Shuffling Against Side-Channel Attacks:
a Comprehensive Study with Cautionary Note

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ASIACRYPT 2012, Bejing, China

Motivation (I)

- ASIACRYPT 2010: masking is an effective countermeasure against side-channel attacks

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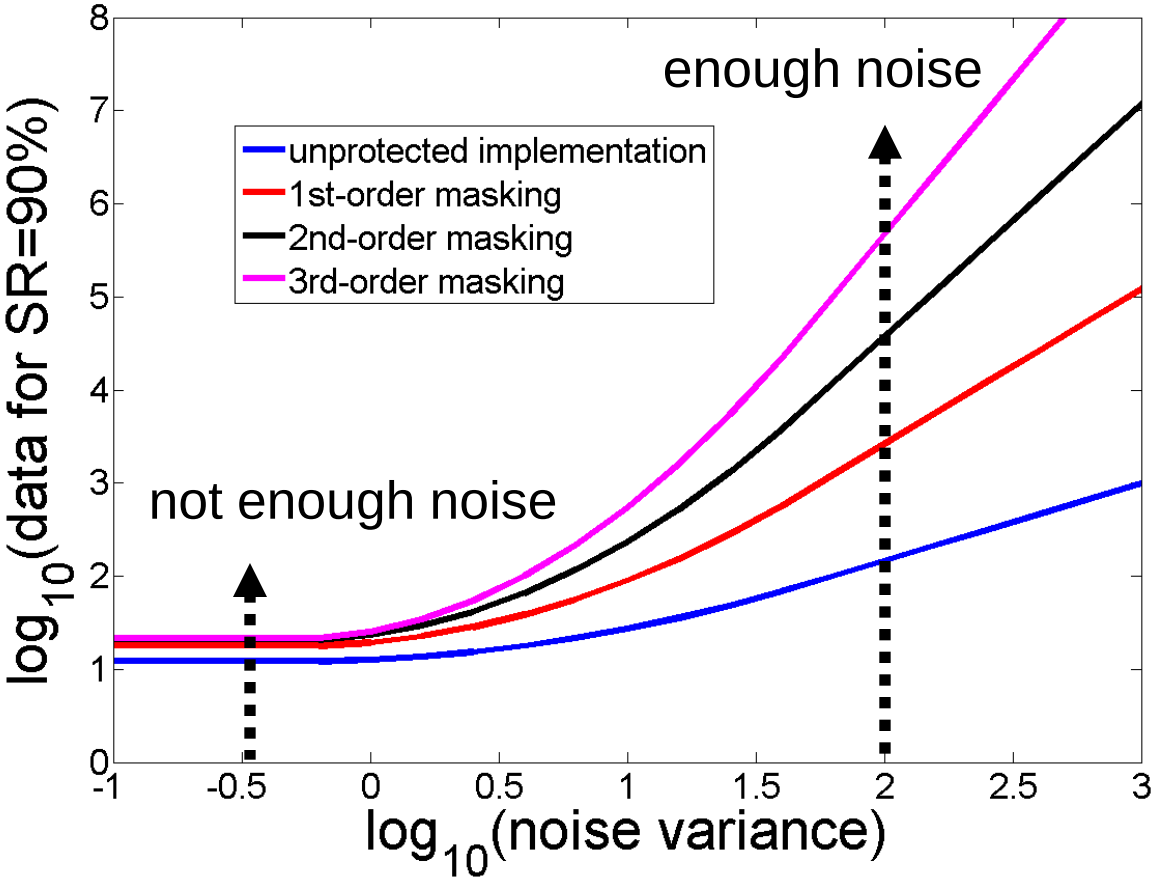
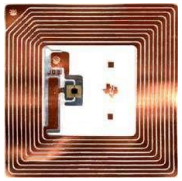
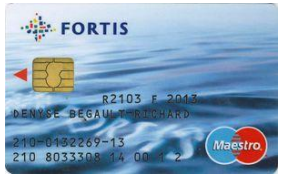
  - *If there is sufficient measurement noise !!!*



Motivation (II)

- Problem: how to generate noise in small devices?





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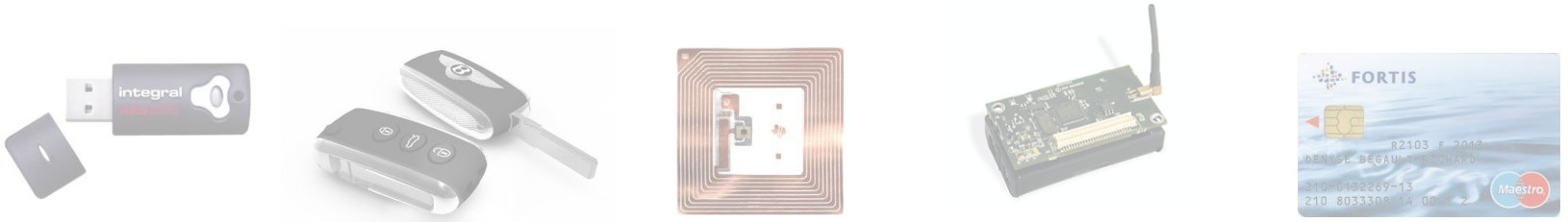

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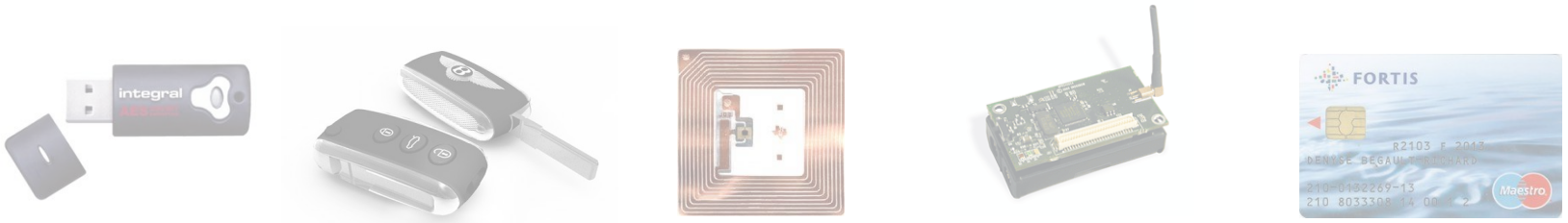

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- But we need to be careful with re-synchronization
  - e.g. random insertion of dummy operations is not enough [Durvaux et al./CARDIS2012]

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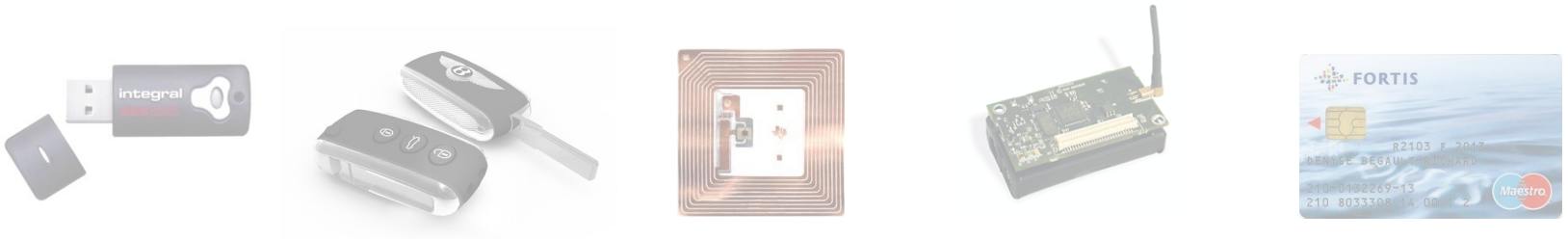

