barthe, Sonia Belaïd, François Dupressoir, Pierre-Alain Fouque, Benjamin Grégoire, Pierre-Yves Strub and Rebecca Zucchini. CCS 2016.

# Composition of gadgets

$$t_0 + t_1 + t_2 + t_3 + t_R \leq t$$

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Oberthur Technologies

Grenoble INP ENSIMAG

PhD thesis

2010

2015

2020

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ECOLE NORMALE SUPERIEURE

THALES



CryptoExperts

Oberthur Technologies

Grenoble INP ENSIMAG

PhD thesis

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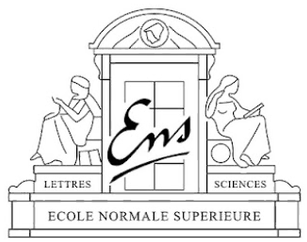


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- Masking Lattice-Based Signature Schemes [IMDEA++]
- Building New Generic Masked Multiplications [ENS]



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PhD thesis

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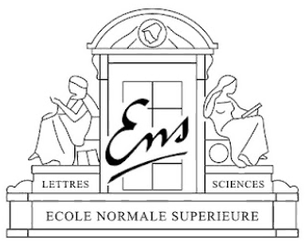


CRYPTO EXPERTS

THALES



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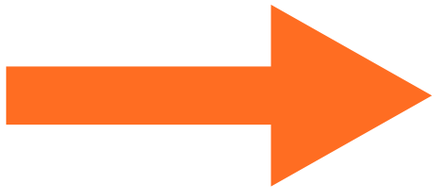
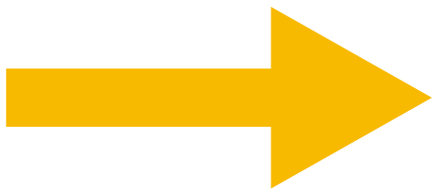
# New Missions, New Organization

# Two New Sequences of Work



Building more efficient composition schemes



Generate and verify masking in the *random probing model*

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# Maternity Leave (4 months)

More flexibility at CRX

Delayed reviews for CHES

People offered to wait for papers

Possible 1-year delay for ERC

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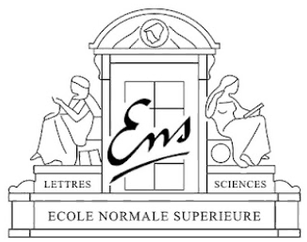
2021!

PhD thesis

2010

2015

2020

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Many collaborations from the people I met:
- Companies
- PhD thesis
- Conferences, seminar, projects

2021!

PhD thesis

2010

2015

2020

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2021!

Always new challenges:
- New papers
- Talks in conferences, seminar

2010

2020

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