Shuffle and Mix: On the Diffusion of Randomness in TI of Keccak

COSADE 2019, Darmstadt

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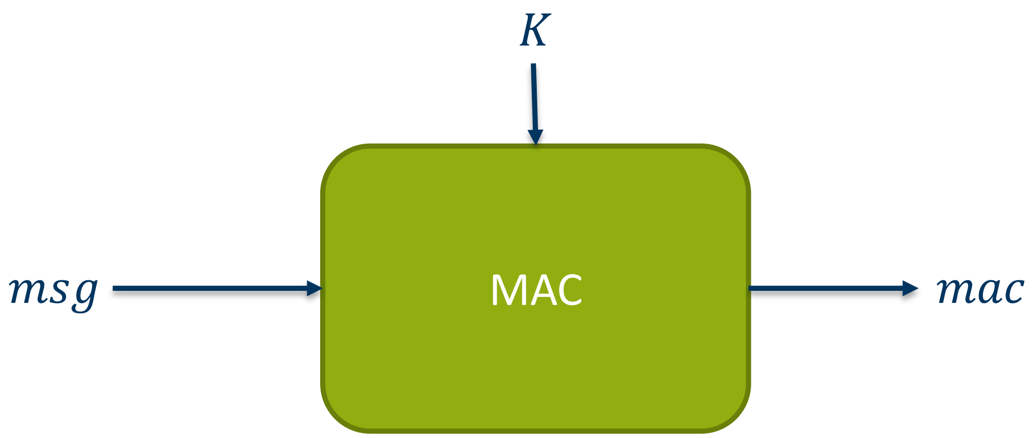
Ruhr University Bochum, Horst Görtz Institute for IT-Security, Germany

Motivation



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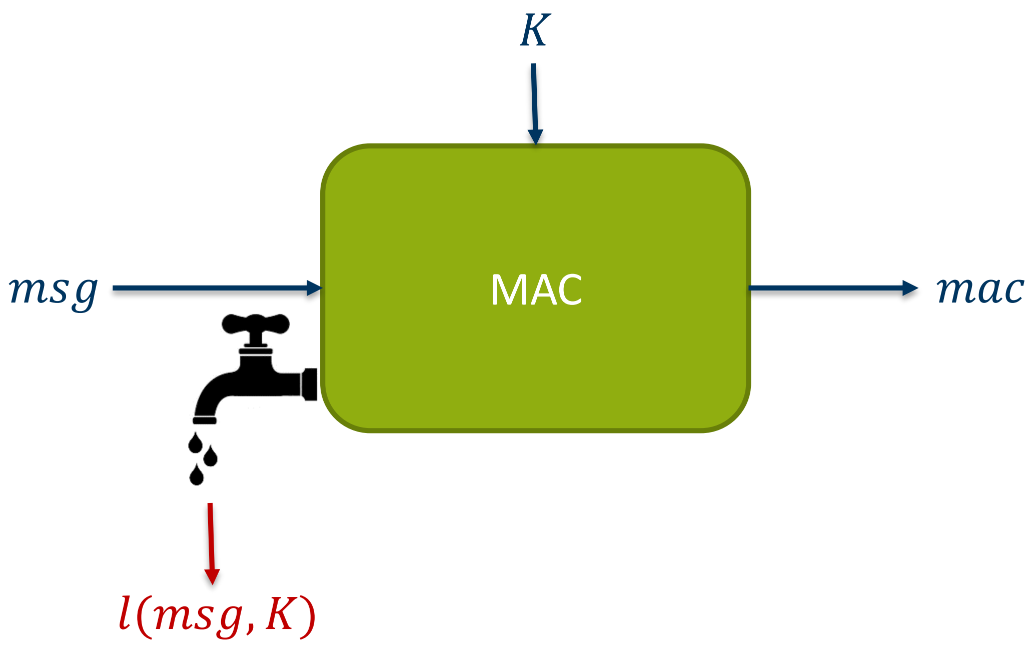

Motivation

RUB

Countermeasures

Masking: Make intermediate value independent of secret
Hiding: Lower SNR

Masking

Boolean Masking

RUB

- Core Idea: Secret x ⟶ multiple shares $\mathrm{X} = (a, b, c)$:

$$x = a \oplus b \oplus c$$

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Boolean Masking

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- In Hardware: Even more difficult due to glitches

Boolean Masking

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- Problem: How to compute a function f on shared values?
- In Hardware: Even more difficult due to glitches

Solution:
Threshold Implementations

Threshold Implementations

RUB

Three properties for first-order secure computations

- Correctness

$$A, B, C = F(a, b, c)$$
$$f(x) = A \oplus B \oplus C$$

Nikova, Rechberger, Rijmen. Threshold Implementations Against Side-Channel Attacks and Glitches, ICICS 2006

Threshold Implementations

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$$A, B, C = F(a, b, c)$$
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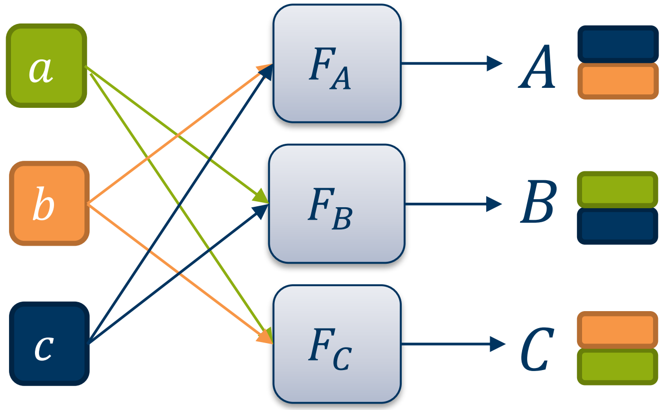
- Non-completeness



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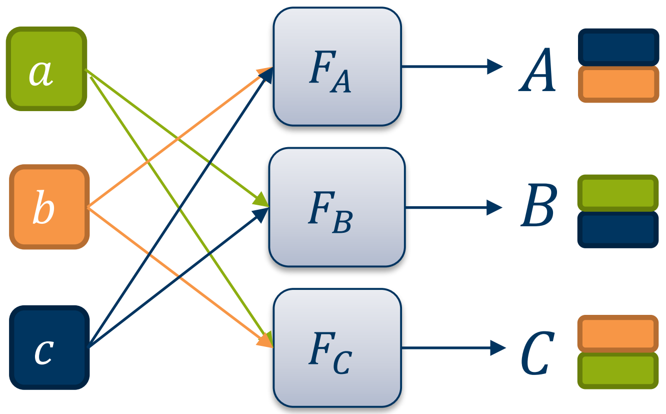
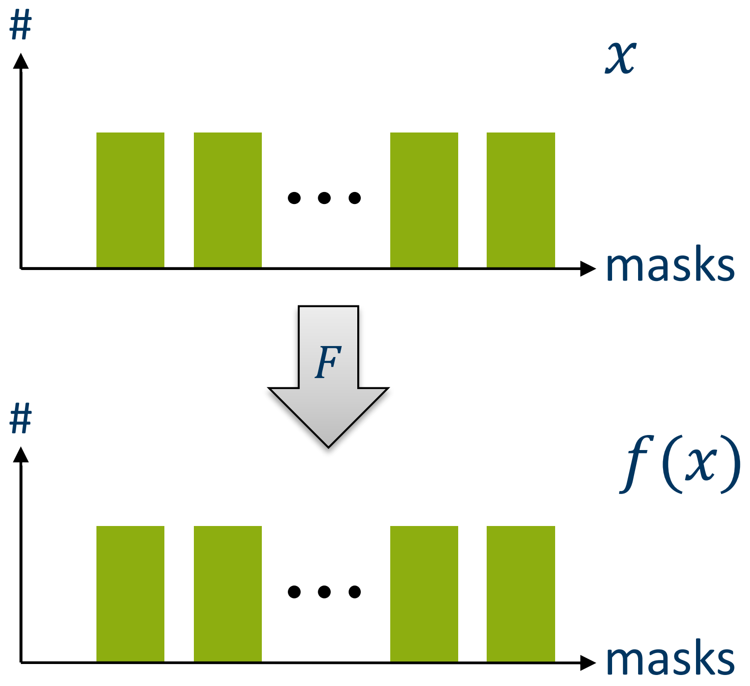


- Uniformity



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Why Uniformity?

RUB

- Locally:

Theorem:
If F is
- correct
- non-complete
- Input is masked uniformly

Then:
Evaluation is first-order secure

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Uniform output <u>not</u> needed

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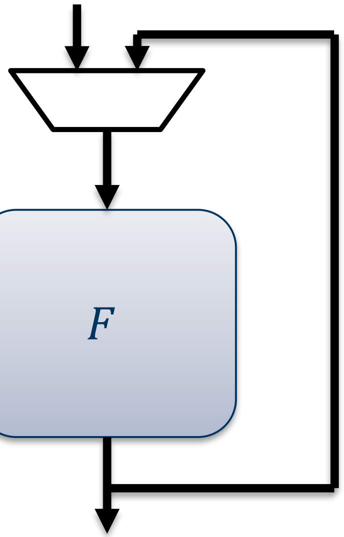

Iterated Round-function

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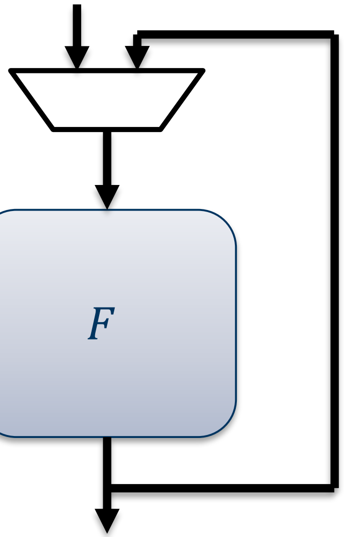


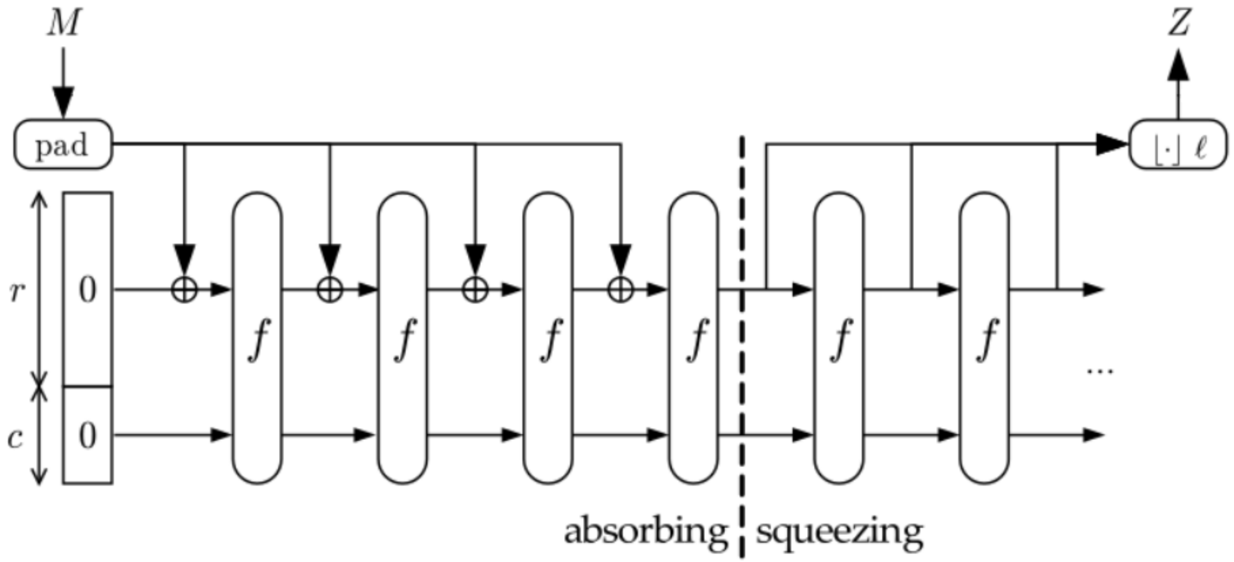
Iterated Round-function

Uniform output needed

Keccak

Keccak

- Sponge-based Hashfunction



- SHA3 in 2015

Bertoni et al. Cryptographic Sponge Functions. Keccak.team

Keccak

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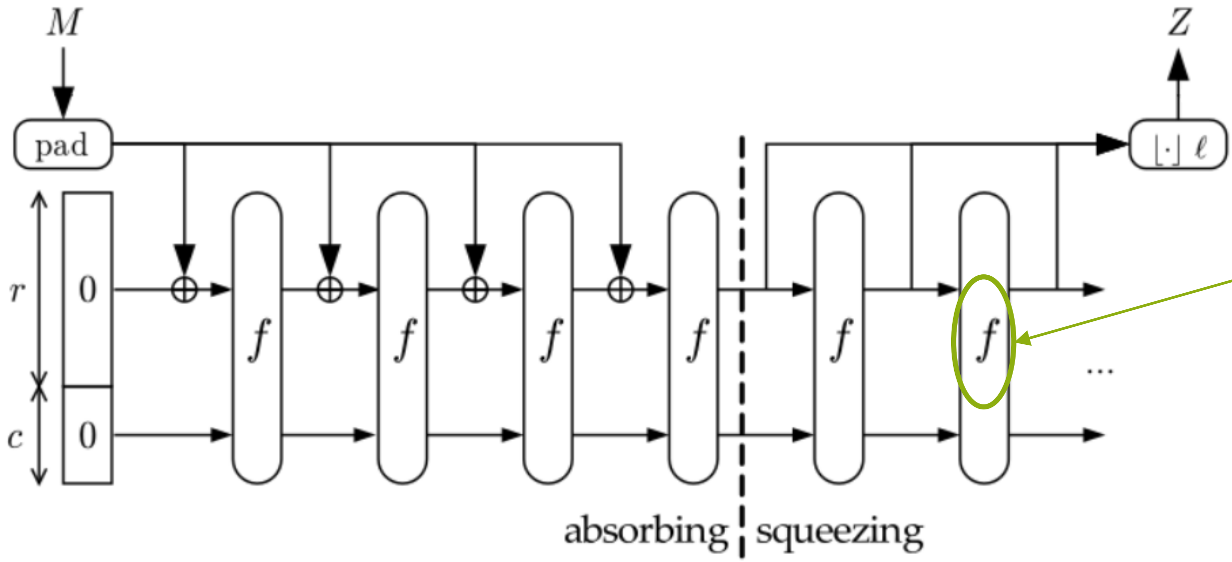

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Keccak-*f*[b]:

- $b = 25 \cdot 2^l,\ l = 0, \dots, 6$
- $n_r = 12 + 2l$
- $R = \iota \circ \chi \circ \pi \circ \rho \circ \theta$

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Keccak

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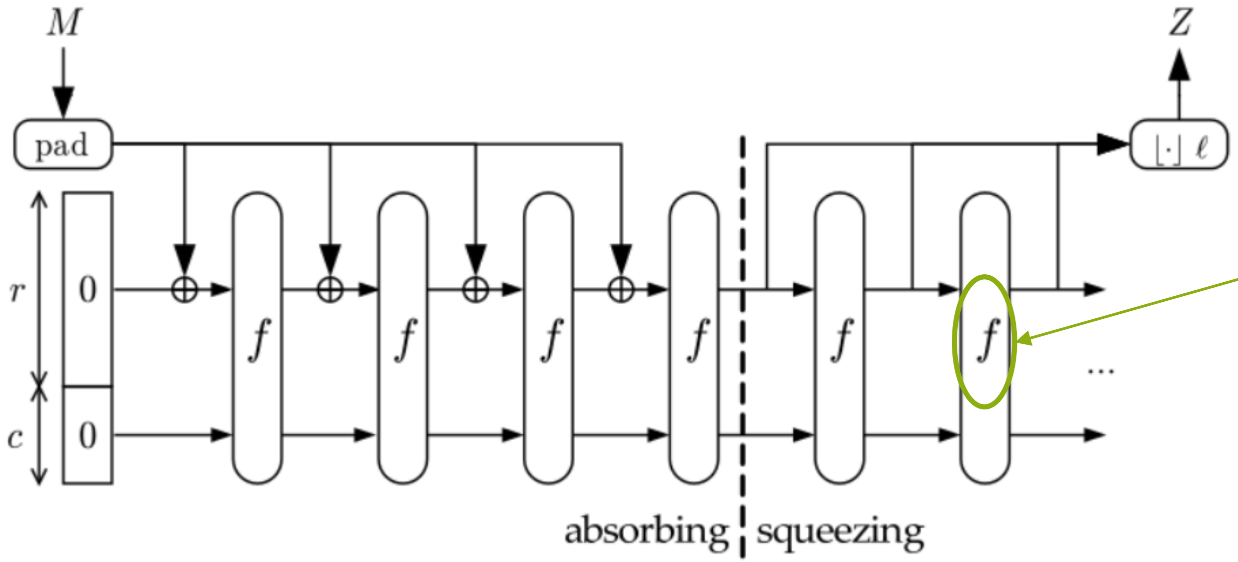

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Here:
Keccak-*f*[200]
18 rounds

Bertoni et al. Cryptographic Sponge Functions. Keccak.team

How to mask Keccak-f?