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- But we need to be careful with re-synchronization
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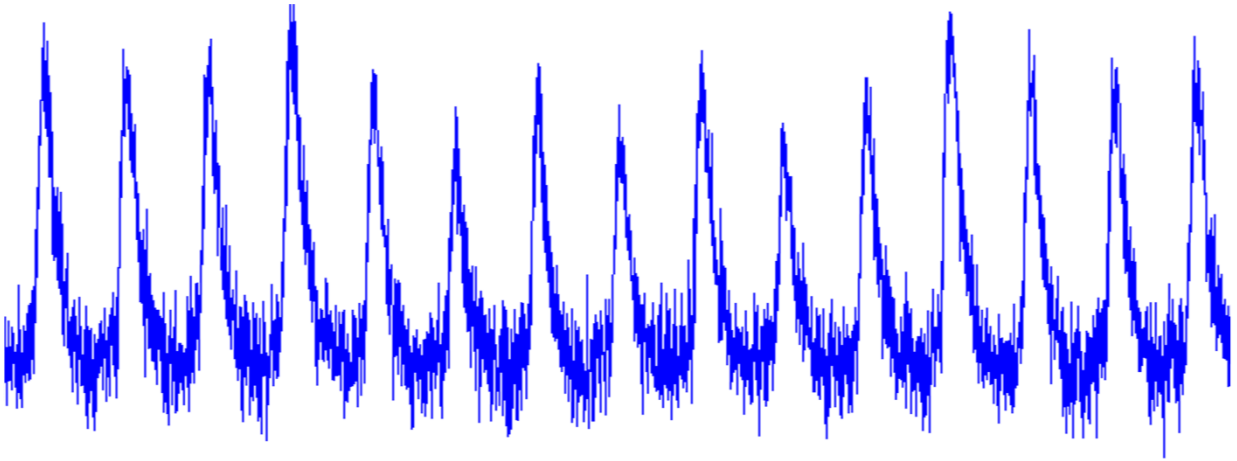
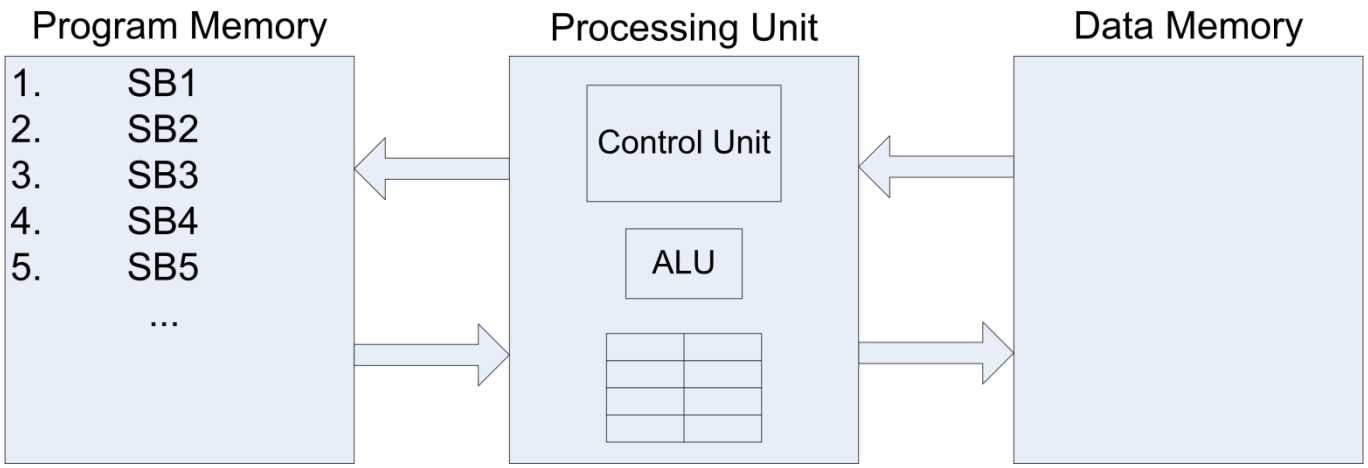
- Best known option so far: shuffling operations

Intuition (I)

- Deterministic execution of the AES S-boxes





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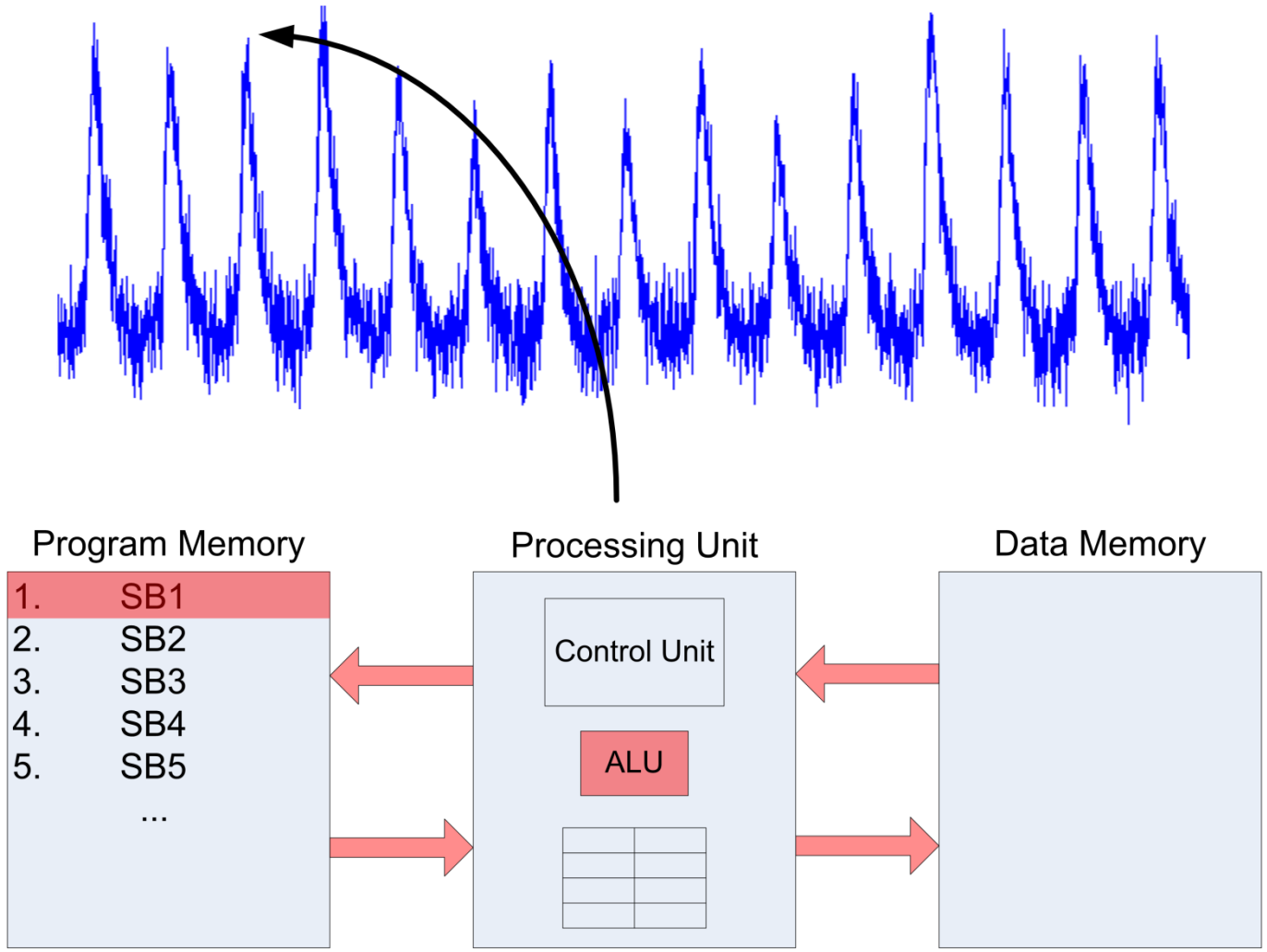

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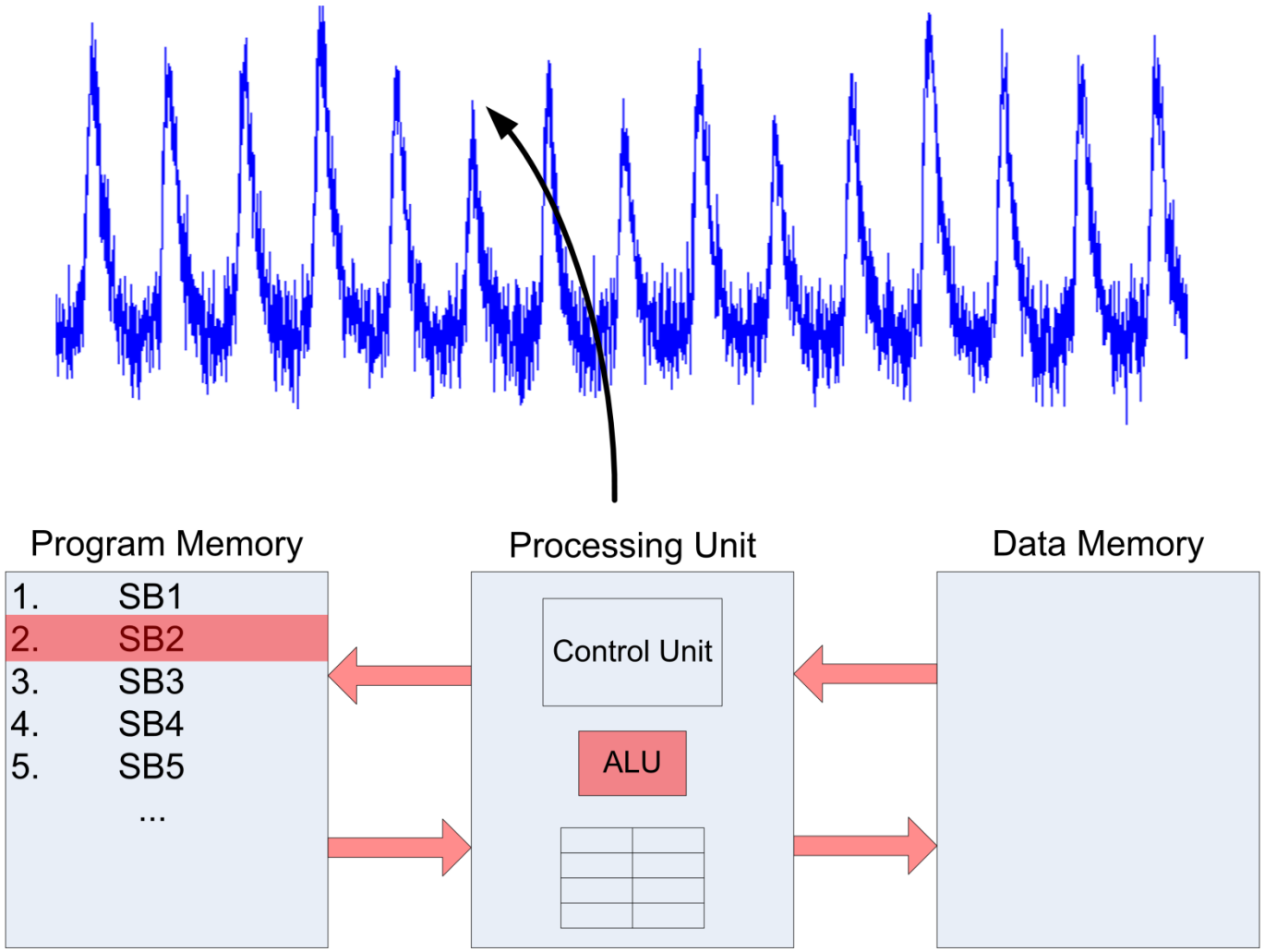

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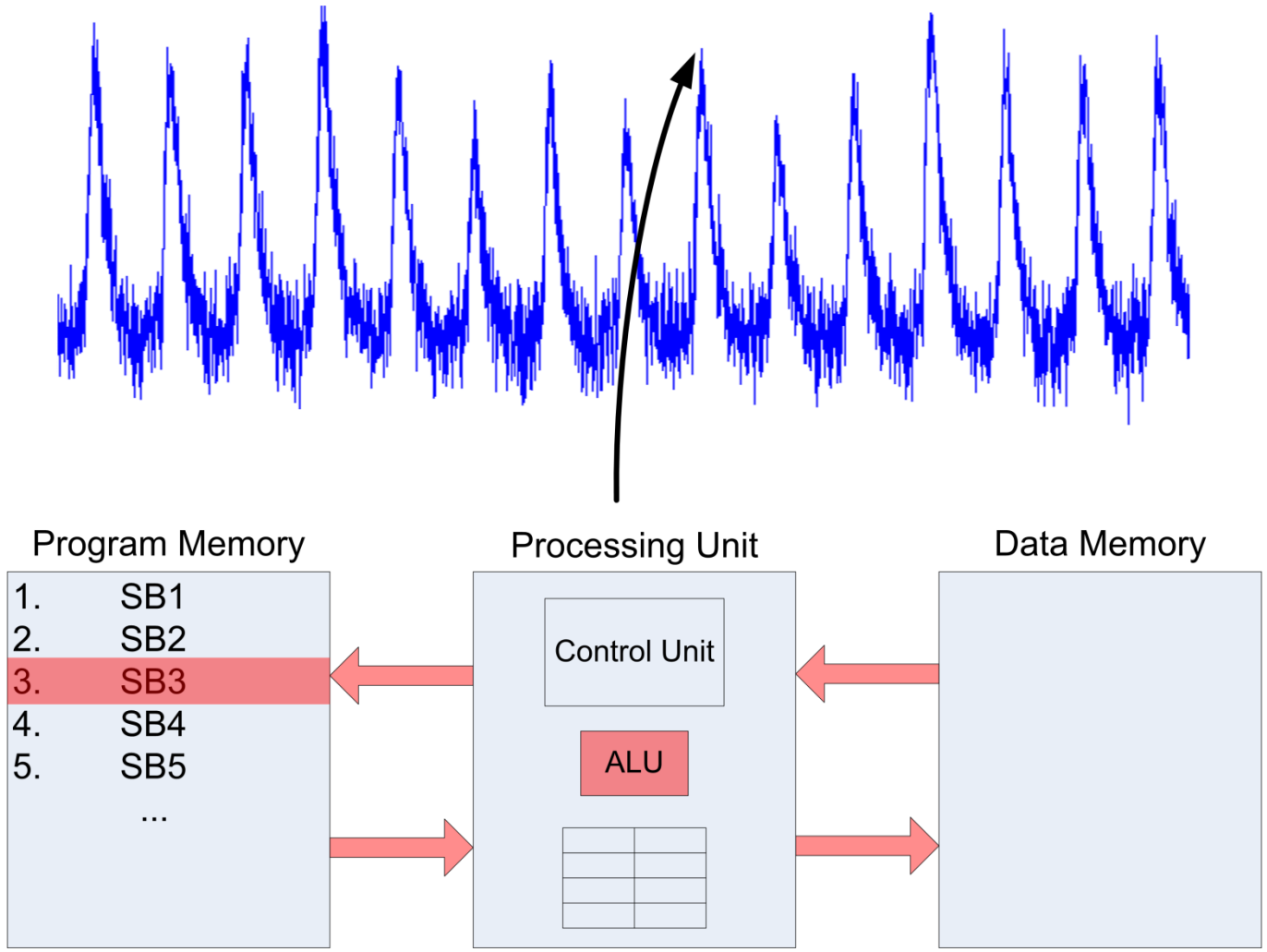