Linear Layer

ρ

π

θ

ι

Linear Layer

RUB

Use linearity:

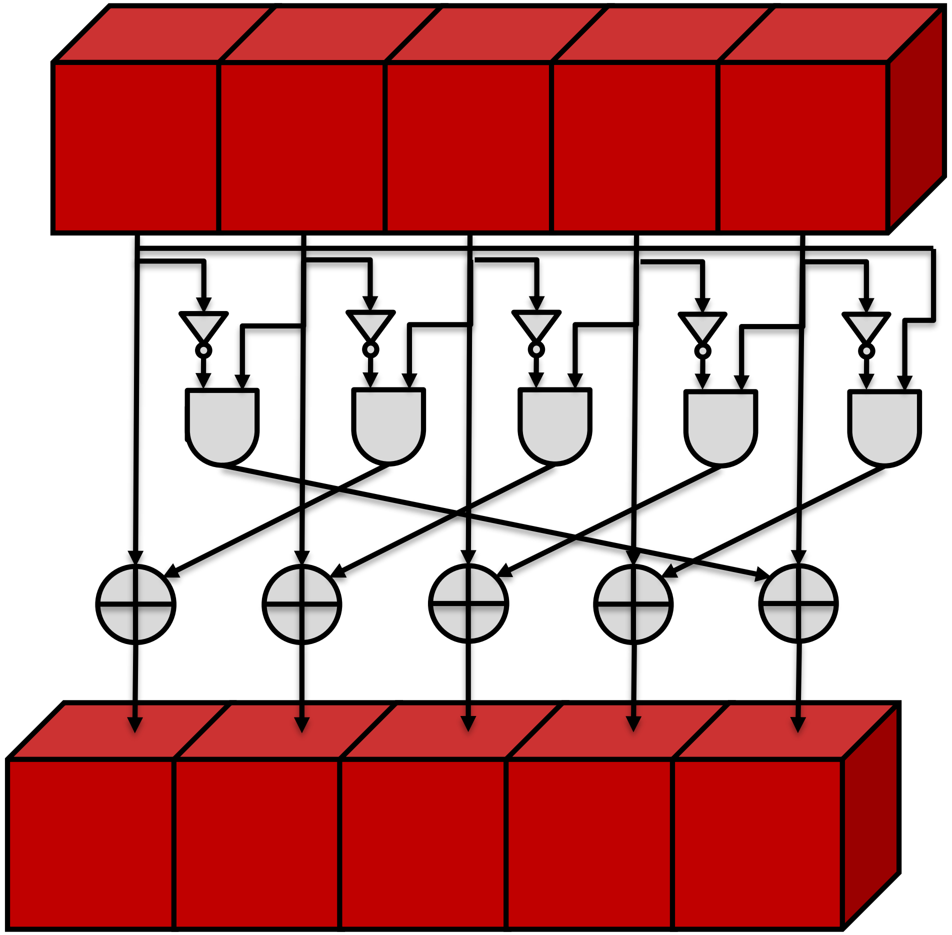
$$L(x_1 \oplus x_2 \oplus x_3) = L(x_1) \oplus L(x_2) \oplus L(x_3)$$

Replication without modification

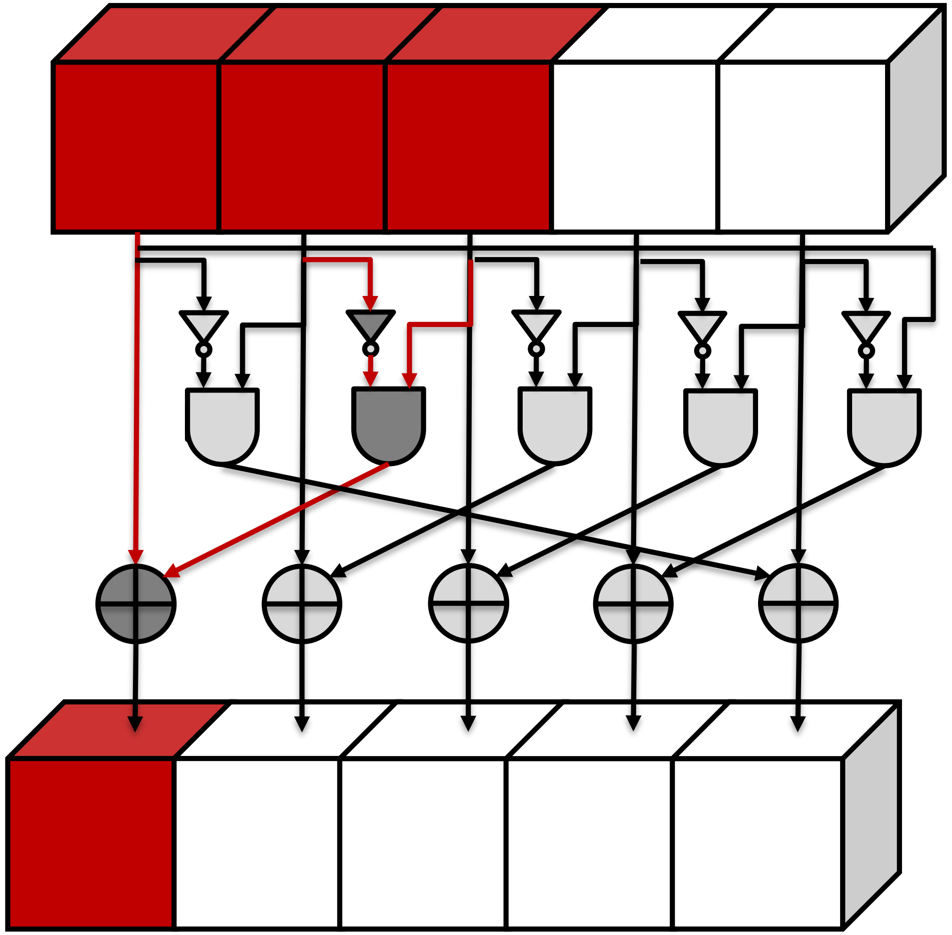
Non-linear Layer

χ

Non-linear Layer



Non-linear Layer



One Coordinate function:

$$y_0 = x_0 \oplus [(1 \oplus x_1) \land x_2]$$
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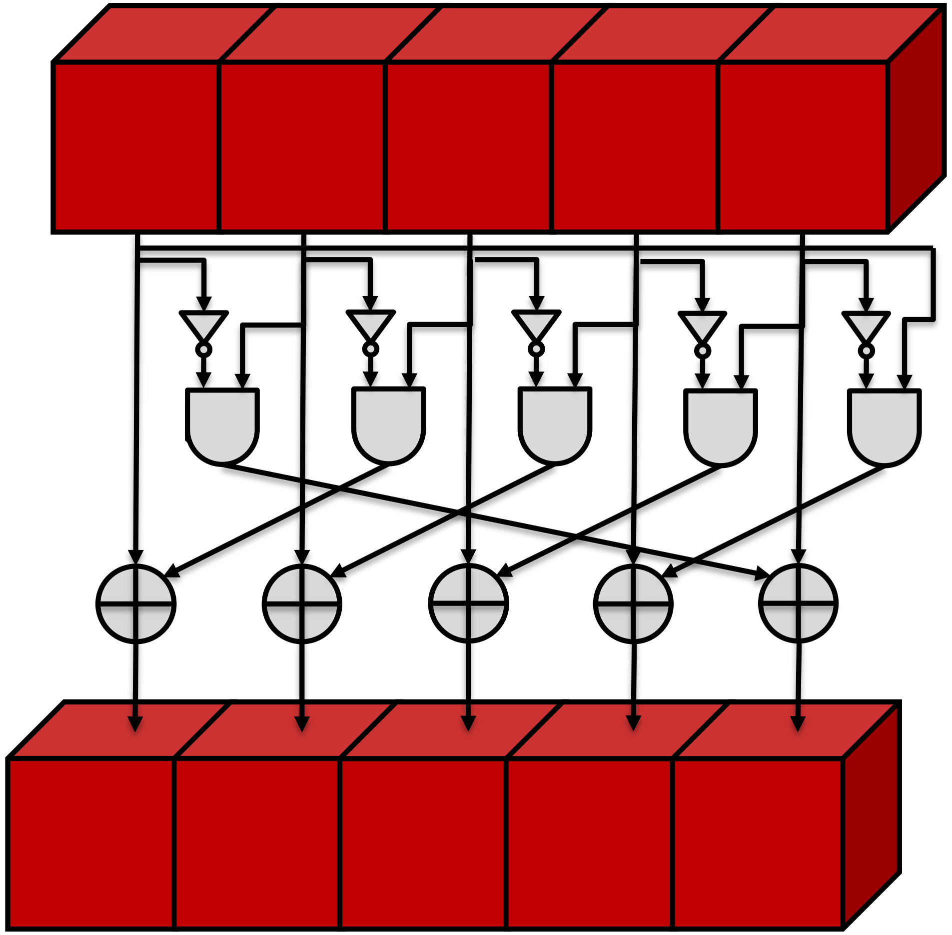
Non-linear Layer

RUB



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Direct Sharing of χ:

$$A_i = b_i \oplus (b_{i+1} \wedge b_{i+2}) \oplus (b_{i+1} \wedge c_{i+2}) \oplus (c_{i+1} \wedge b_{i+2}) \oplus b_{i+2}$$
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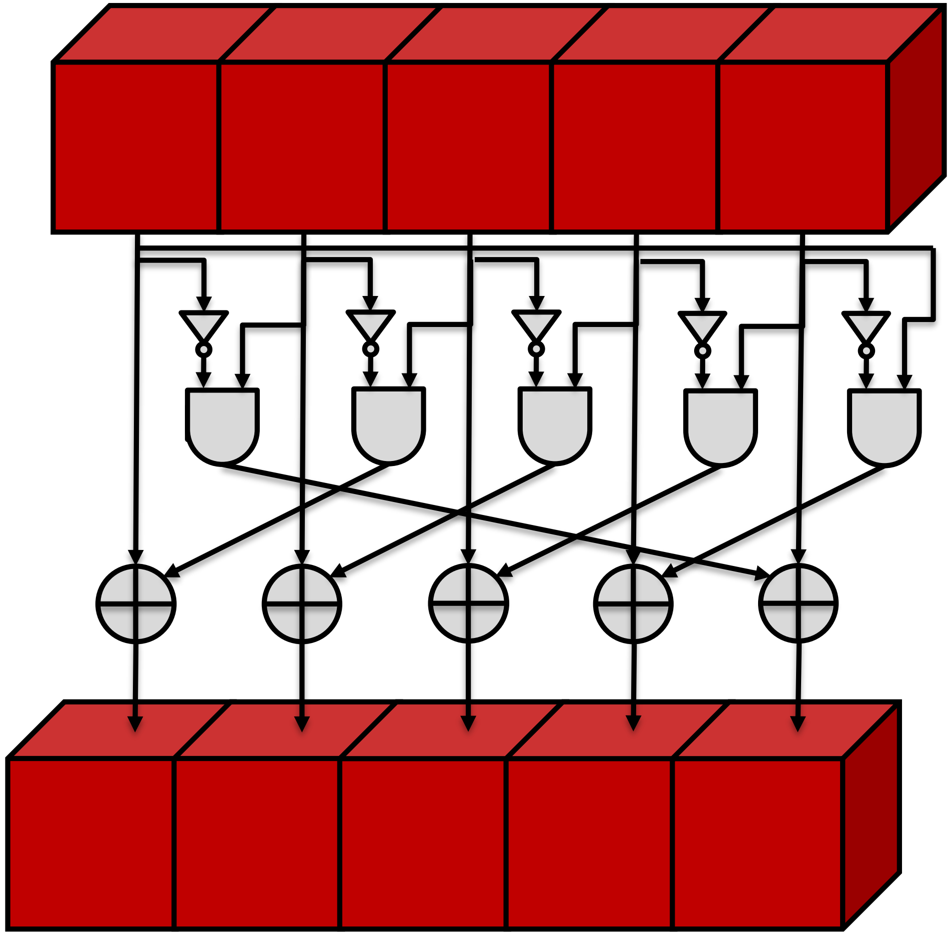
Bertoni, Daemen, Peeters, Van Assche: Keccak. EUROCRYPT 2013

Non-linear Layer



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Non-complete ✔

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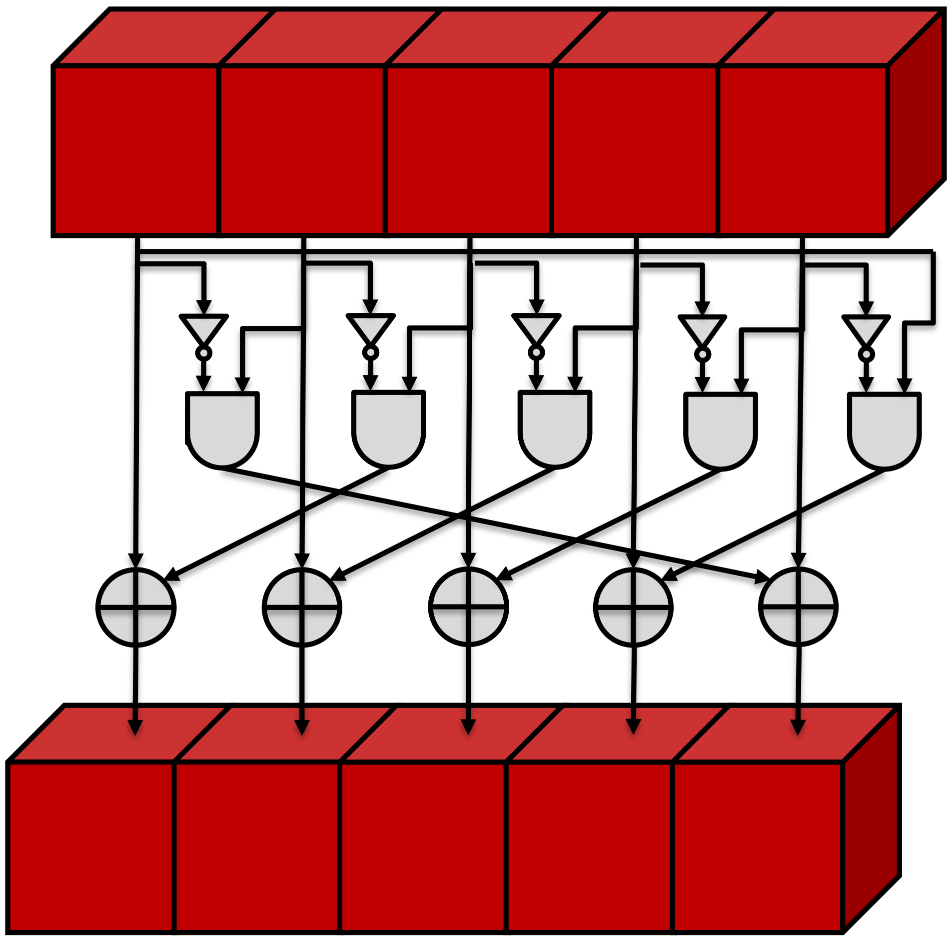

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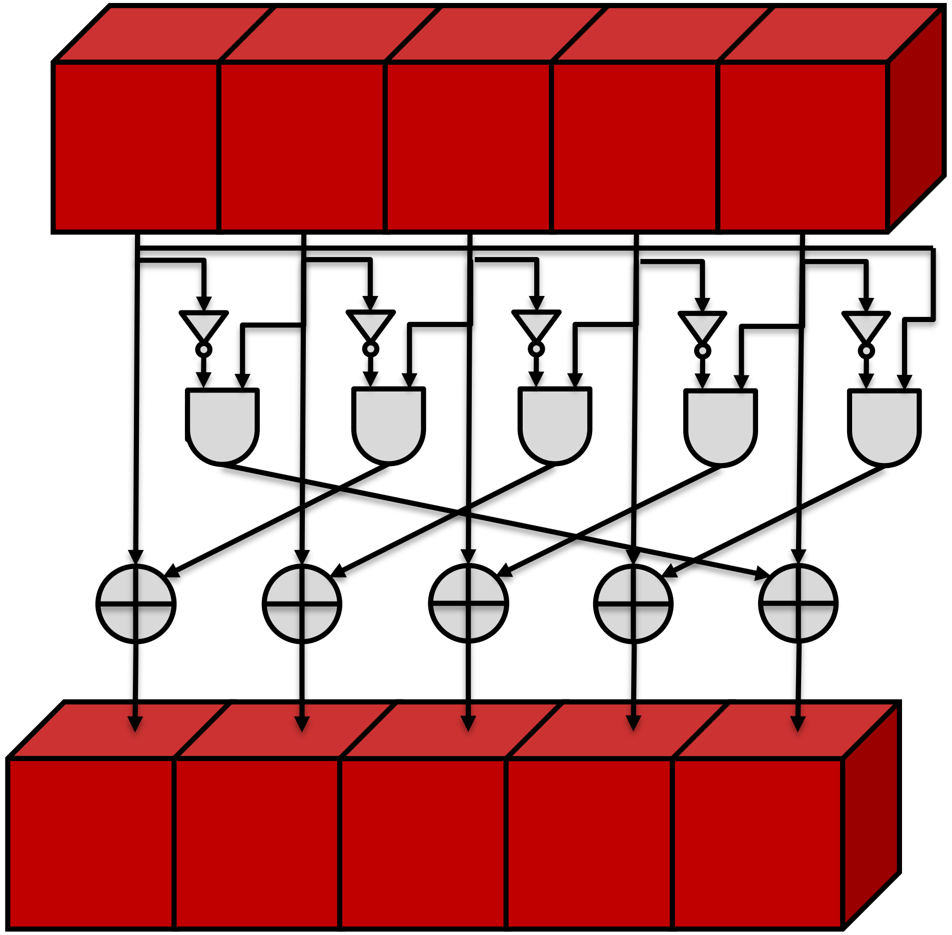
NOT Uniform ✘

Non-linear Layer

RUB



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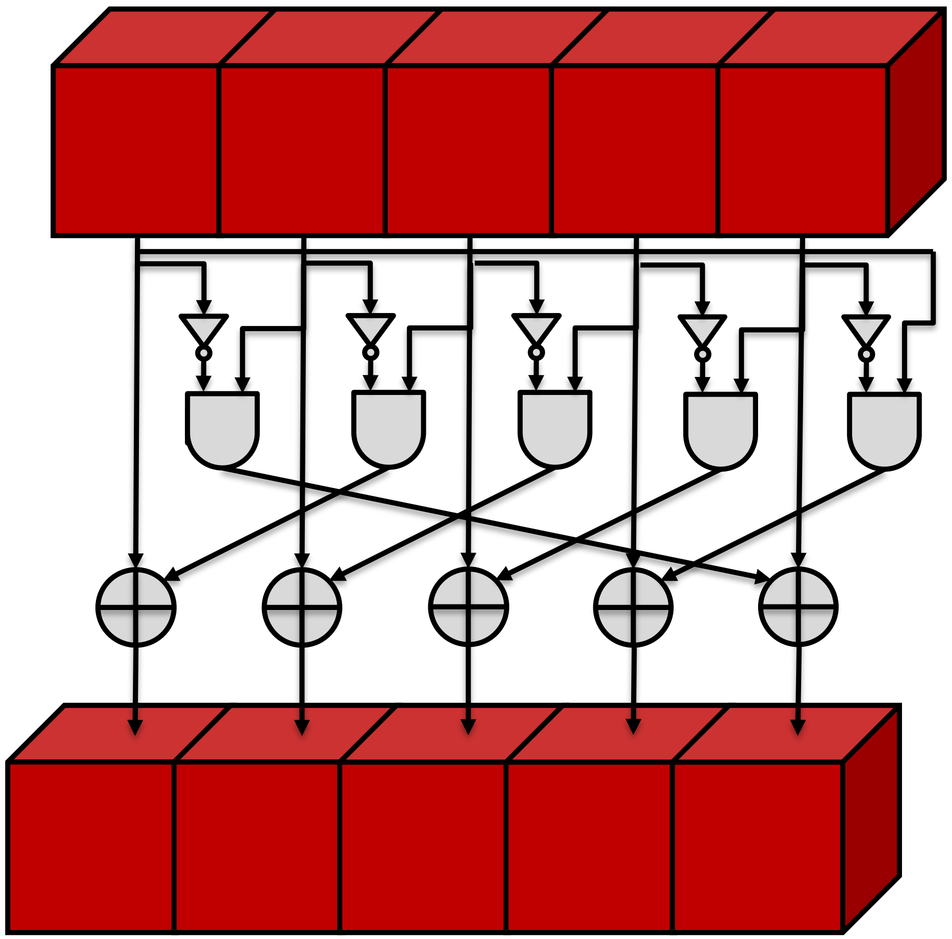
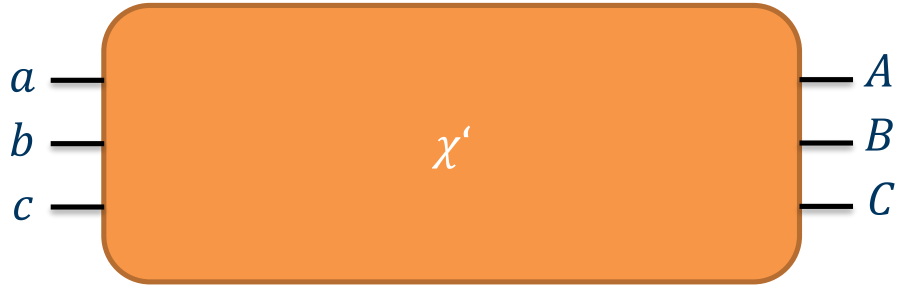
Non-complete ✔