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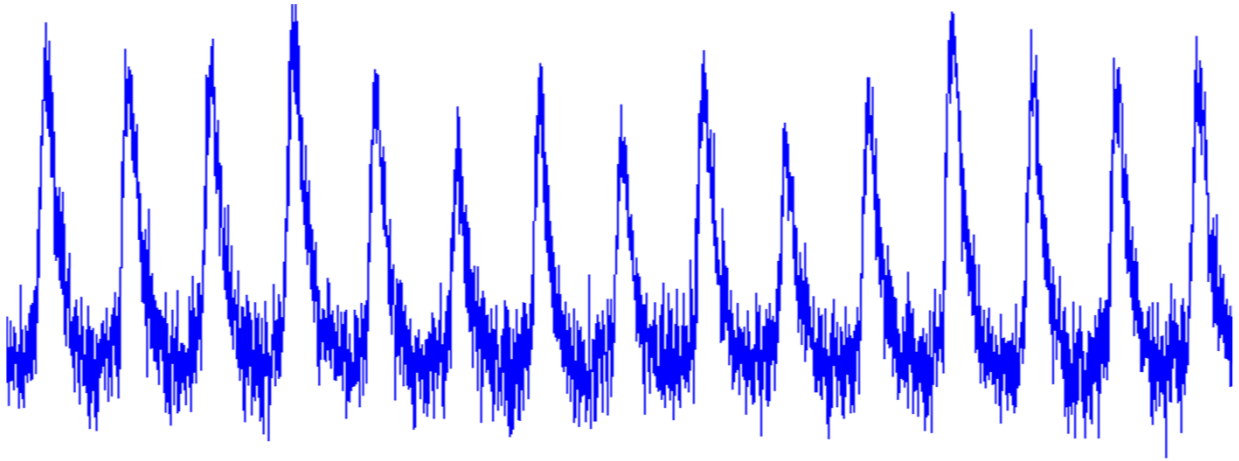

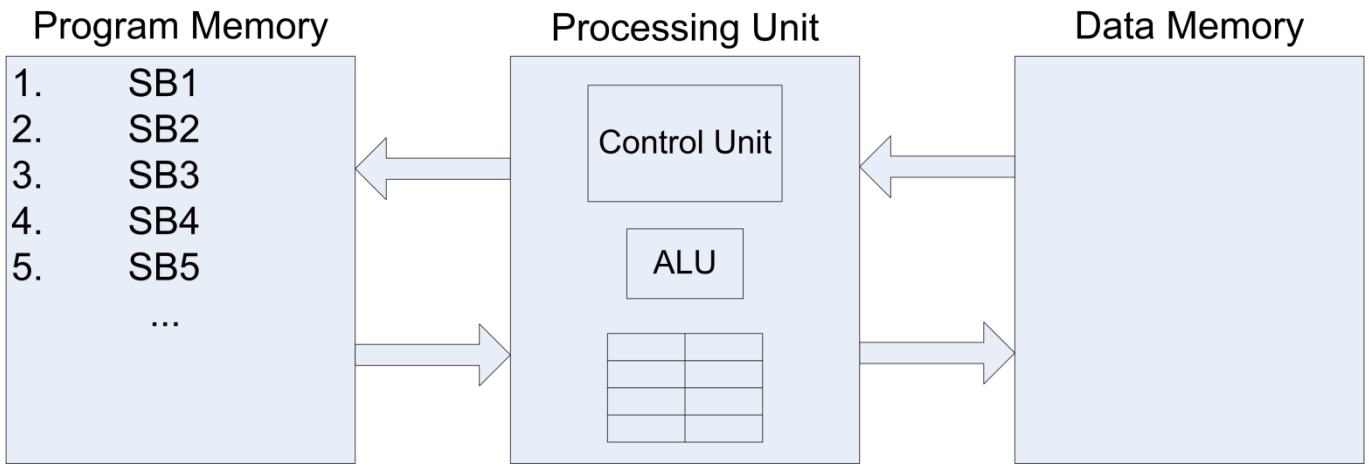

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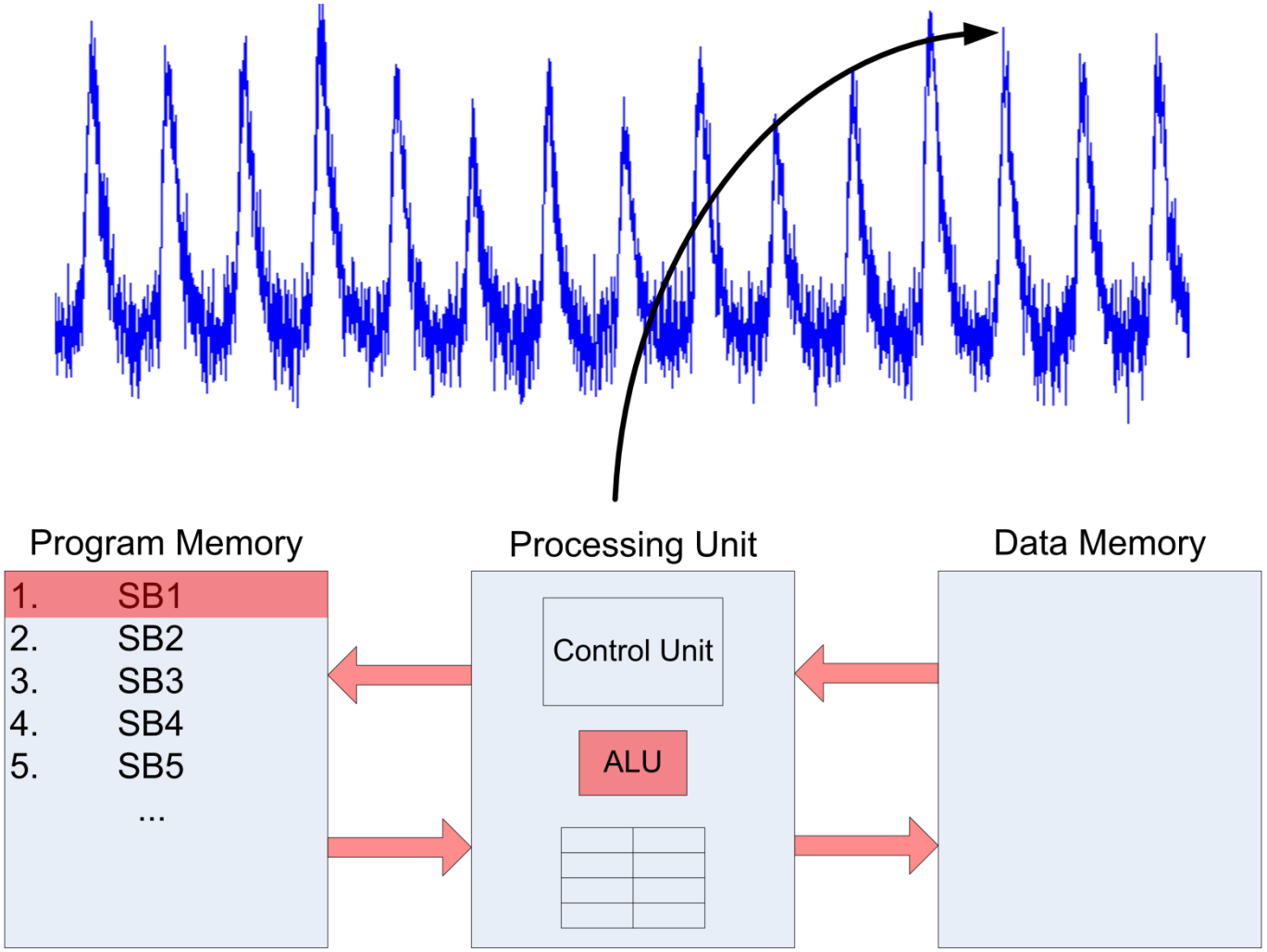

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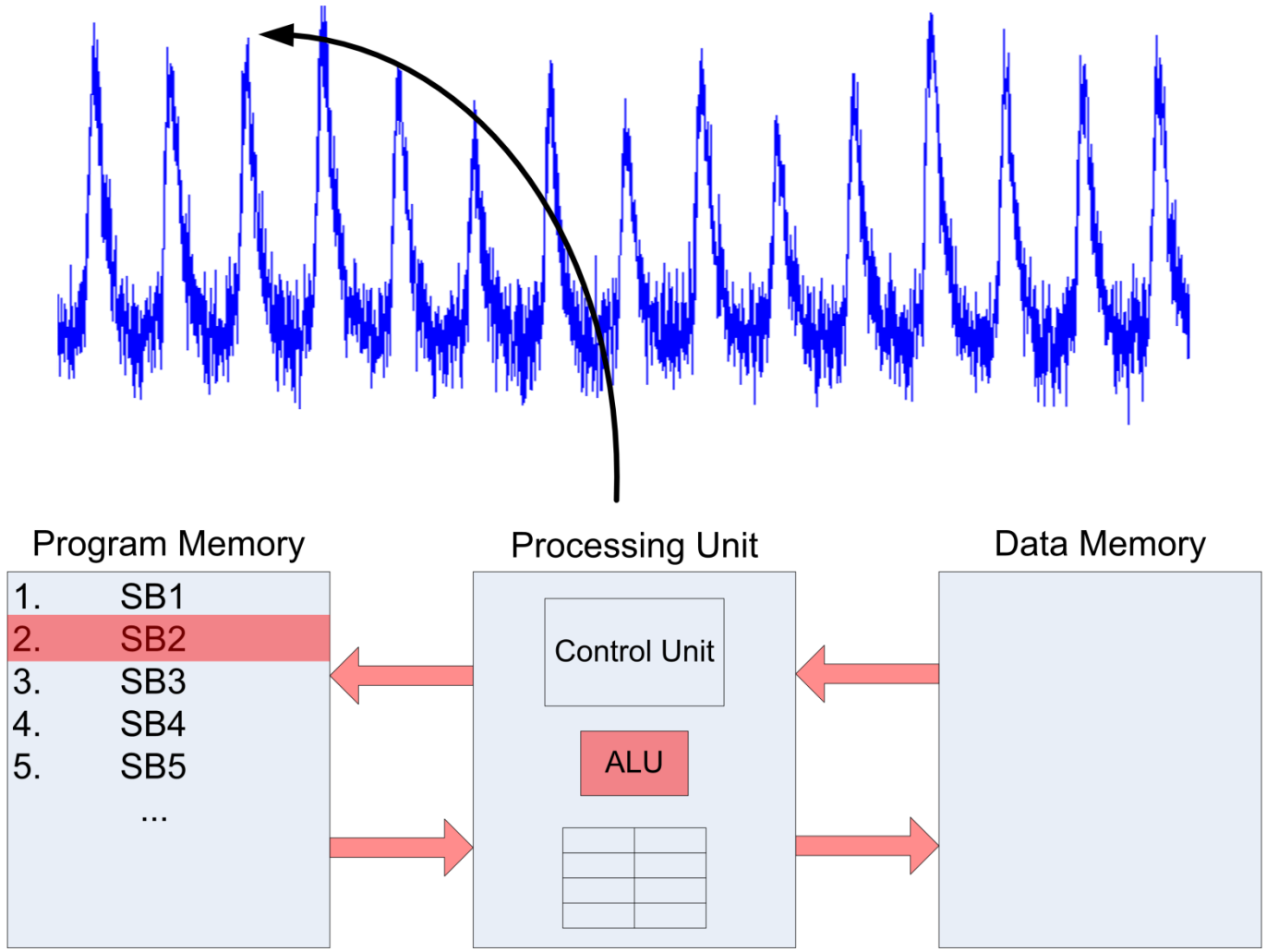