Partially Uniform

Non-linear Layer

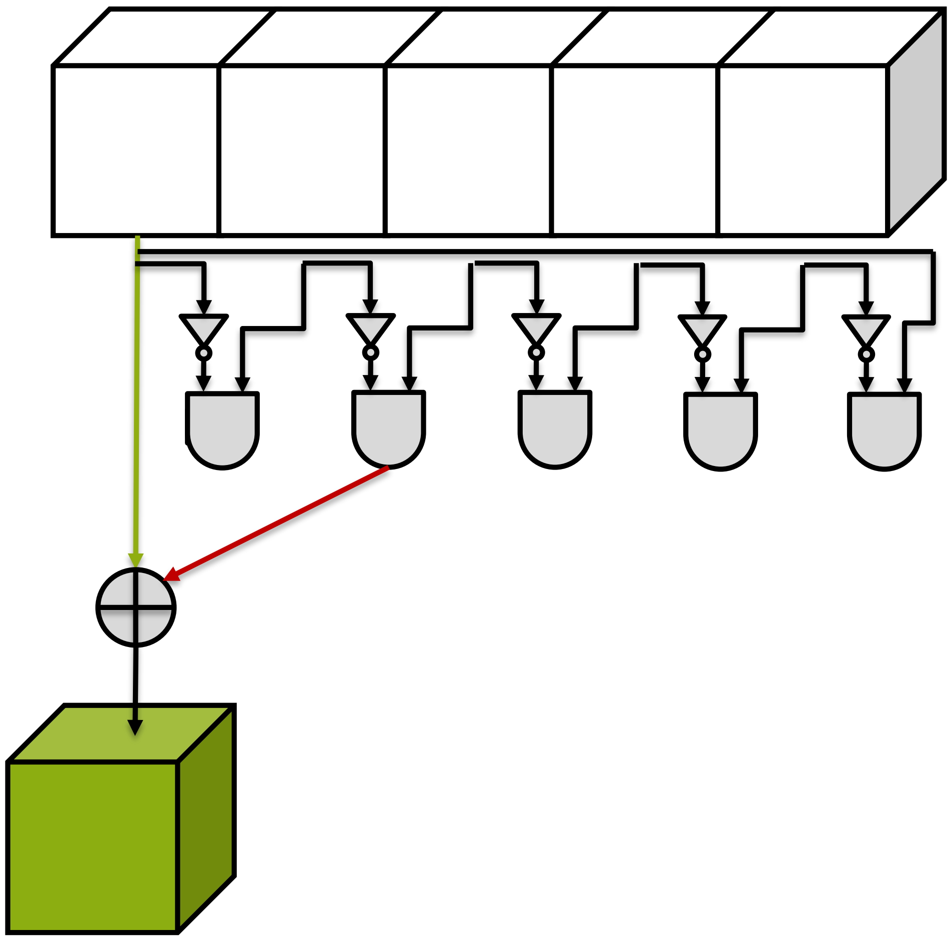


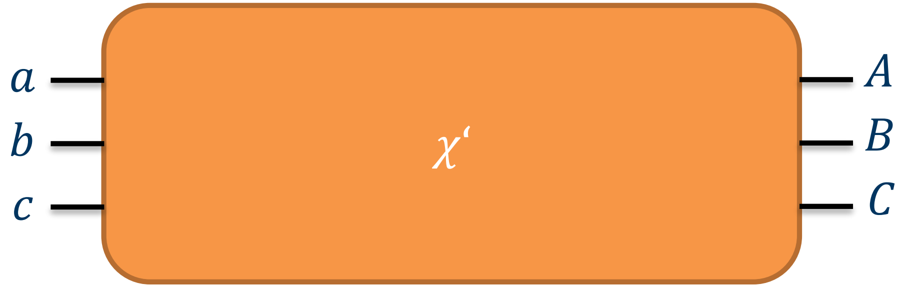


Non-complete ✔

Partially Uniform

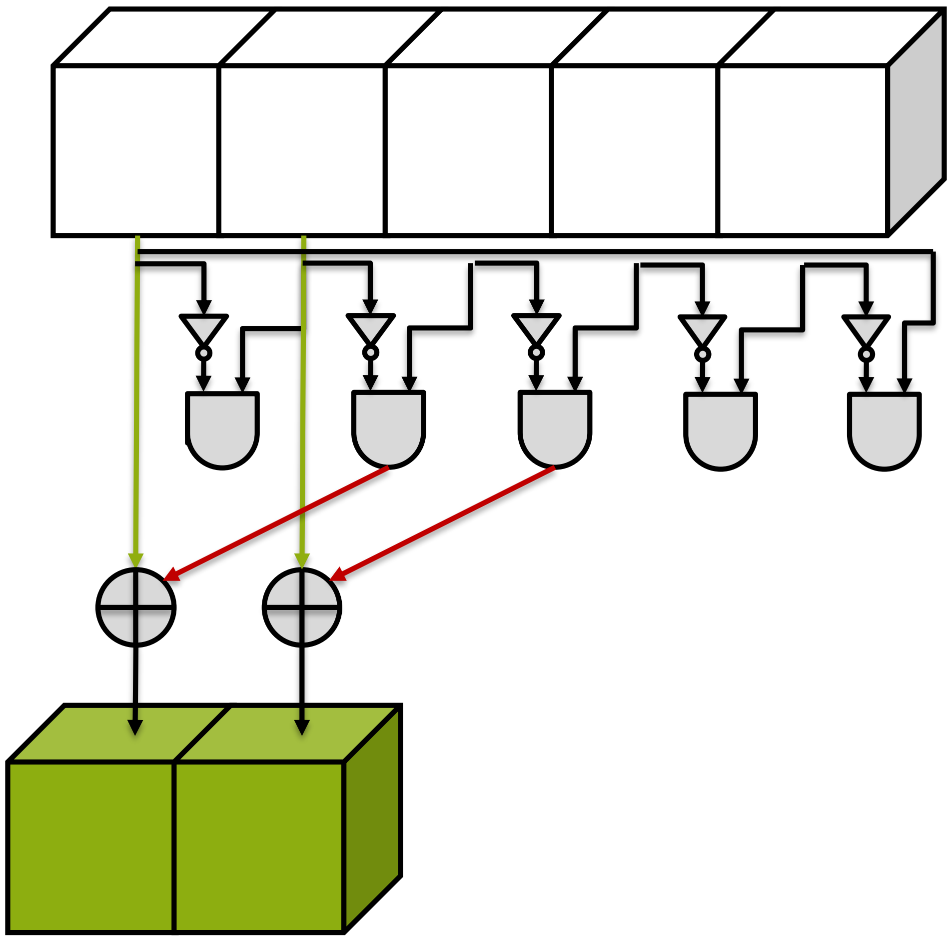
Non-linear Layer

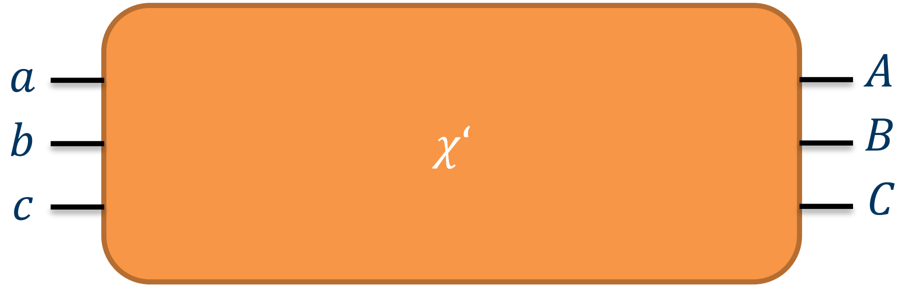




1 single bit: uniform

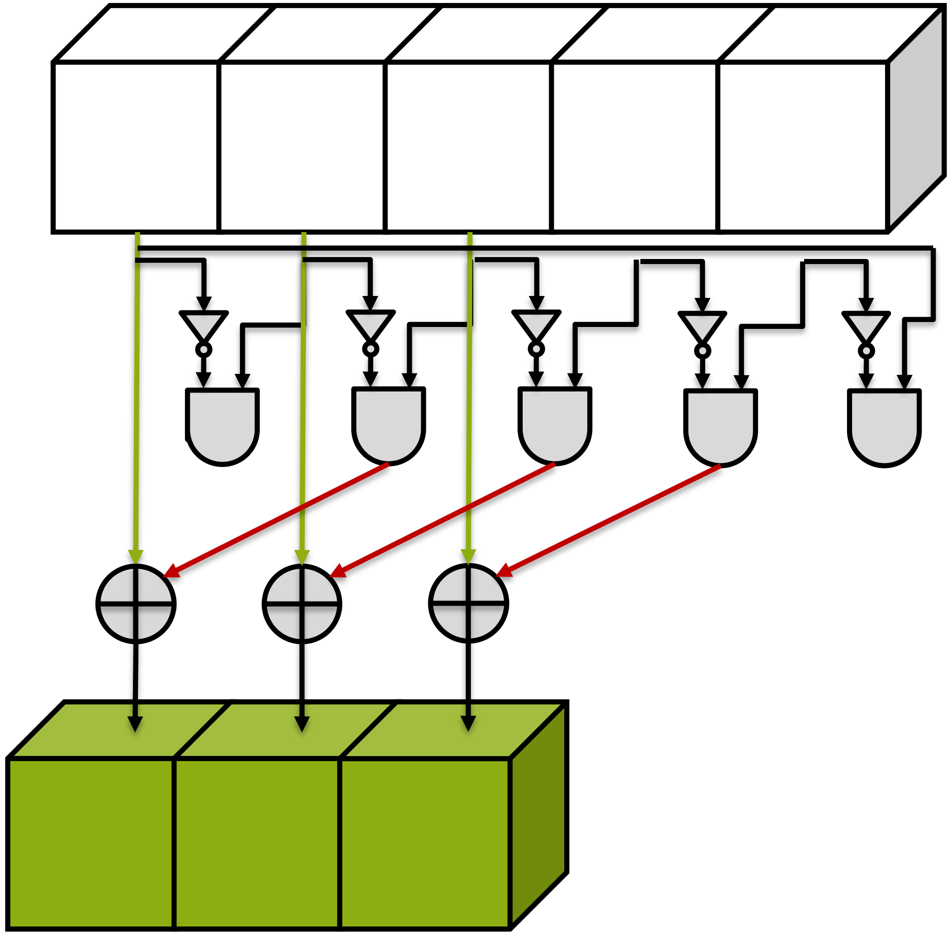
Non-linear Layer

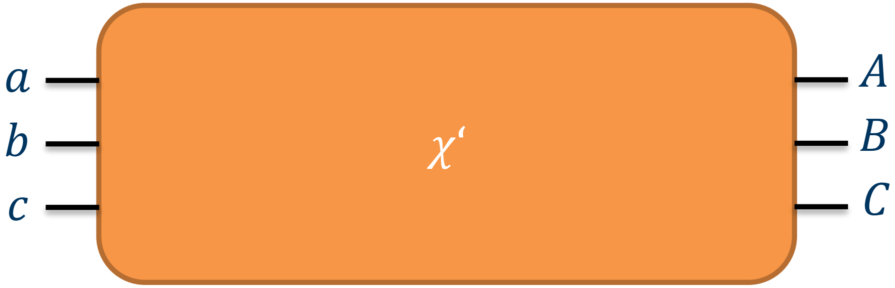




2 bits: jointly uniform

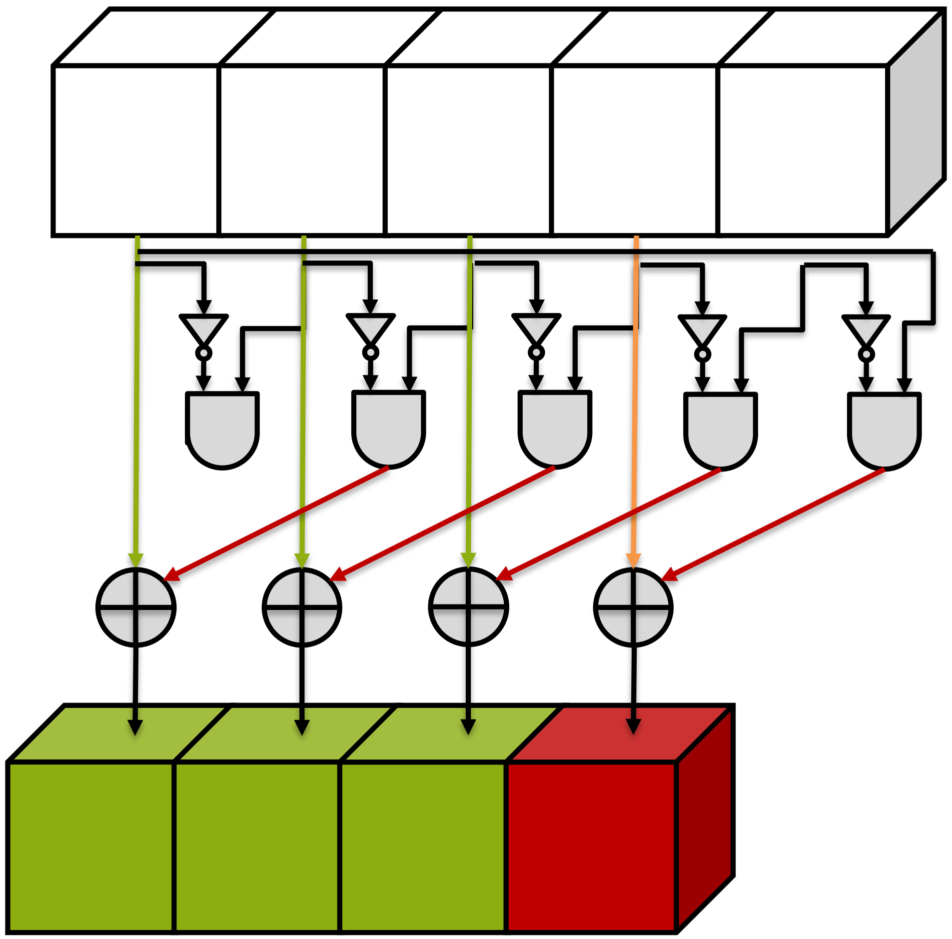
Non-linear Layer

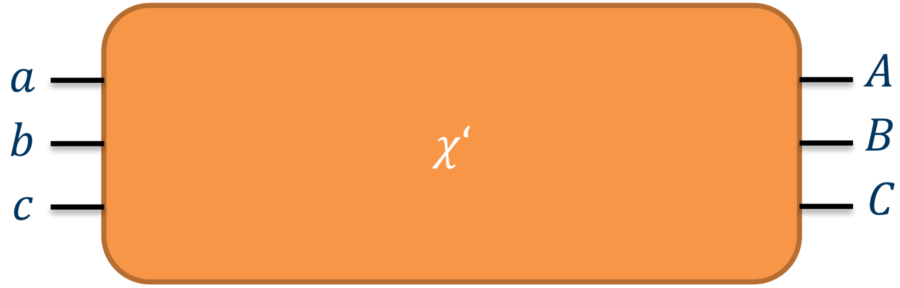




3 bits: jointly uniform

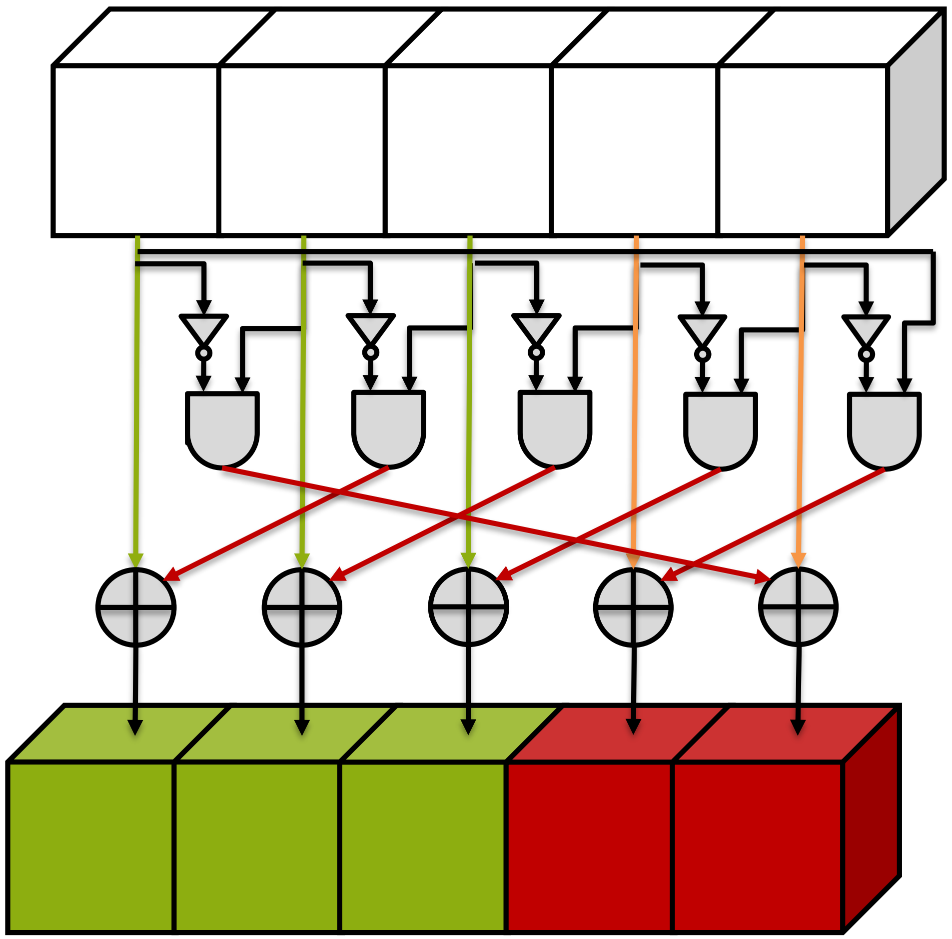
Non-linear Layer

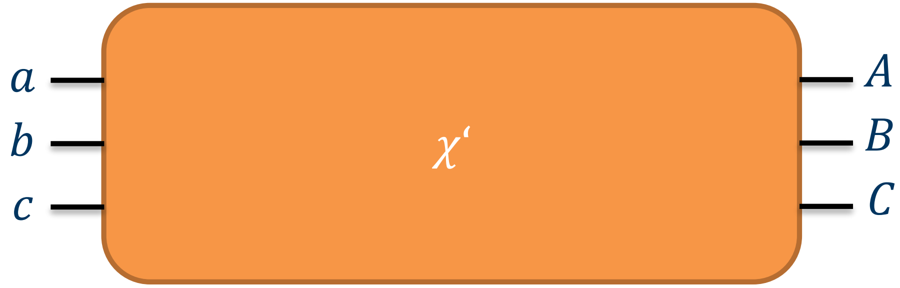




4 bits: not jointly uniform

Non-linear Layer



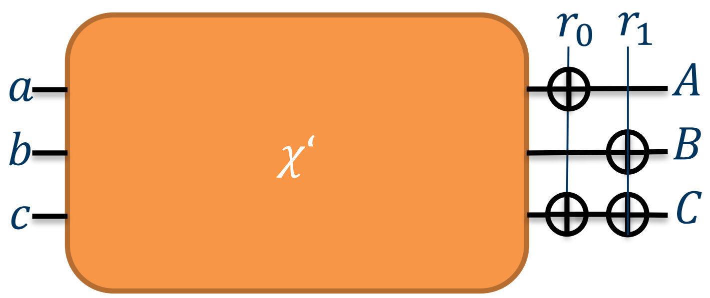


2 out of 5 bits not jointly uniform*

*Bilgin et al. Efficient and First-Order DPA Resistant Implementations of Keccak, CARDIS 2013

Fixing Non-Uniformity

Refresh with 4 bits of fresh randomness*



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**Daemen. Changing of the Guards: A Simple and Efficient Method for Achieving Uniformity in Threshold Sharings. CHES 2017

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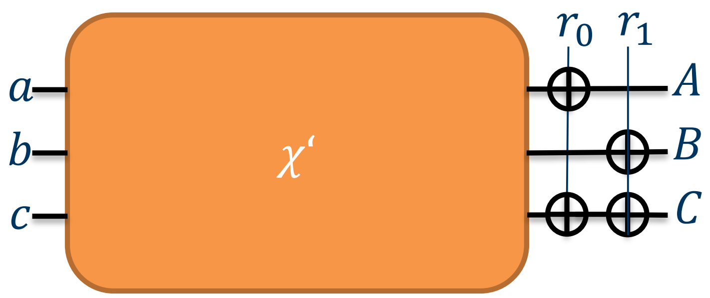
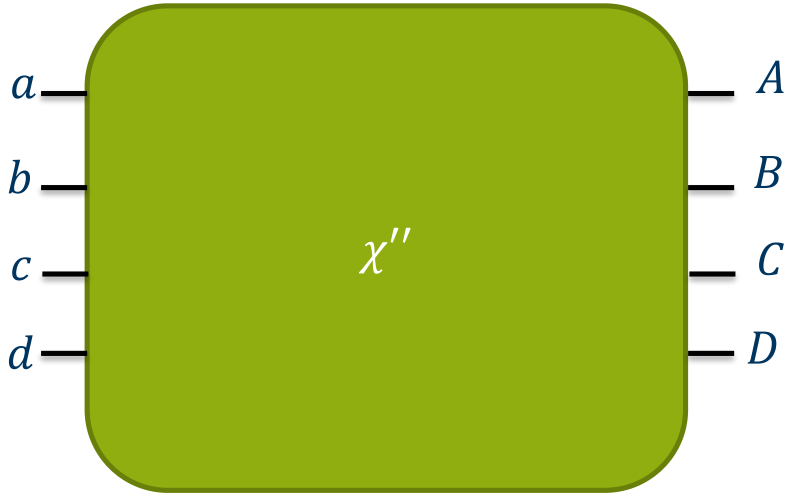


Use 4 shares*



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RUB

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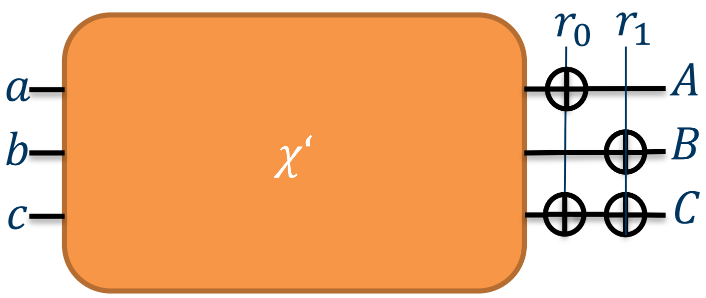

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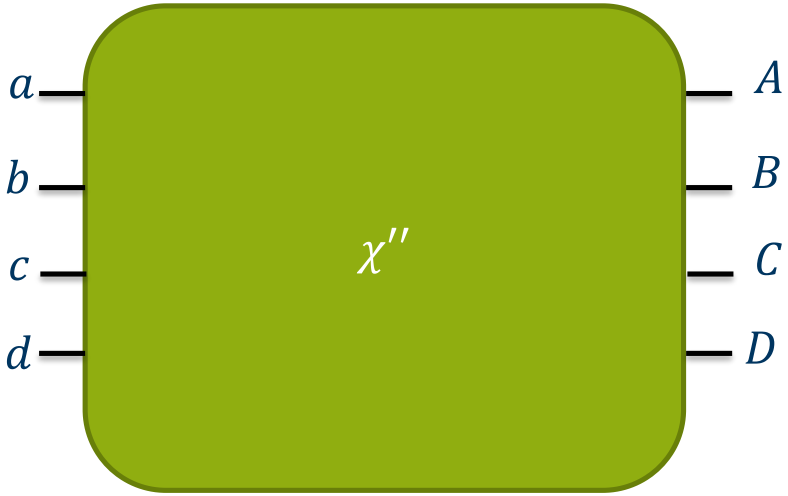
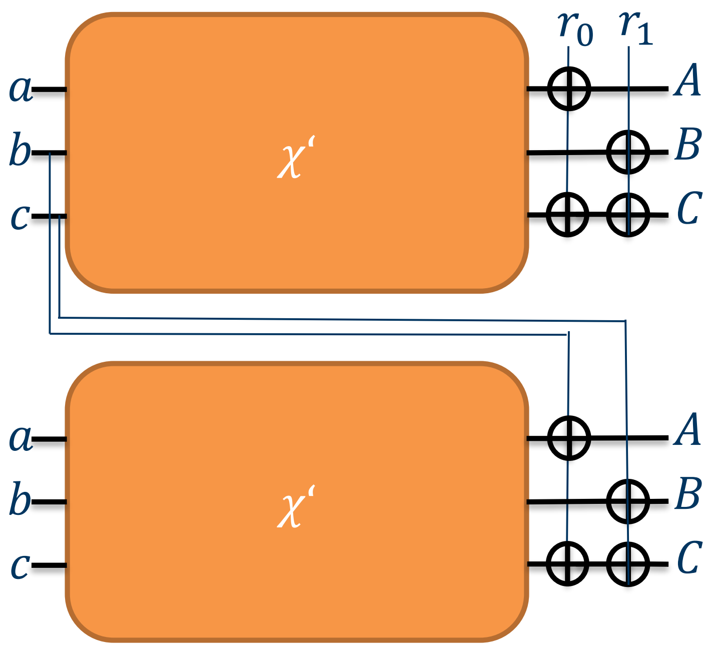


Changing of the Guards**



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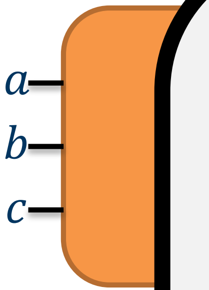

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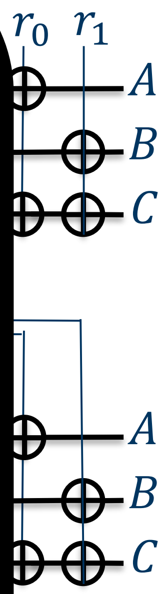

This Work: Don‘t fix it.

Consequences?

Use 4 sha

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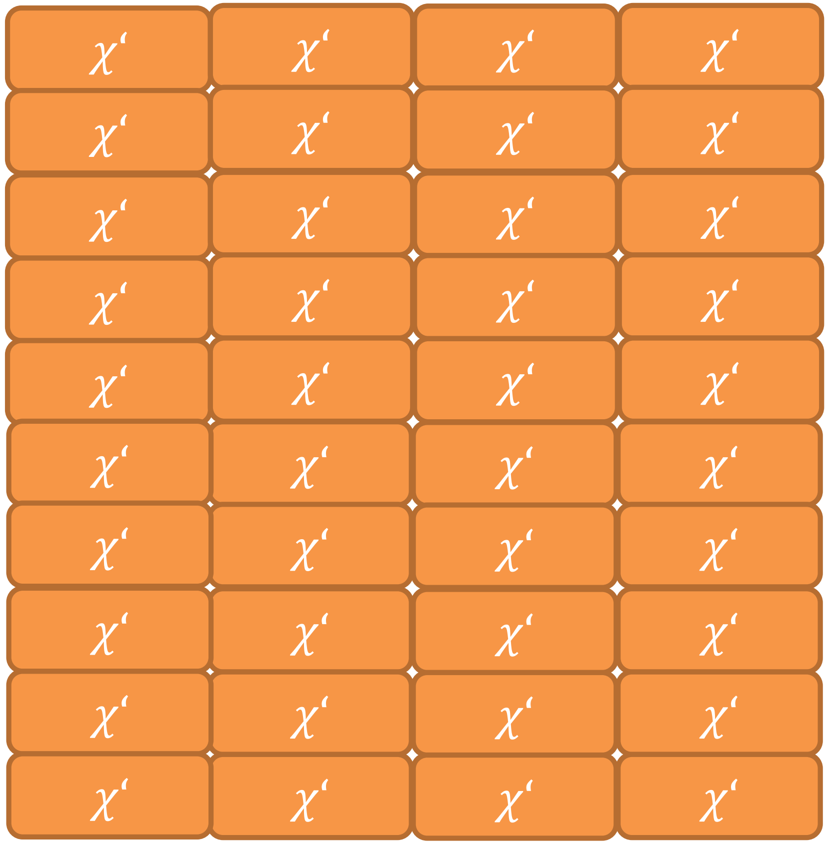
Hardware Target

Hardware Architecture

How many parallel S-boxes?

Serialized

Round-based



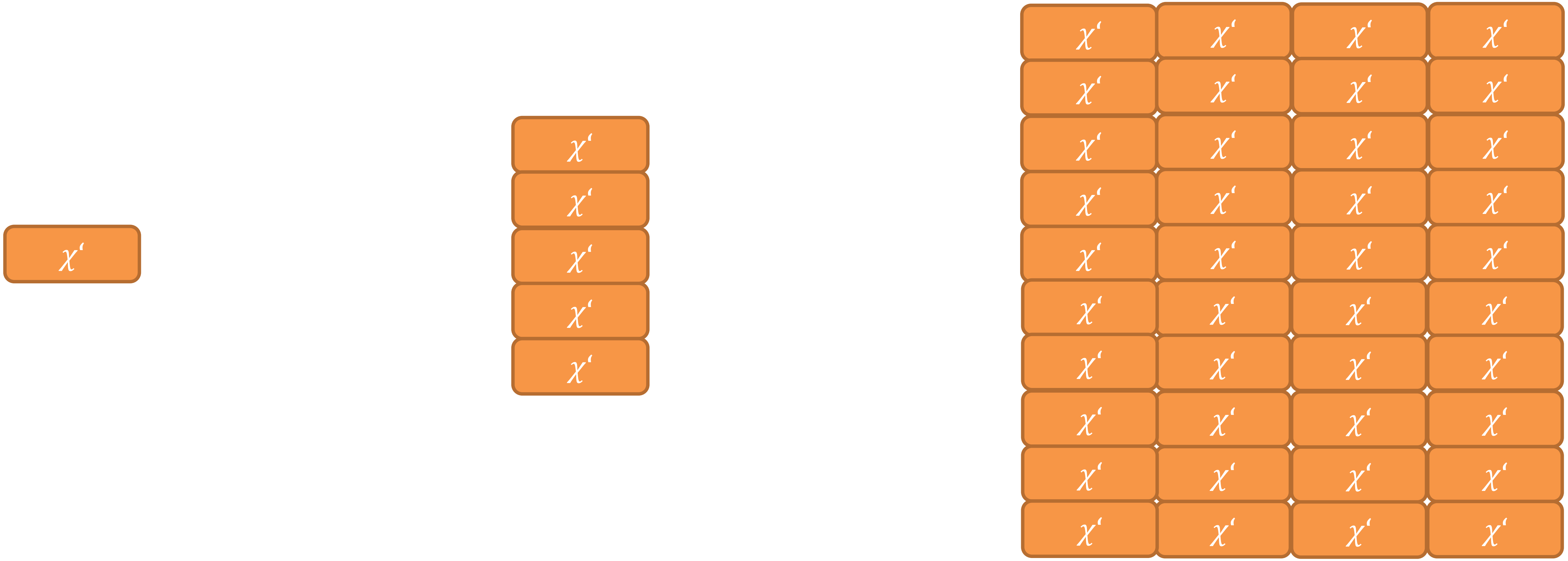
Hardware Architecture

How many parallel S-boxes?

Serialized

Slice-based

Round-based



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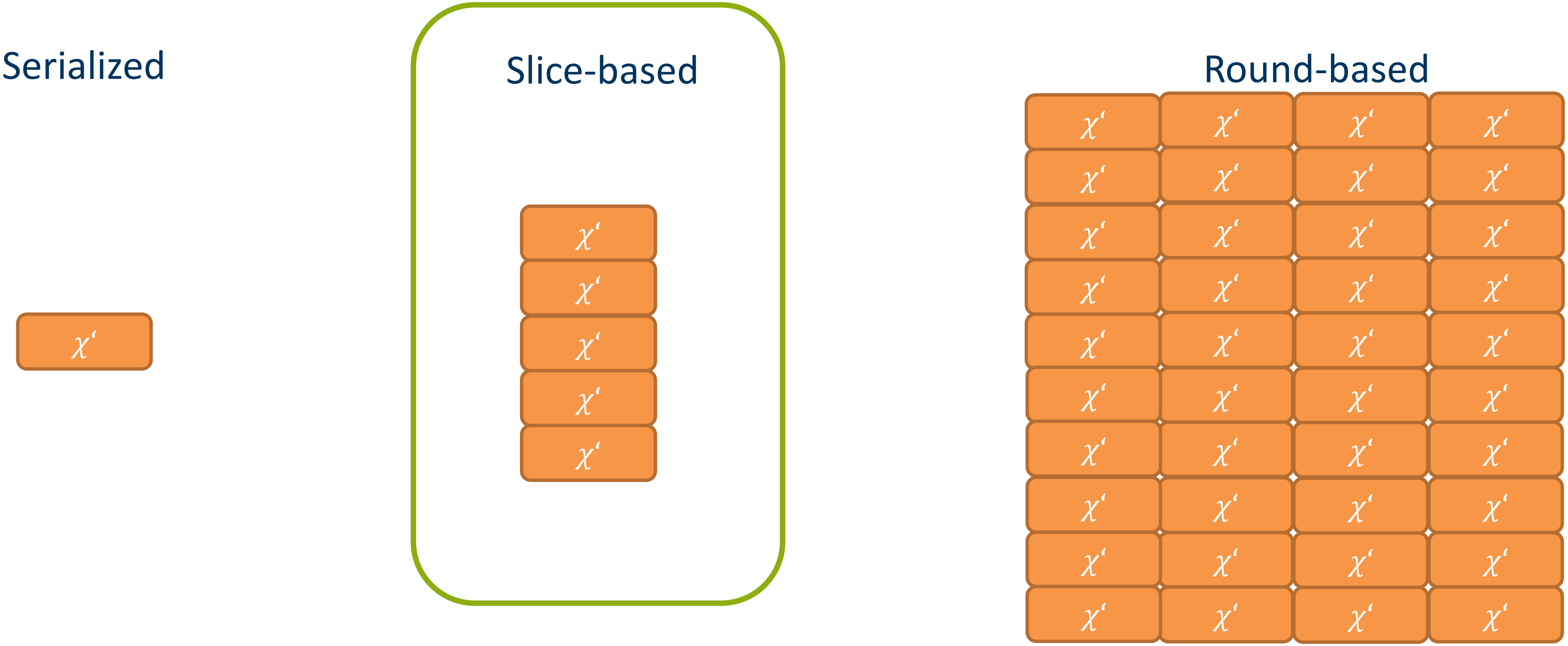
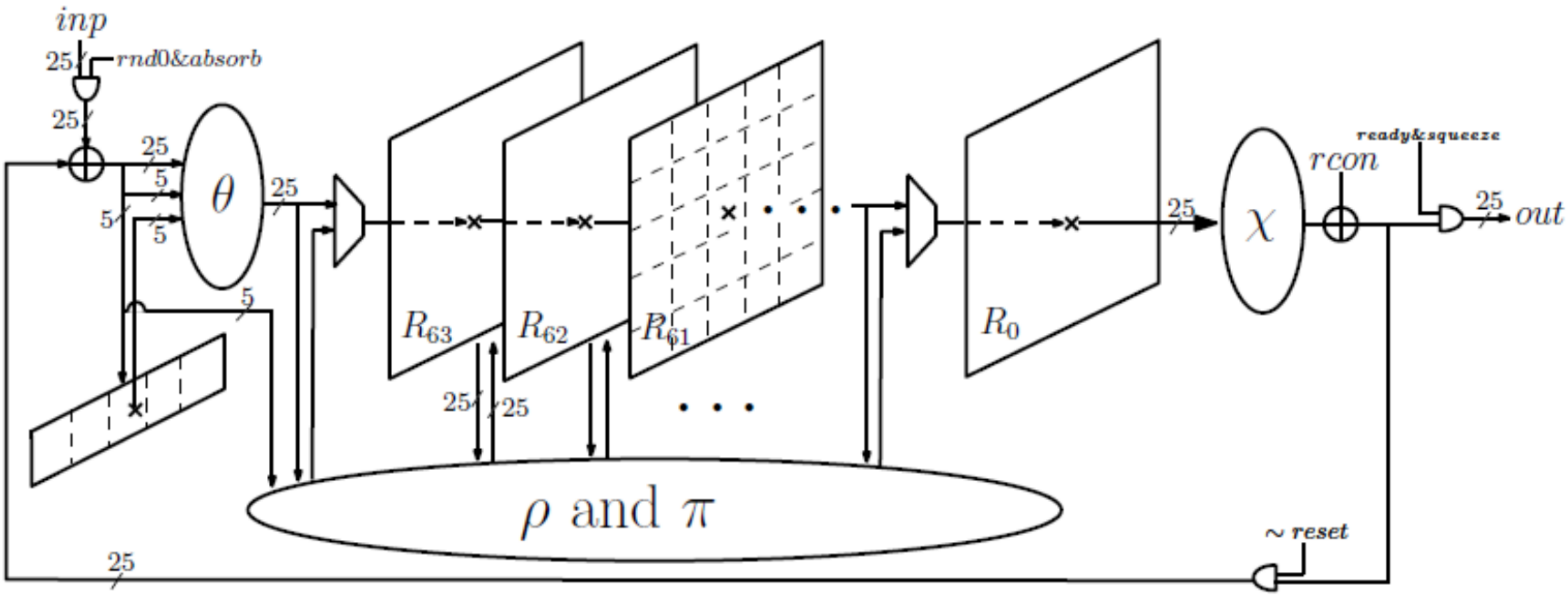