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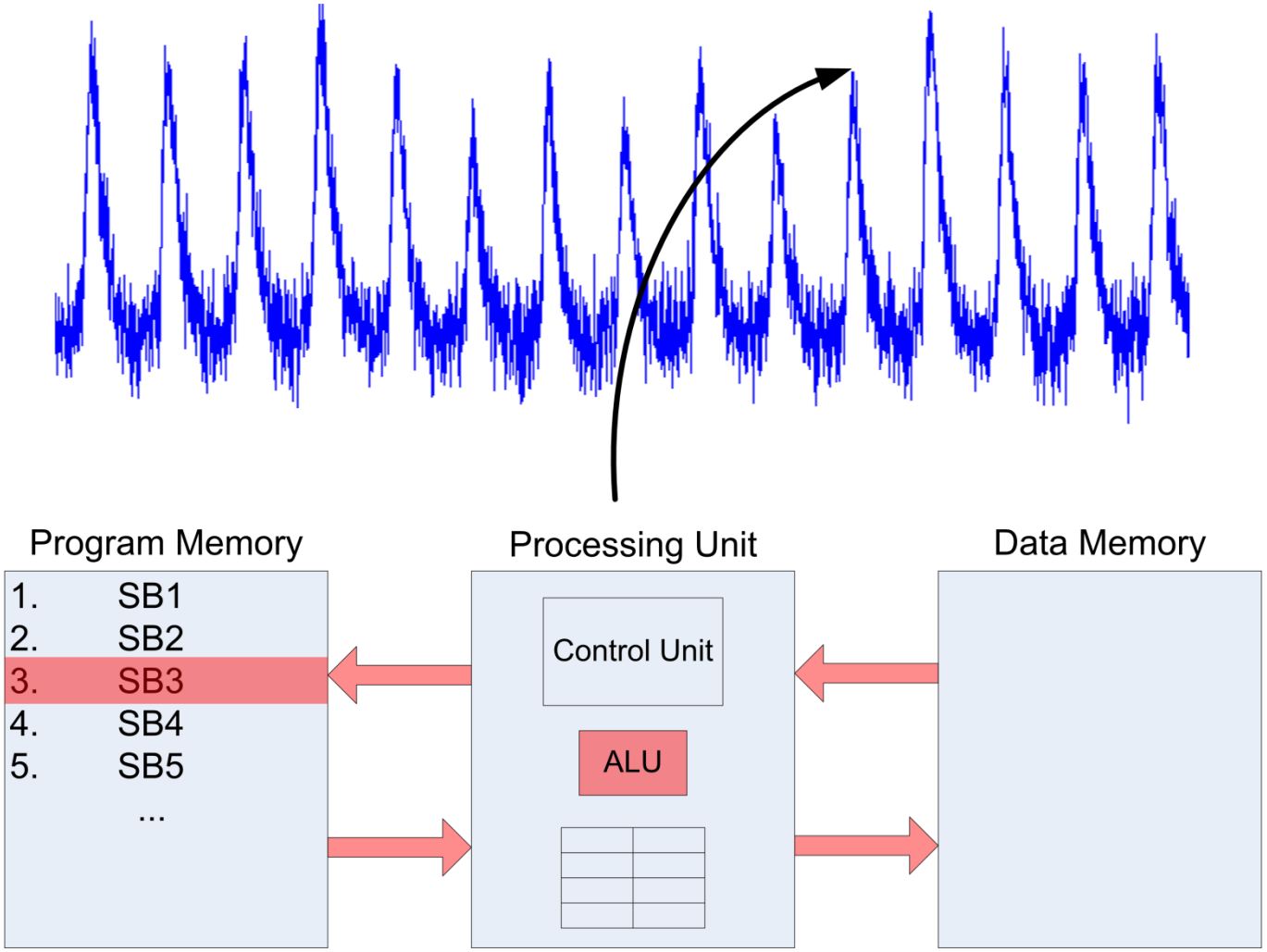

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$\Rightarrow$ Attack data complexity increases accordingly

Talk outline

1. Implementation: how to shuffle efficiently?
   (Permutation generation - see paper)
   a. Double indexing
   b. (new) Randomized execution path
   c. (new) Randomized program memory

2. Security evaluation: “better than integrating”
   a. Information theoretic analysis
   b. Actual chip measurements

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Double indexing (S-box example)

Shuffled AES :
Program Memory

1. Load shuffle index from memory
2. Load state byte from memory
3. SB(state(index))
4. Store state byte in memory
5. Load shuffle index from memory
6. Load state byte from memory
7. SB(state(index))
8. Store state byte in memory

...

Data Memory

Permutation

1. 3
2. 15
3. 6

...

State

1. byte0
2. byte1
3. byte2
4. byte3

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- Two RAM accesses per R/W access to operands
  $\Rightarrow$ Very large cycle counts

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Randomized execution path

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7.	SB1
	...

Data Memory

Permutation

1.	1
2.	15
3.	0
	...

Address array

1.	6
2.	45
3.	3
	...

State

1.	byte0
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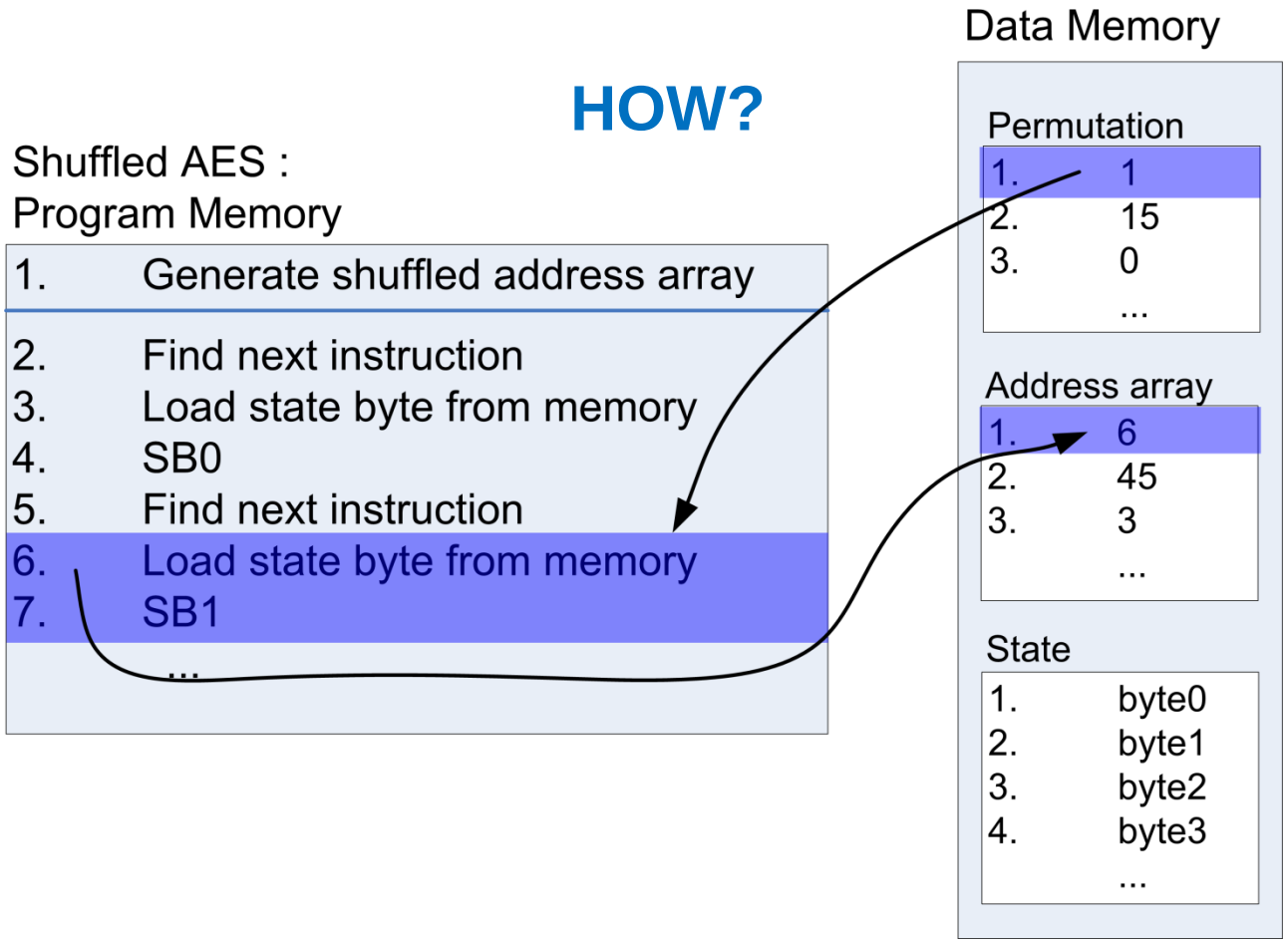

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- Better exploitation of registers
  $\Rightarrow$ Significantly reduces the cycle count

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- Large precomputations (technology dependent)
  - Somehow similar to a one-time program
- Minimum “online” cycle count (~ unprotected)

Evaluations on Atmel AtMega644p

- Includes shuffling of other AES operations (among 16 for each of them – see paper for the details)

Implementation	Clock Cycles
Unprotected AES	2739 (3546 with KS)
Double Indexing shuffling	30202 (46395 with KS)
Randomized Path shuffling	6934 (14834 with KS)
Randomized Memory shuffling	3299*

** Excludes precomputations (approx. 18 milliseconds)*

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$\Rightarrow$ Natural next step: include them in analysis

Our model

- Standard (sensitive operation) leakages

$$L_0 \leftsquigarrow \mathsf{Sbox}(k_{\mathsf{P}(0)} \oplus X_{\mathsf{P}(0)}), \qquad L_1 \leftsquigarrow \mathsf{Sbox}(k_{\mathsf{P}(1)} \oplus X_{\mathsf{P}(1)}),$$
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- Let S*c* = P(*c*) be the part of the master key manipulated at cycle *c*, with P the shuffling perm.
- We additionally consider permutations leakages

$$L'_c \leftsquigarrow S_c$$

EC09 information theoretic analysis (I)

- Based on the leakage probability distribution

$$\Pr[\mathbf{L} = \mathbf{l} | K_s = k] = \sum_c \frac{\mathsf{f}(c, s, \mathbf{l}')}{\sum_{c'} \mathsf{f}(c', s, \mathbf{l}')} \Pr[L_c = l_c | K_s = k]$$

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  - Random Start Index (RSIENUM-TA)

$$\mathrm{f}(c, s, \mathbf{l}') = \prod_{i=0}^{15} \Pr[L'_i = l'_i | S_i = (s - c + i) \bmod 16]$$

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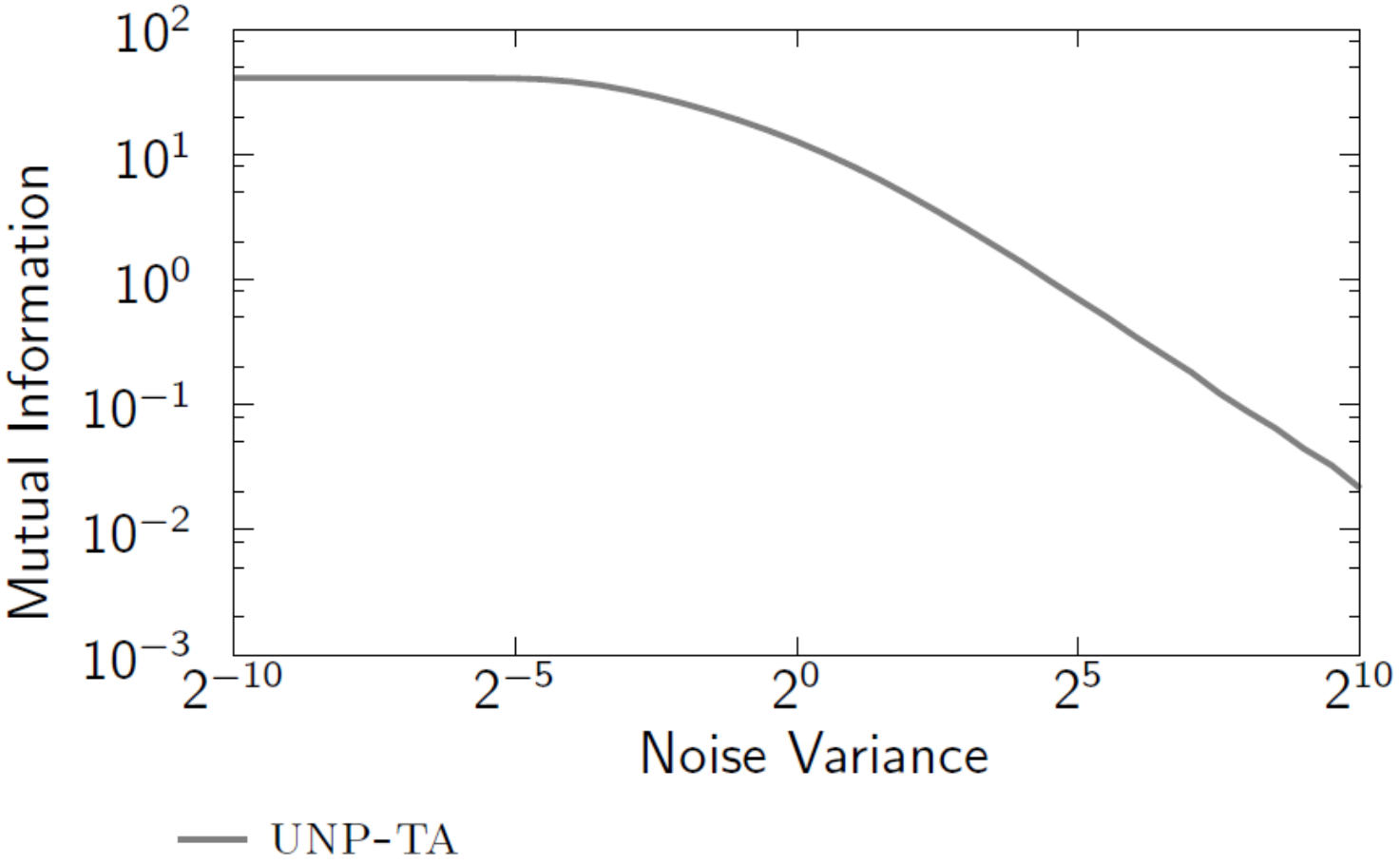