Hardware Architecture

- Slice-Serial: 5 parallel χ evaluations
- Special treatment: θ applied to slice 0



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Leakage Evaluation

SCA-Measurements

RUB

Evaluation methodology:

- Non-specific T-test „fixed vs. Random“
  - over entire 200bit state
  - with 100 million traces
- Each trace: entire last round

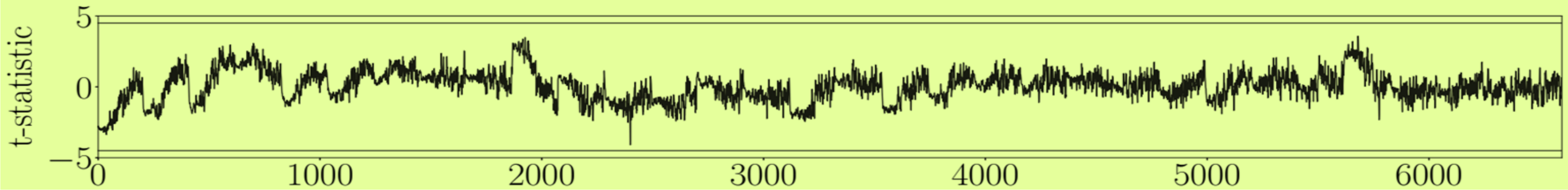
Measurement Setup:

- SAKURA-G board @ 1.5Mhz
- Picoscope 6402 @ 625 MS/s
- Amplifier: ZFL-100LN+ (Mini-Circuits)

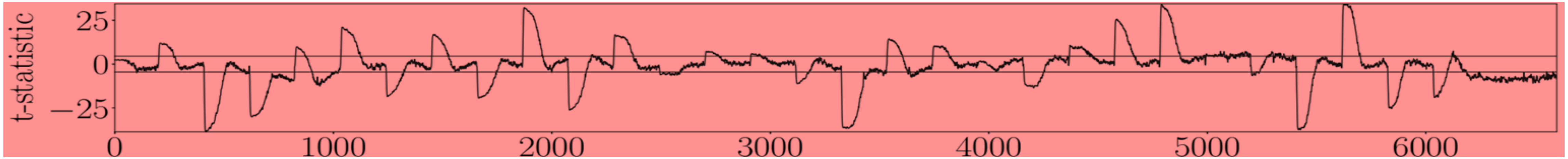
Schneider, Moradi. Leakage Assessment Methodology - a clear roadmap for side-channel evaluations, CHES 2015

18 Rounds of Keccak

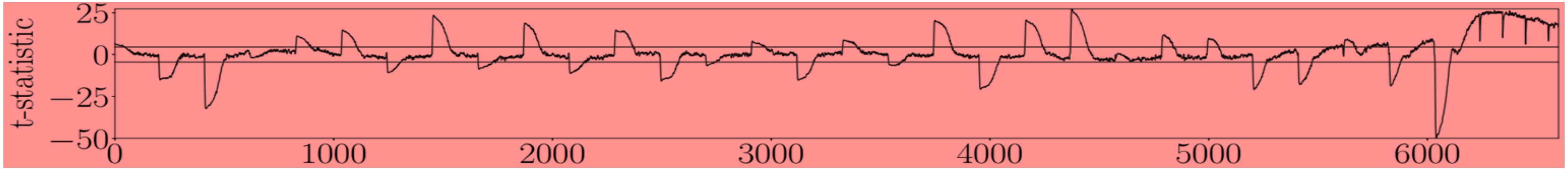
1. order over time



2. order over time



3. order over time



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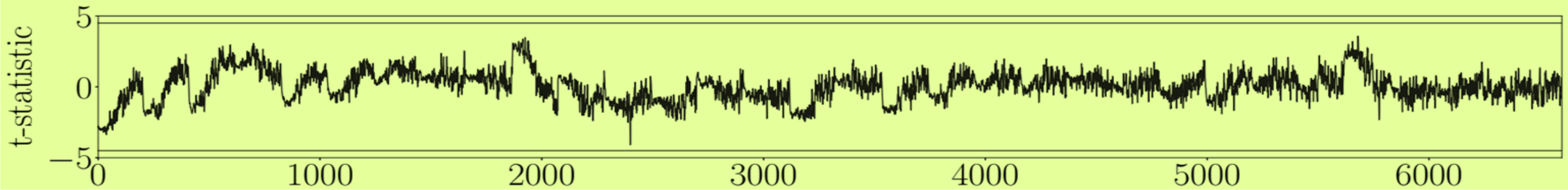
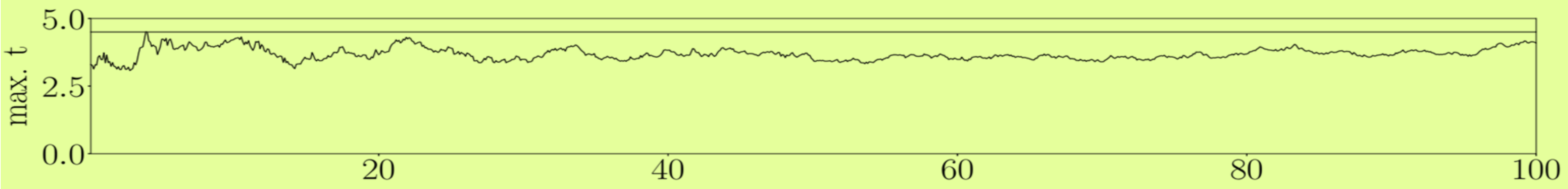


1. order over traces



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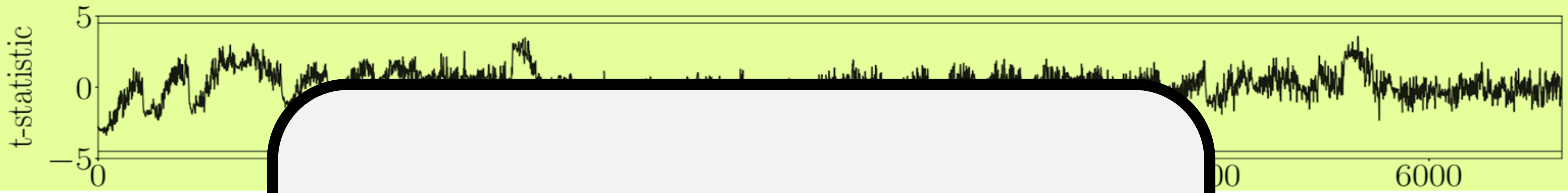
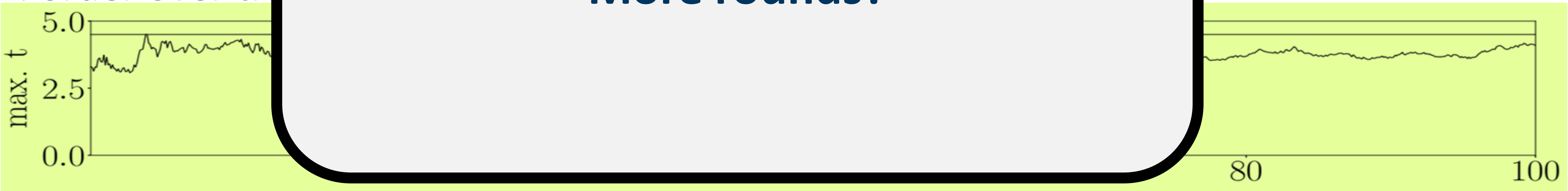


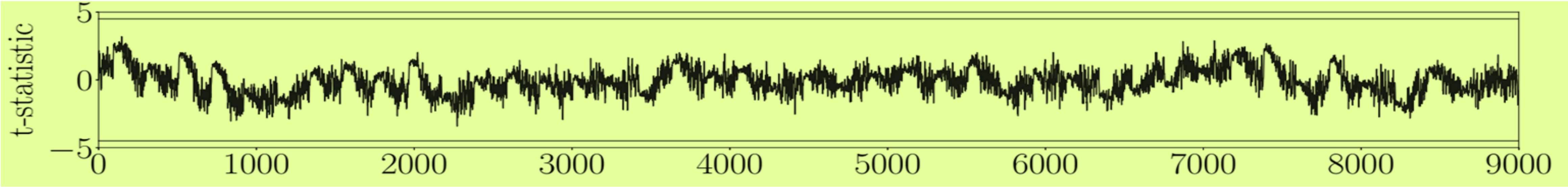
Works fine.
More rounds?

1. order over tra

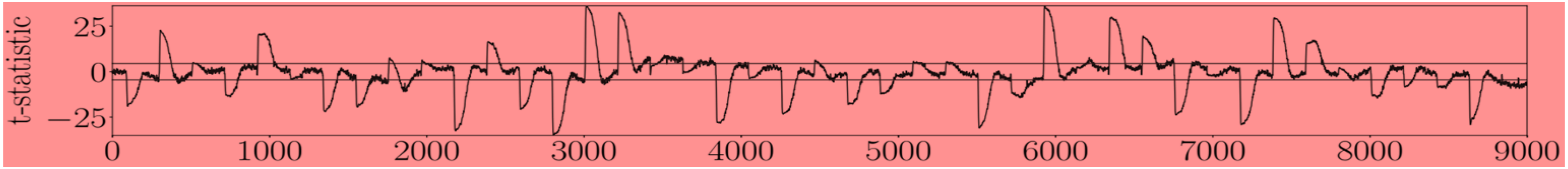


1800 Rounds of Keccak

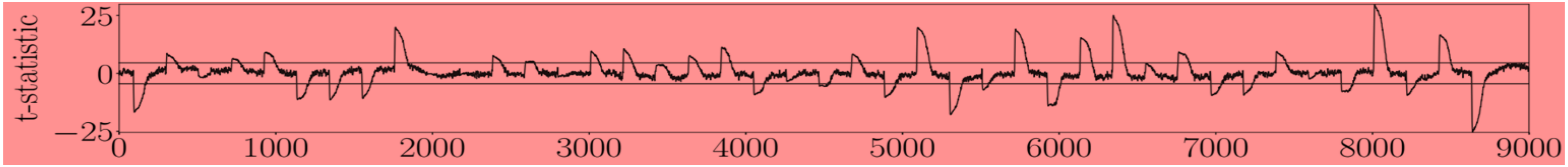
1. order over time



2. order over time



3. order over time



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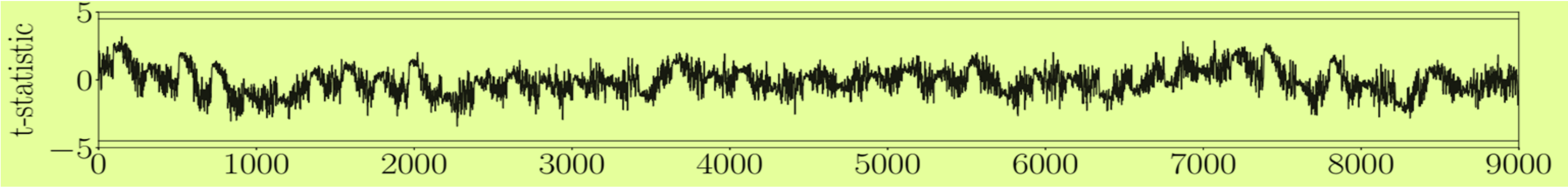
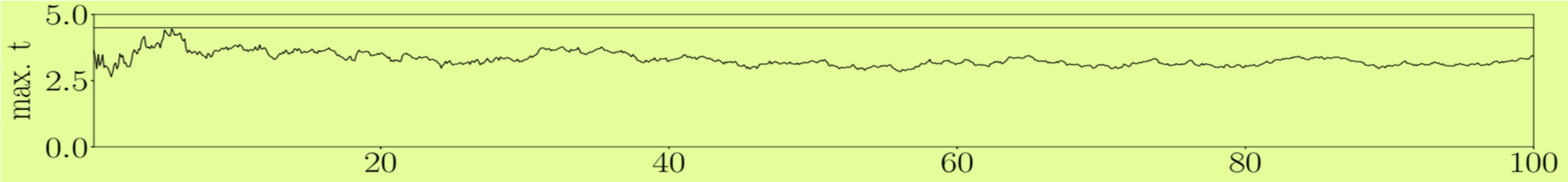


1. order over traces



1800 Rounds of Keccak

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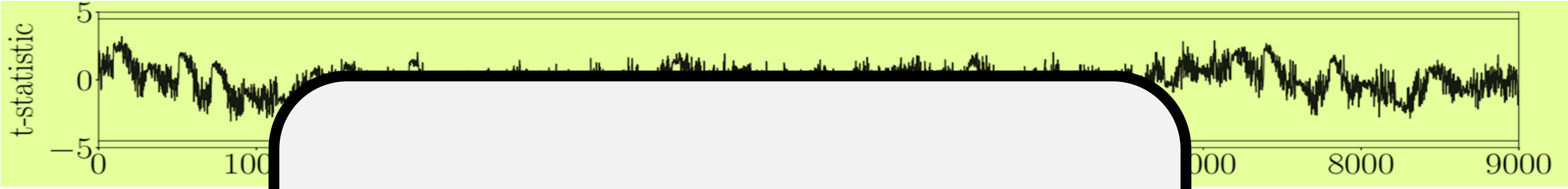
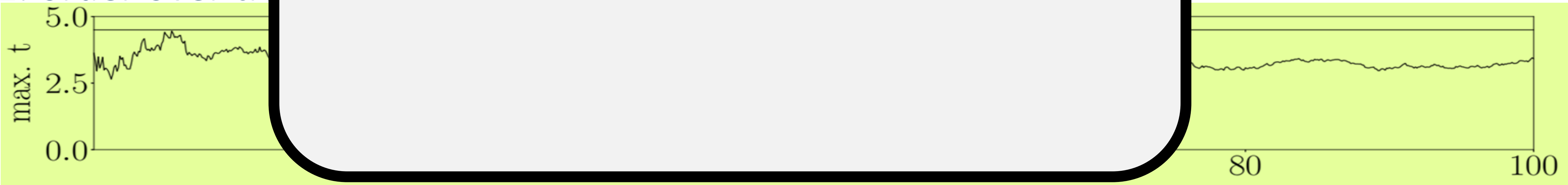
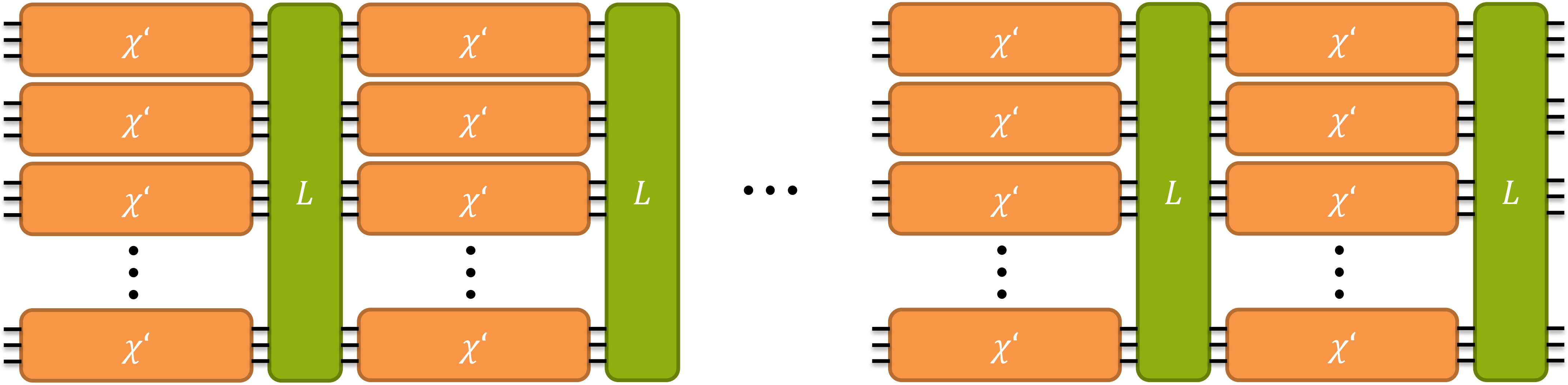


1. order over tra



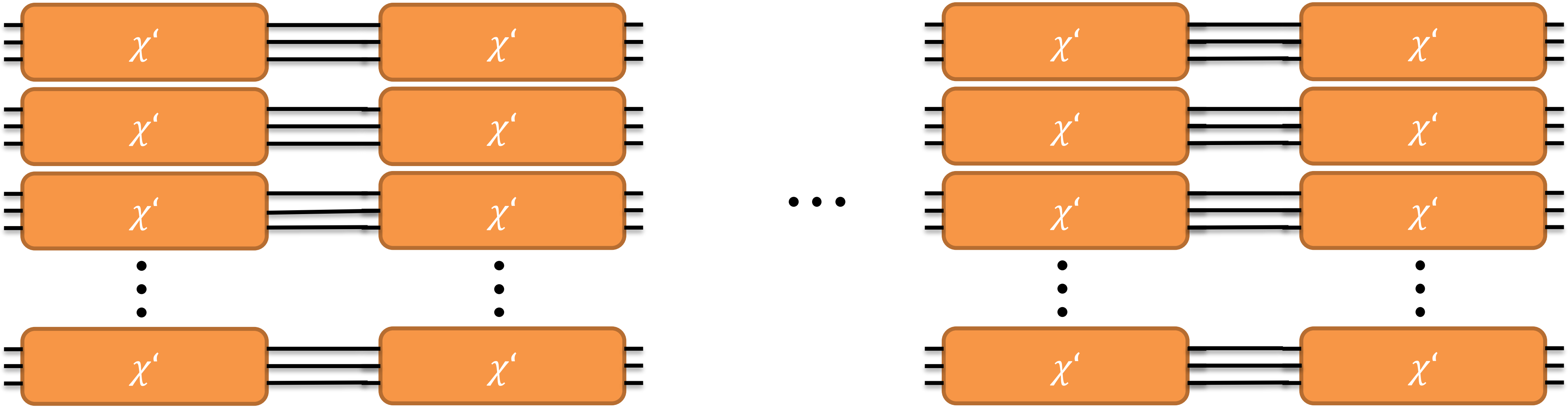
Origin of entropy?

Source of Diffusion: Linear Layer



Experiment: Remove Linear Layer

RUB



Simulation Part I

- Compute one instance of χ' on all 2^{15} inputs
- Feed outputs back into it
- Stop when plateau reached

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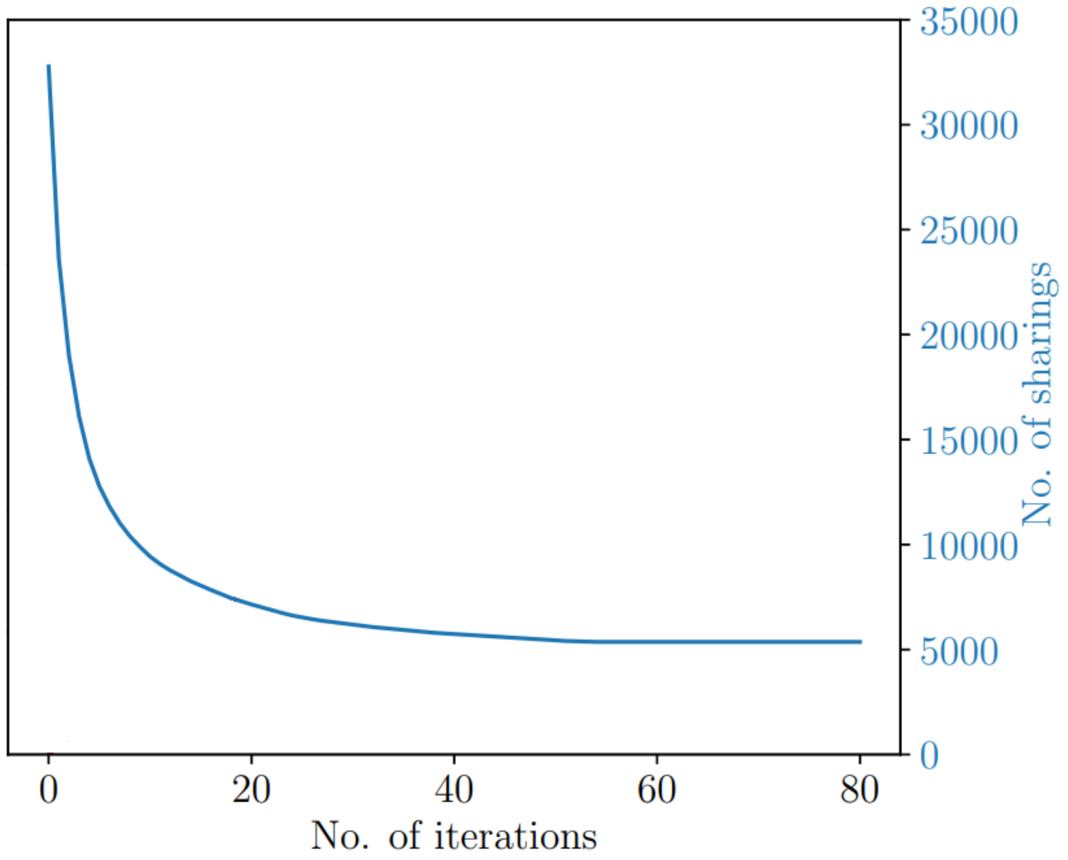
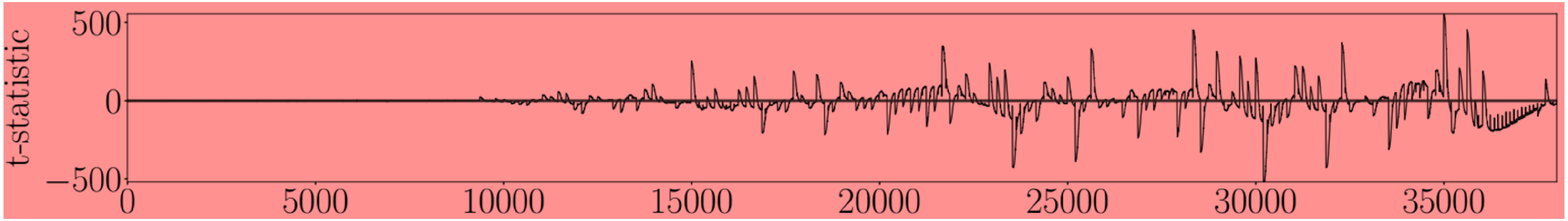
Result:

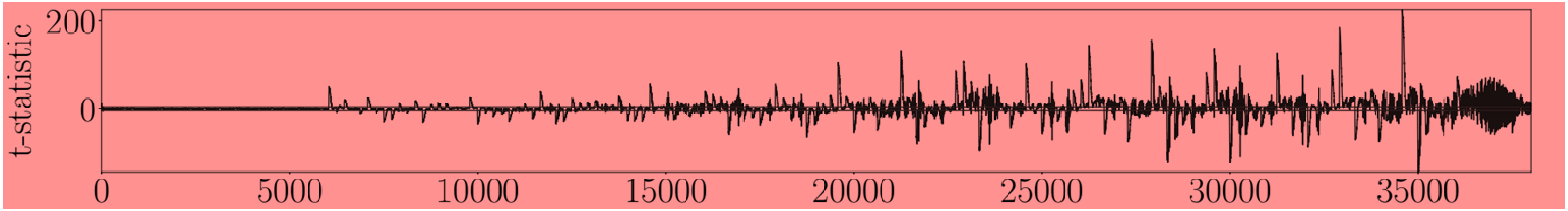


18 Rounds of χ'

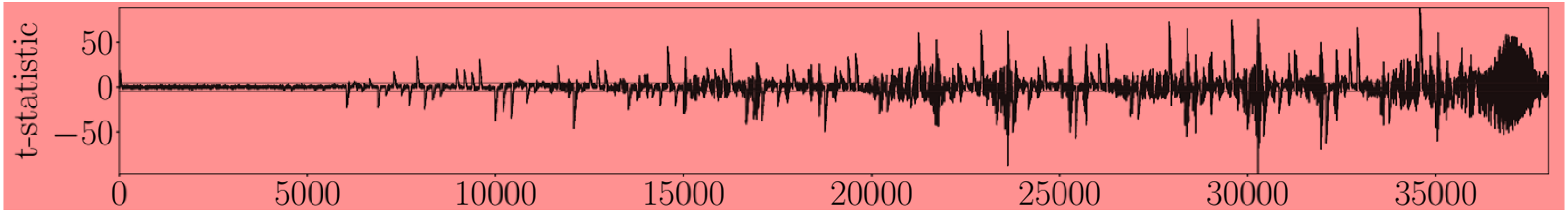
1. order over time



2. order over time



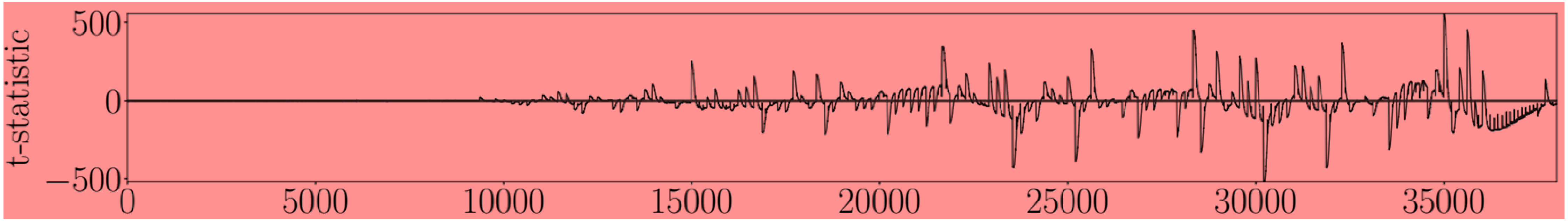
3. order over time



18 Rounds of χ'

RUB

1. order over time



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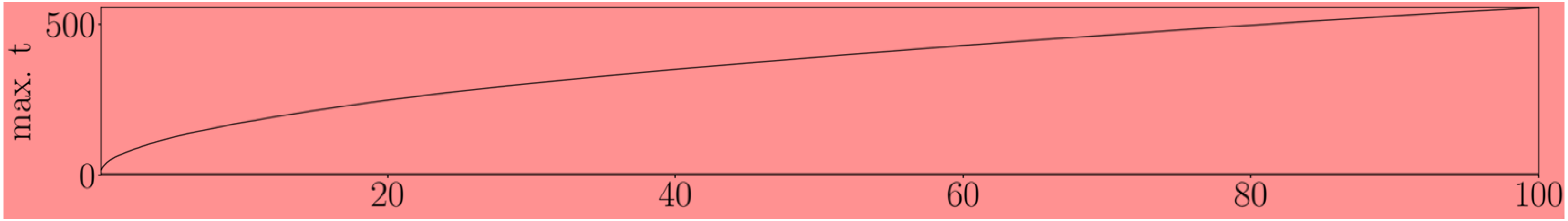
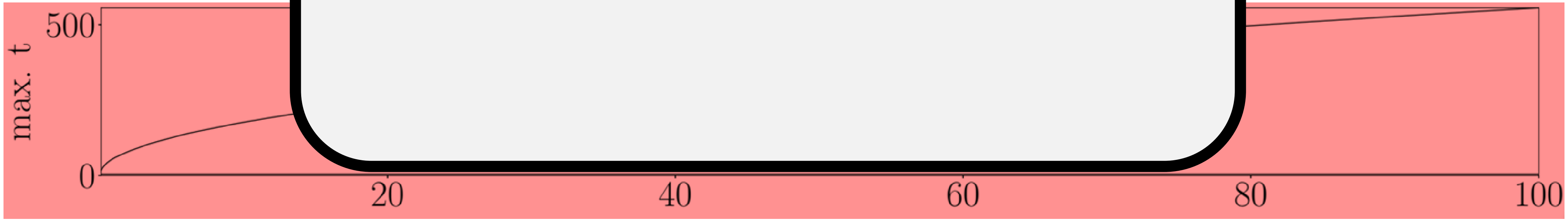


18 Rounds of χ'

1. order over time

1. order over tra



How much diffusion is needed?

Linear Layer: Shuffling and Mixing

RUB

ρ

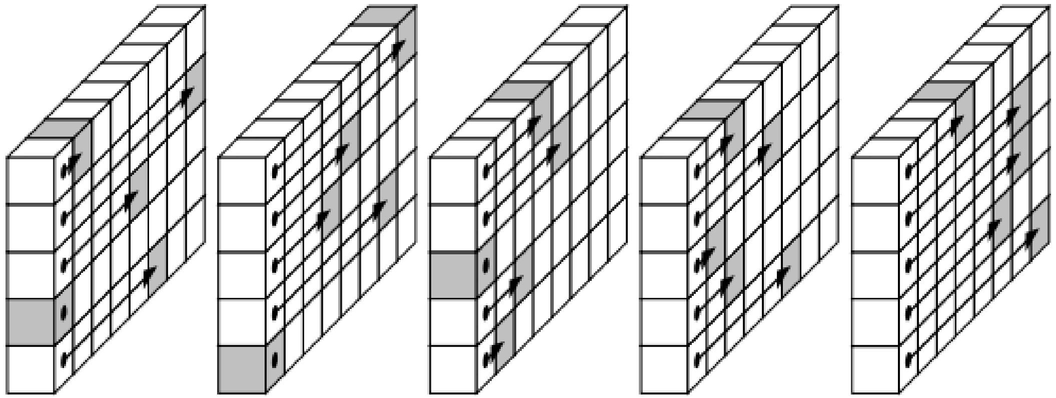
π

θ

ι

Linear Layer: Shuffling and Mixing

RUB



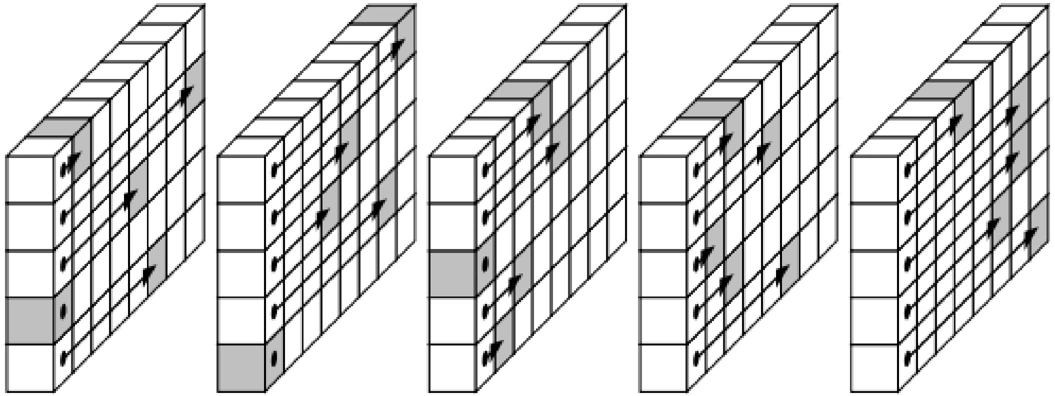
π

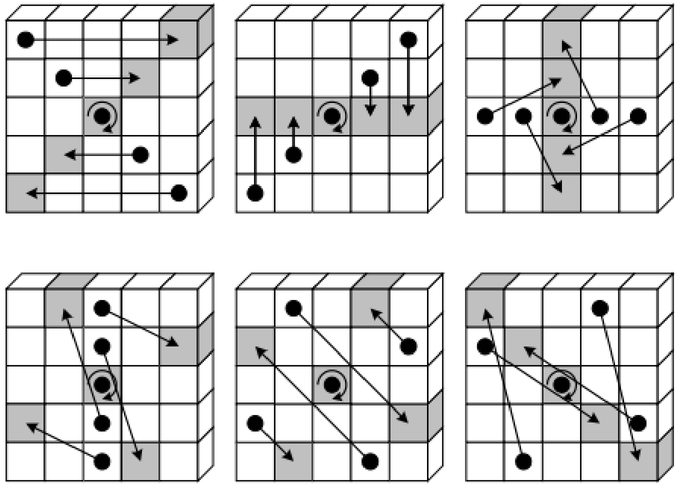
θ

ι

Bertoni et al. The Keccak Reference

Linear Layer: Shuffling and Mixing





θ

ι

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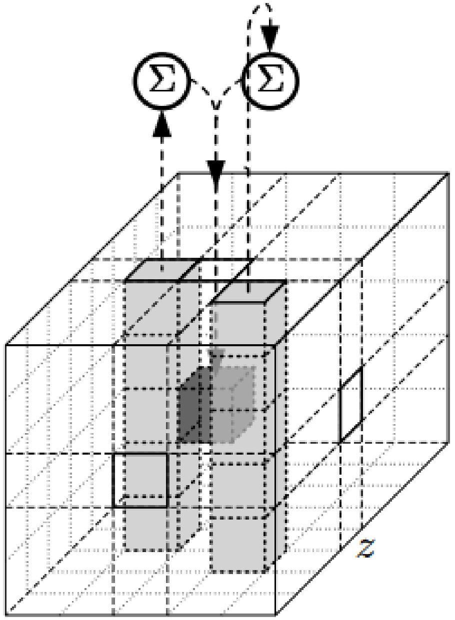
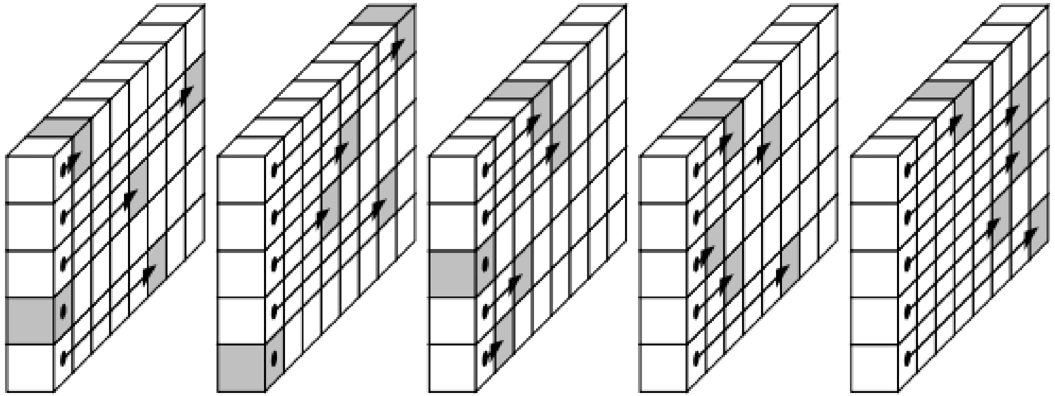
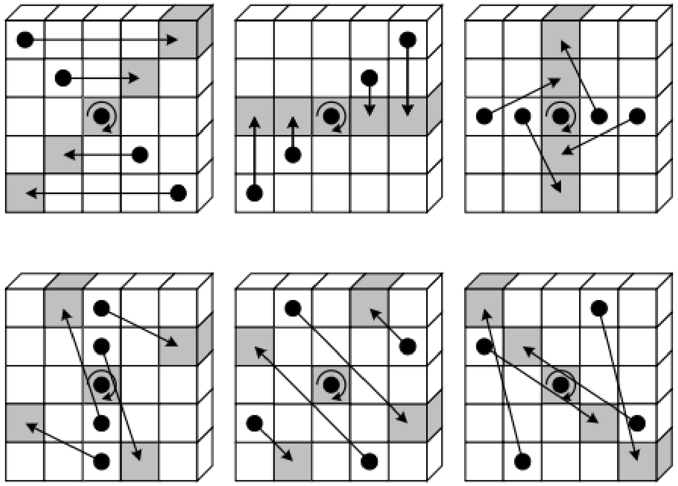
Linear Layer: Shuffling and Mixing







ι

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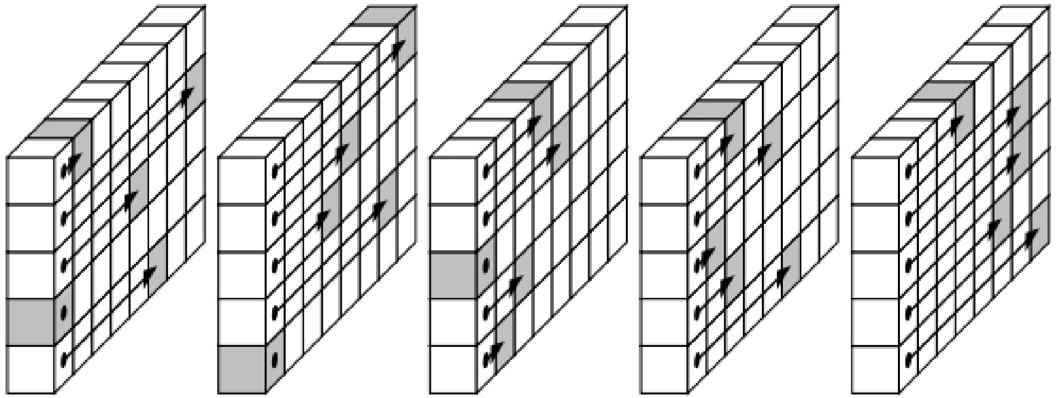
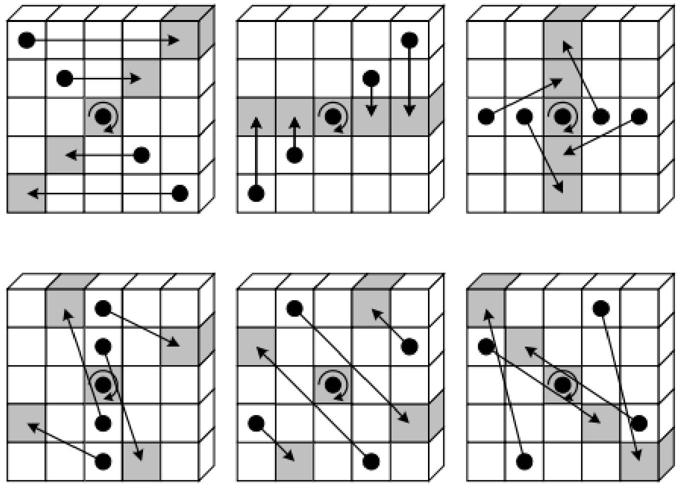
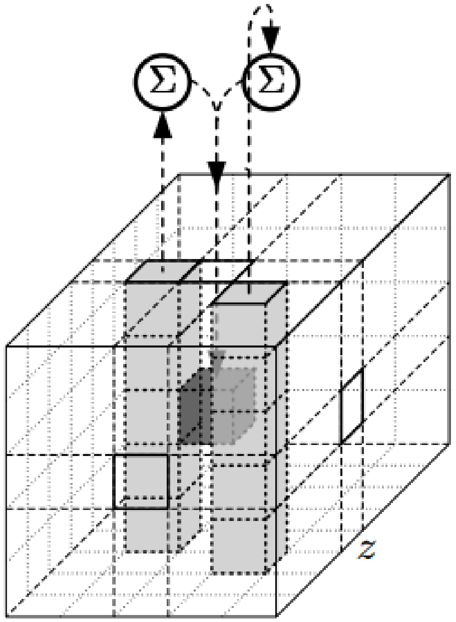
Linear Layer: Shuffling and Mixing





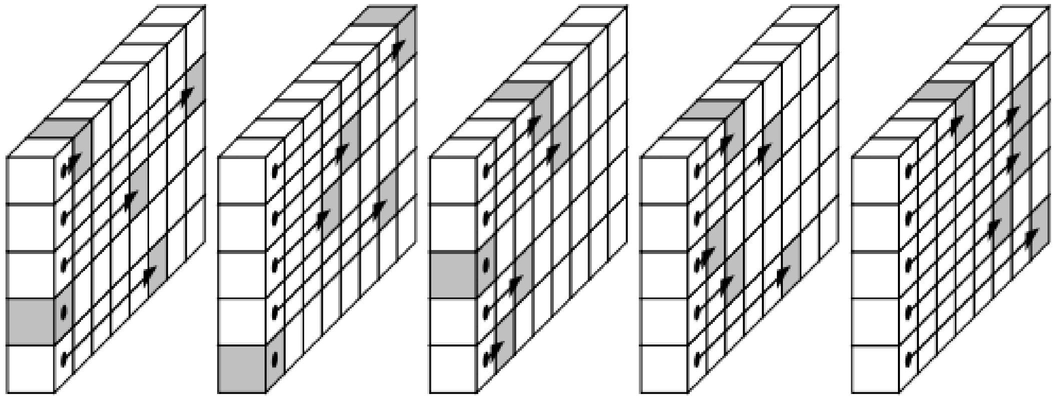


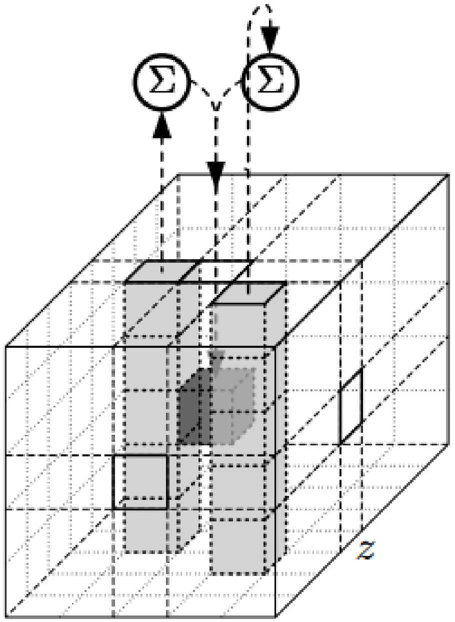
round constant

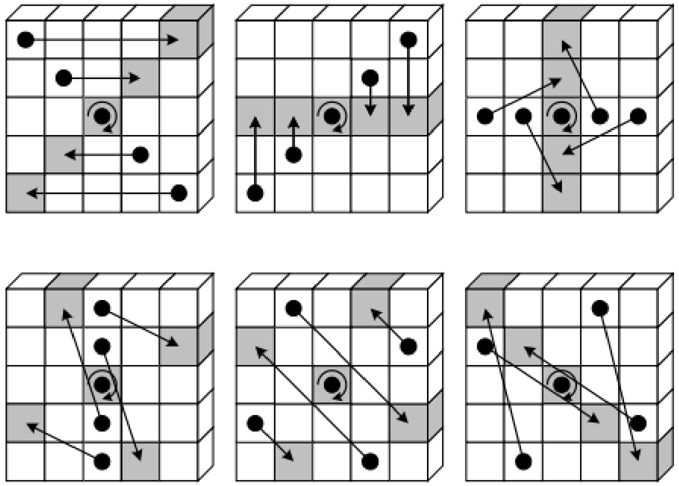
Bertoni et al. The Keccak Reference

Linear Layer: Shuffling and Mixing

RUB





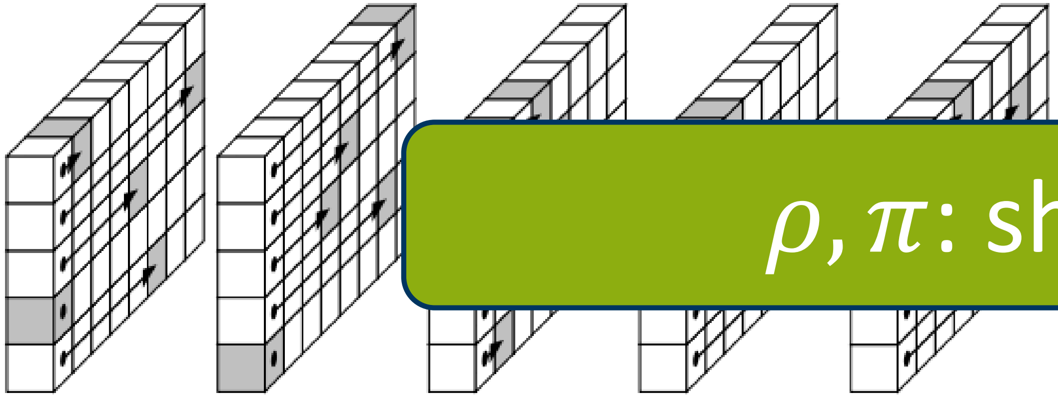


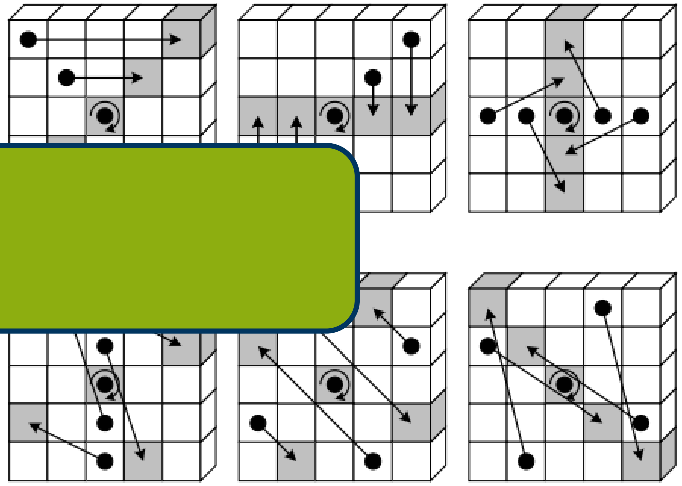
~~round constant~~

Bertoni et al. The Keccak Reference

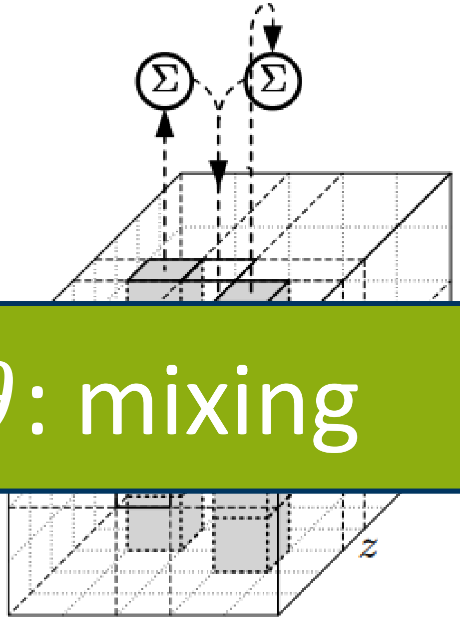
Linear Layer: Shuffling and Mixing

RUB





ρ, π: shuffling



θ: mixing

Bertoni et al. The Keccak Reference

Simulation Part II

RUB

How to simulate entropy of masked Keccak-*f*[200]?

Exhaustive Testing:
2^{600} states - impossible

Simulation Part II

RUB

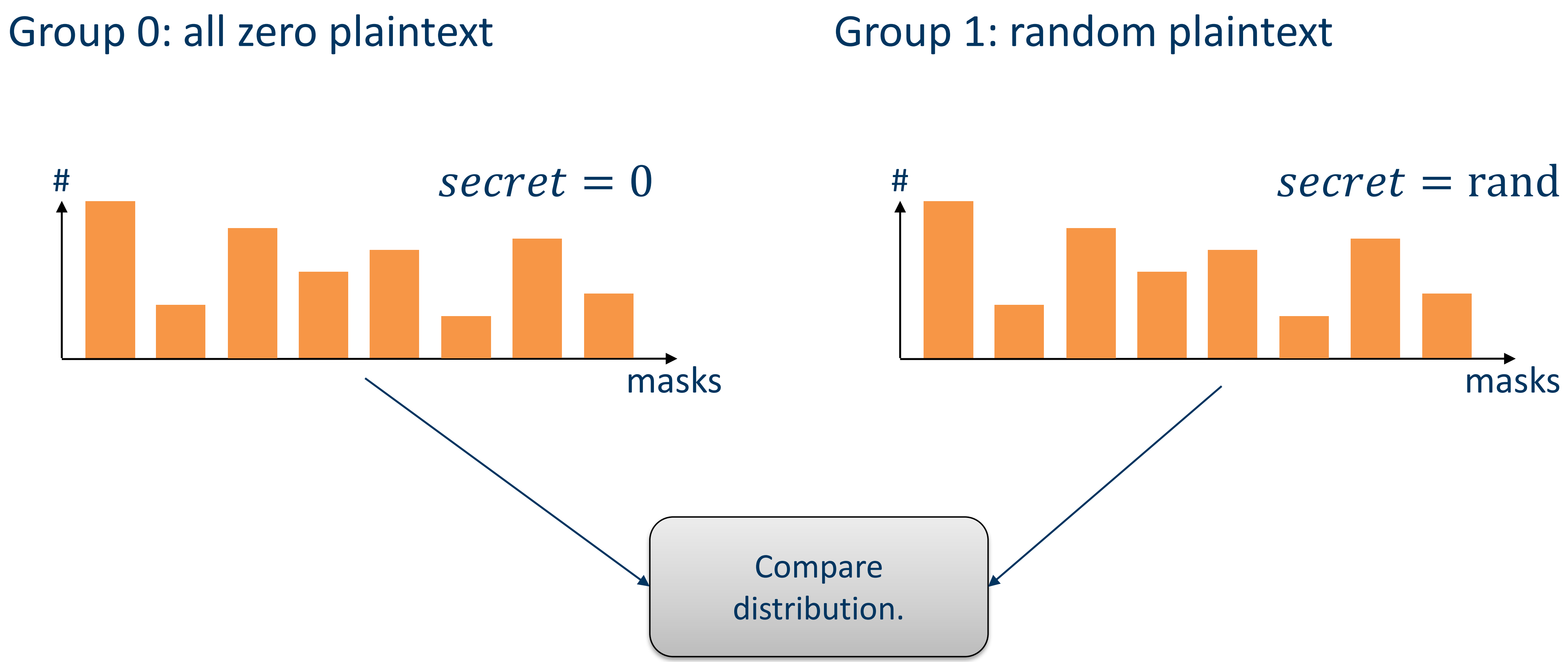
How to simulate entropy of masked Keccak-*f*[200]?

Exhaustive Testing:
2^{600} states - impossible

Sampling:
„fixed vs. random“
without power model

Simulation Part II

RUB



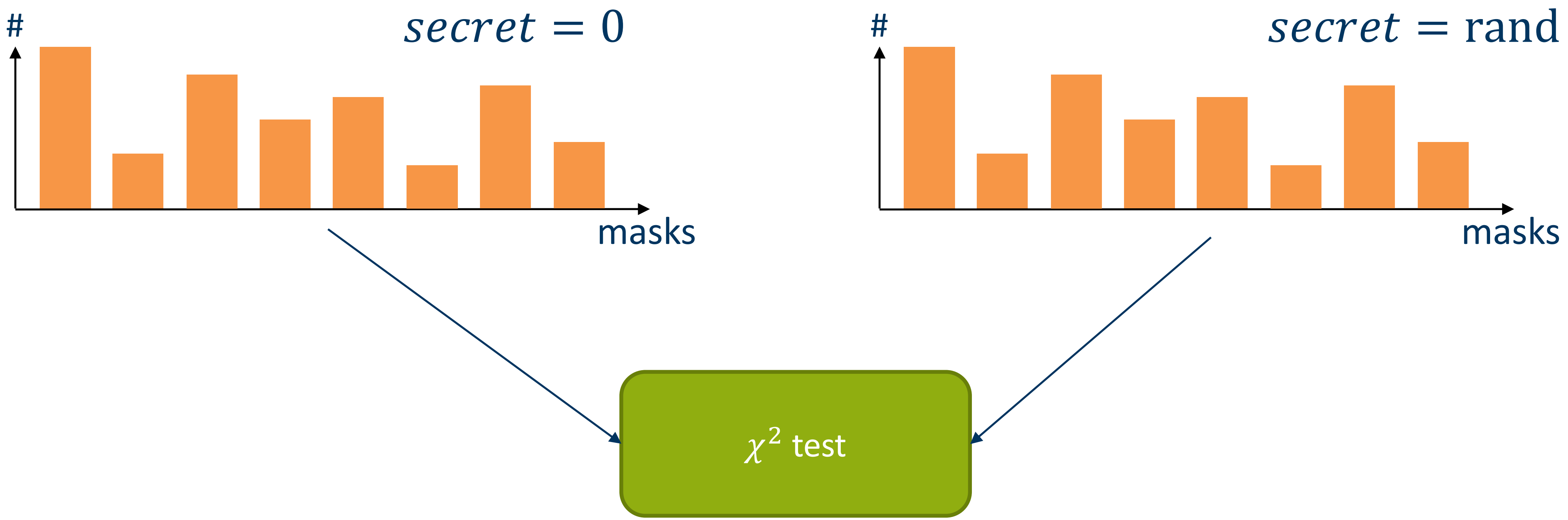
De Meyer, Bilgin, Reparaz. Consolidating Security Notions in Hardware Masking.

Simulation Part II

RUB

Group 0: all zero plaintext

Group 1: random plaintext



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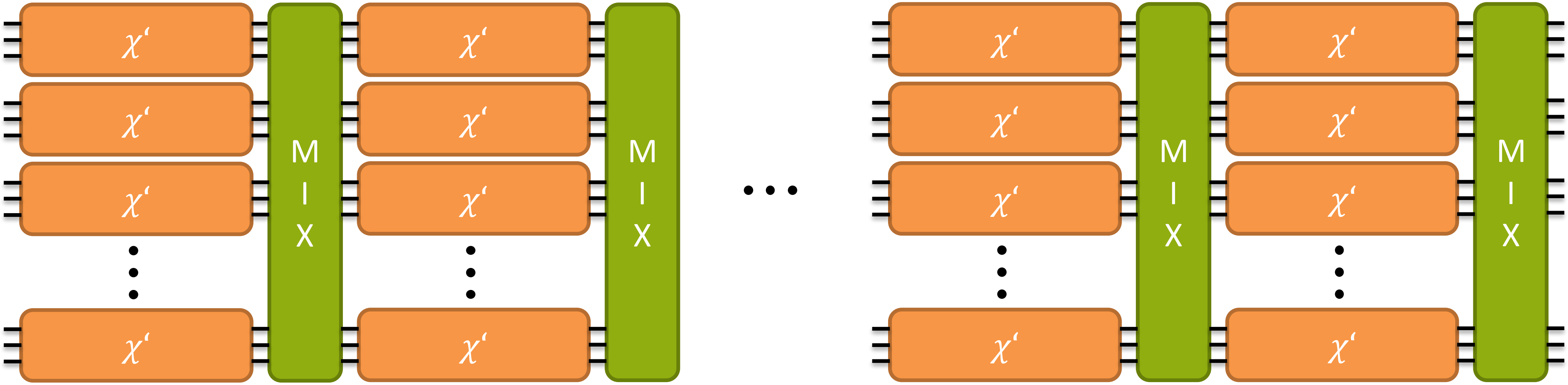
Next Design: Mix Only



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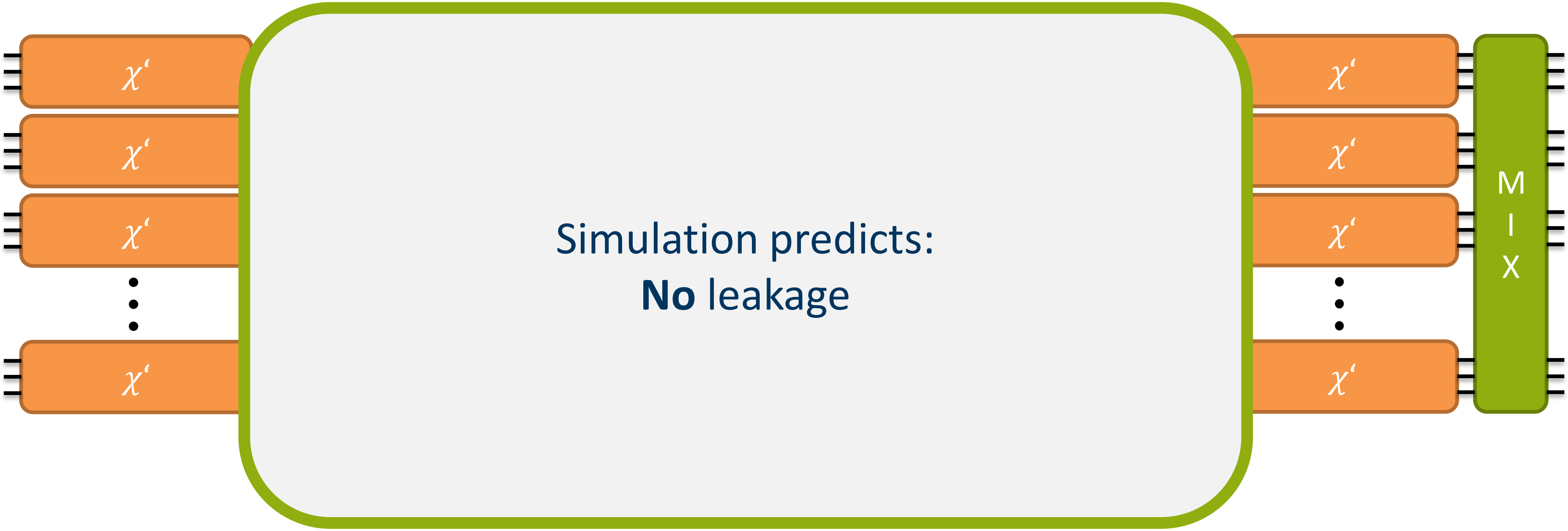
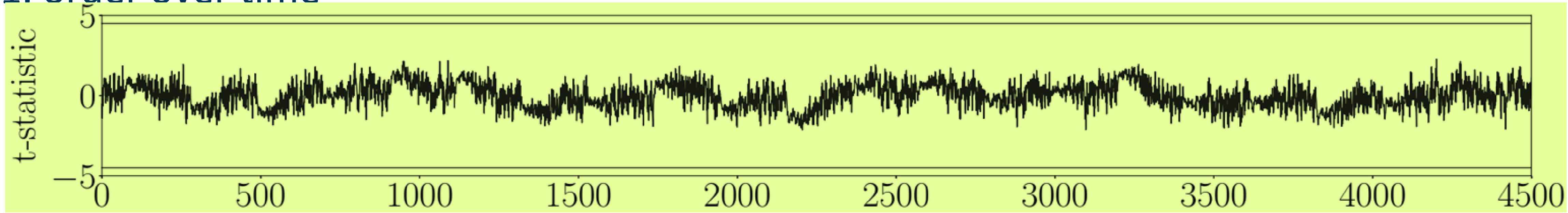
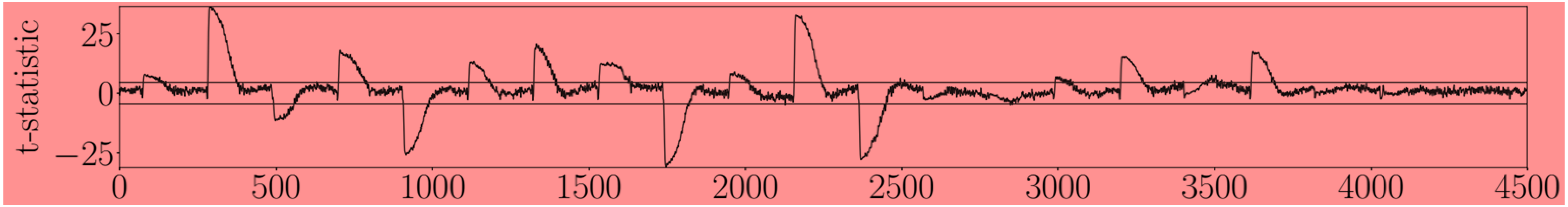


18 Rounds of Mixing: χ', θ

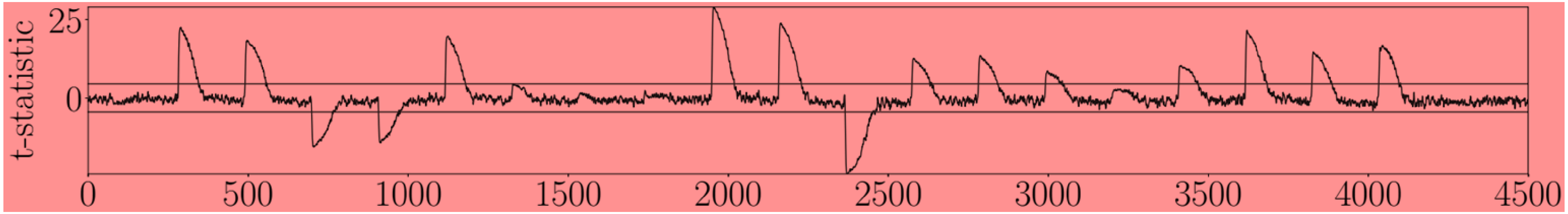
1. order over time



2. order over time



3. order over time



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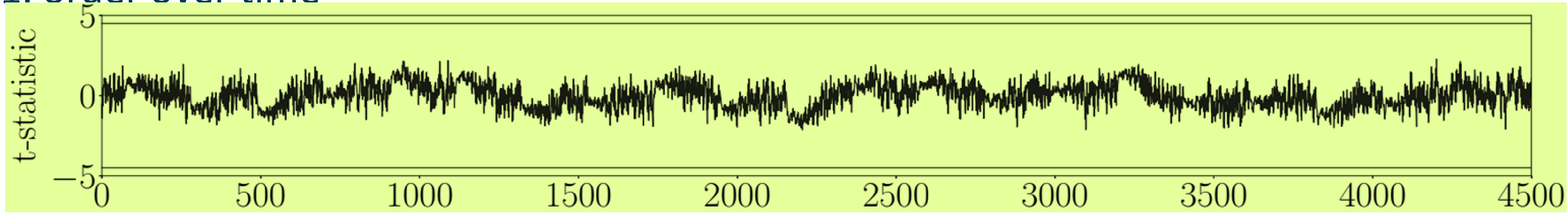

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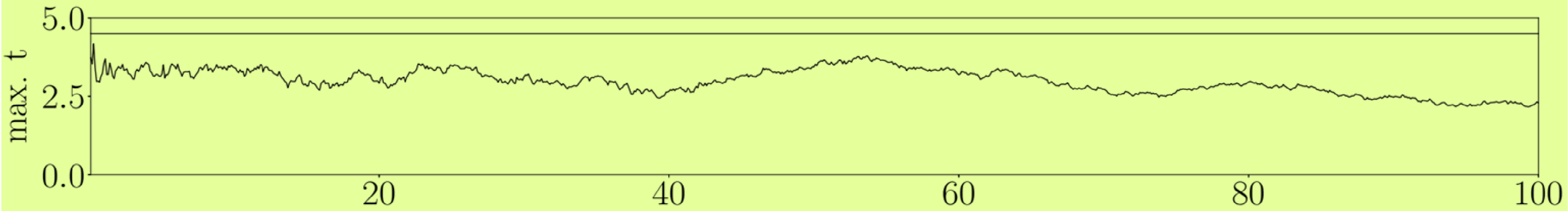
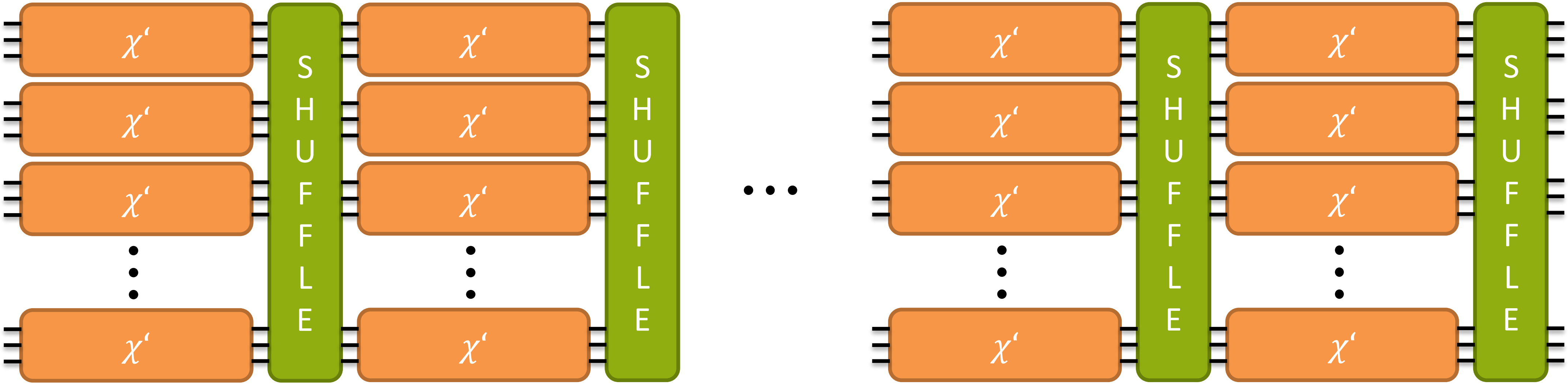


Next Design: Shuffle Only



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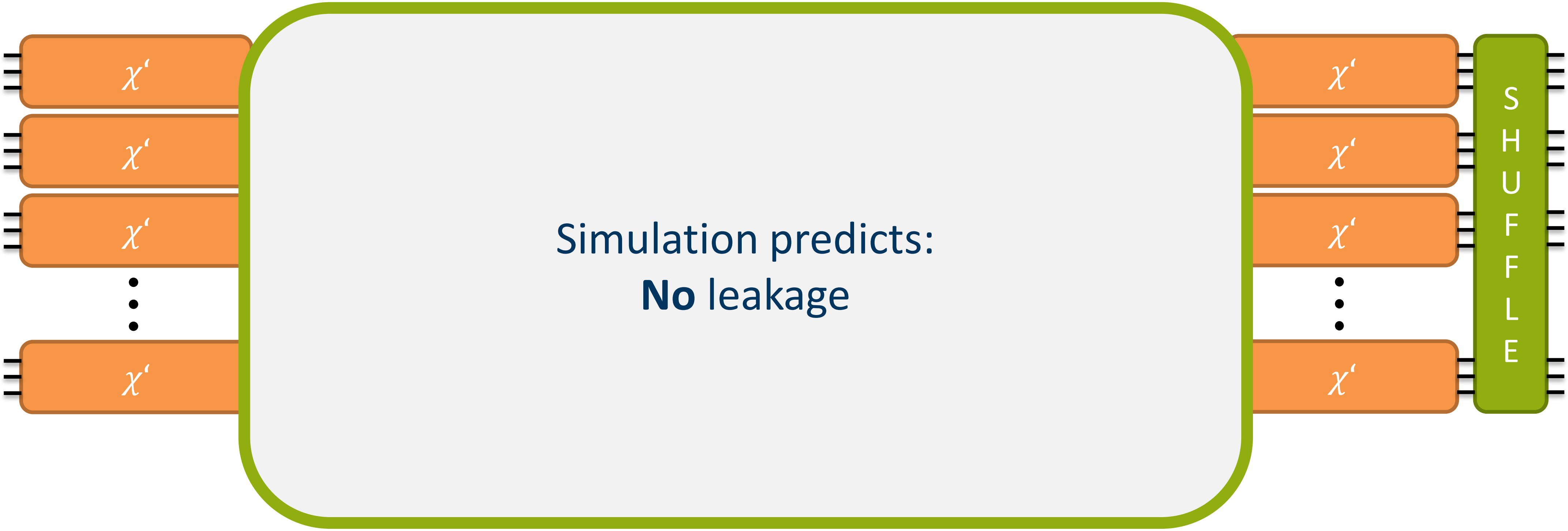

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RUB

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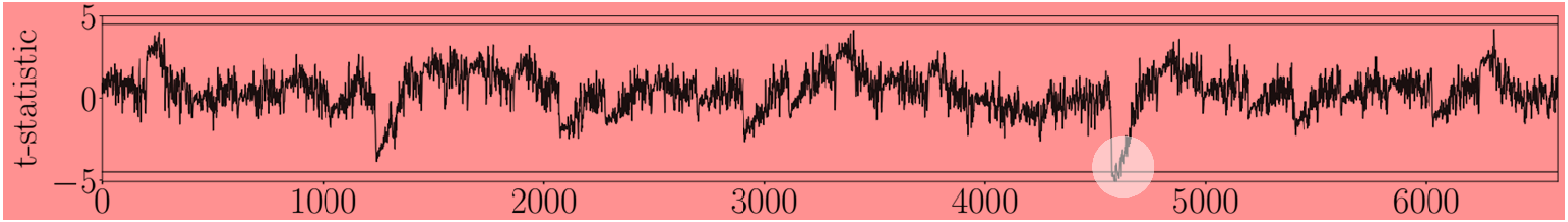

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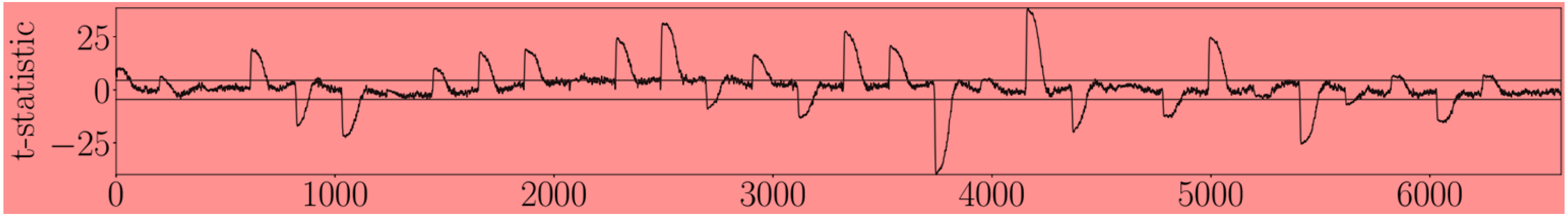

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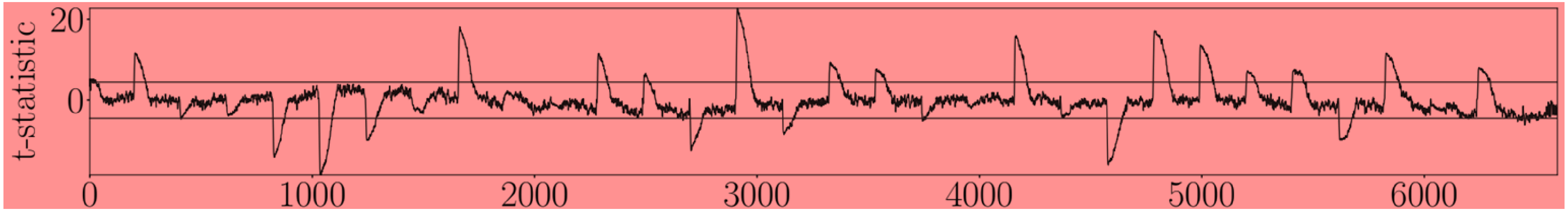

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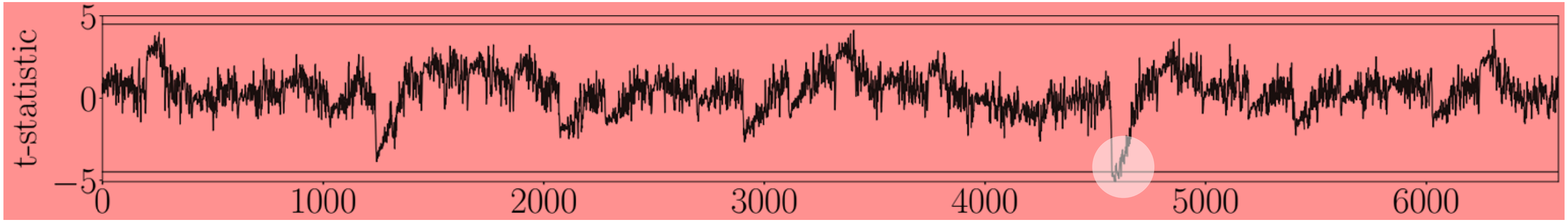

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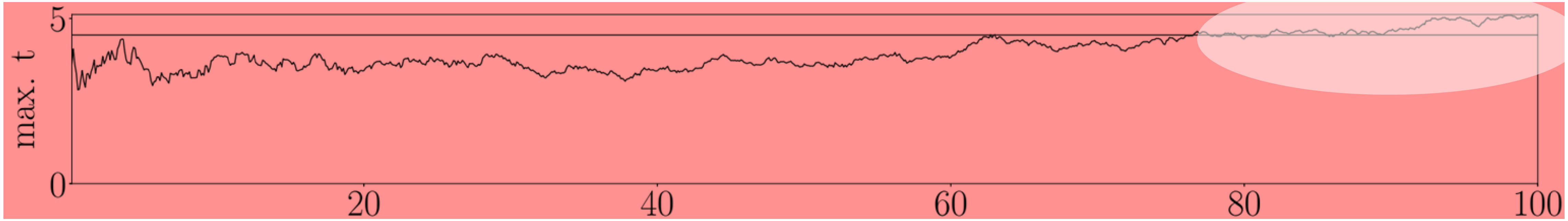

Summary of Results

RUB

Practical Measurements

Active Layers	Detectable Leakage?
Sbox χ'	Yes!
Mix χ', θ	No.
Shuffle χ', ρ, π	**Yes.**
Shuffle and Mix χ', ρ, π, θ	No.

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Conclusion

RUB

Takeaways:

- Use Shuffle **and** Mix for entropy diffusion
- Combine simulations with practical evaluations

Caveats:

- Uniformity is essential in decomposed S-boxes:

Future Work:

- Evaluation of exploitable leakage
- Diffusion in other ciphers (e.g. ASCON)
- Quality criteria for RNG

Thanks! Any questions?

felix.wegener@rub.de

Felix Wegener, Christian Baiker, Amir Moradi

Ruhr University Bochum, Horst Görtz Institute for IT-Security, Germany

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