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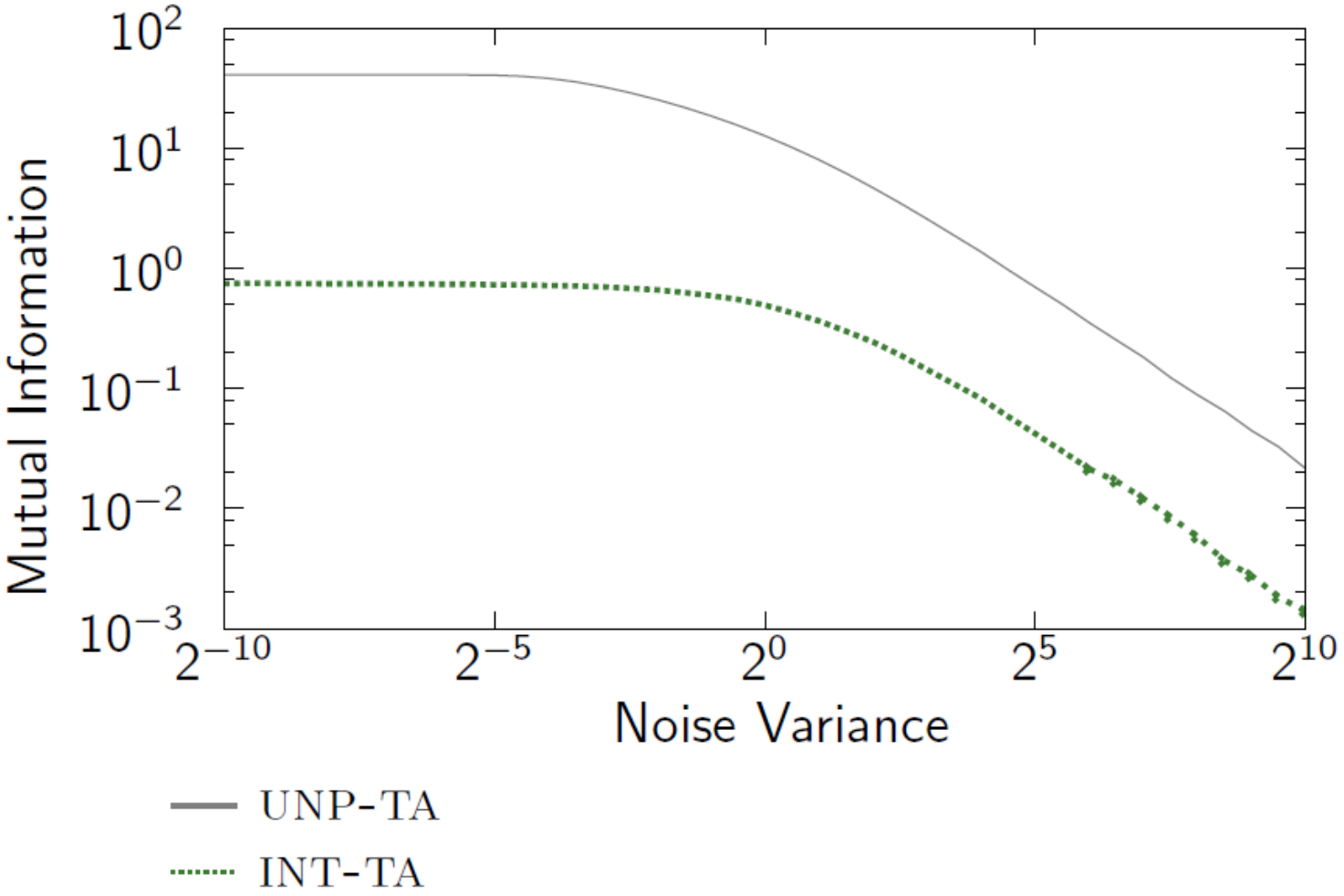

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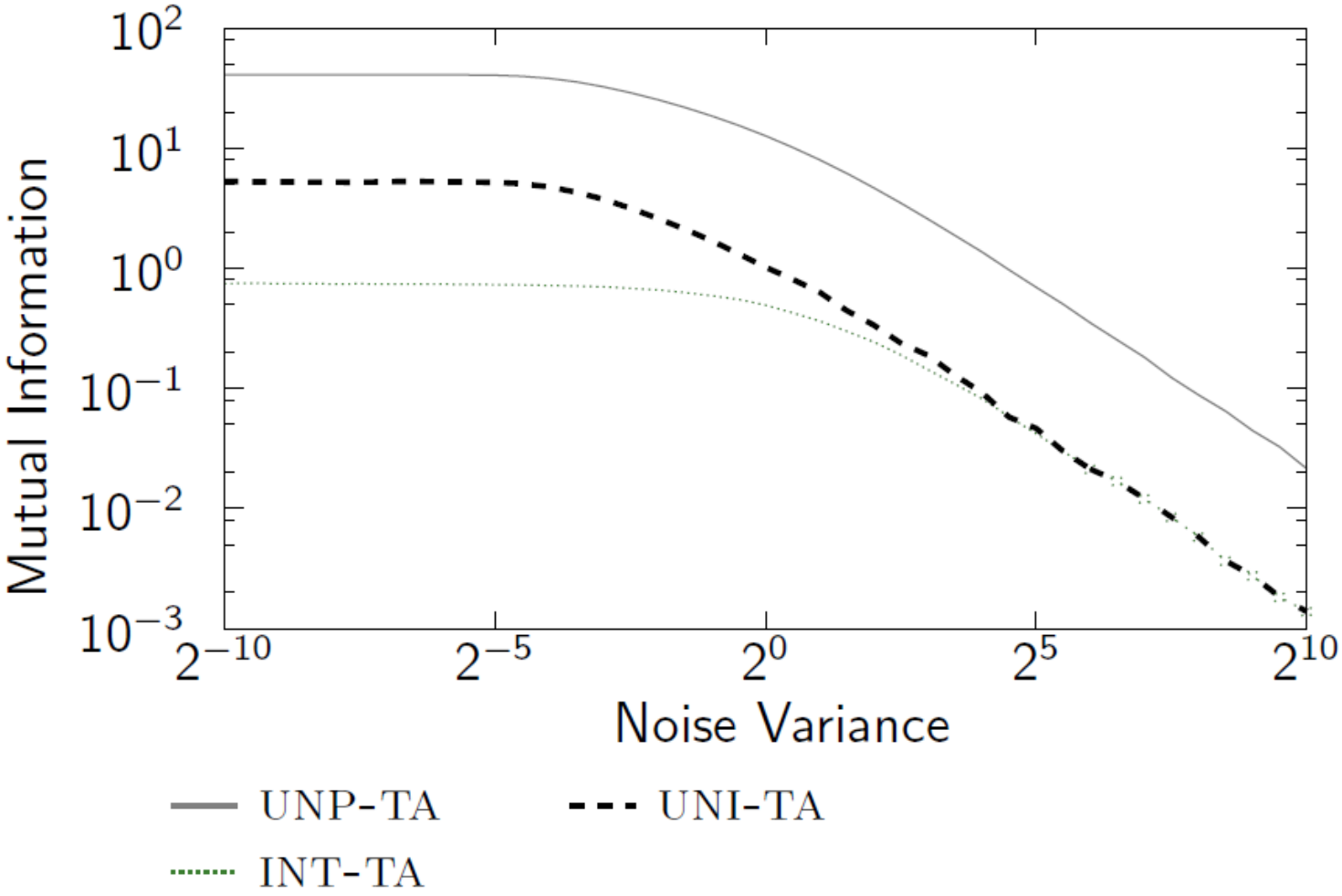

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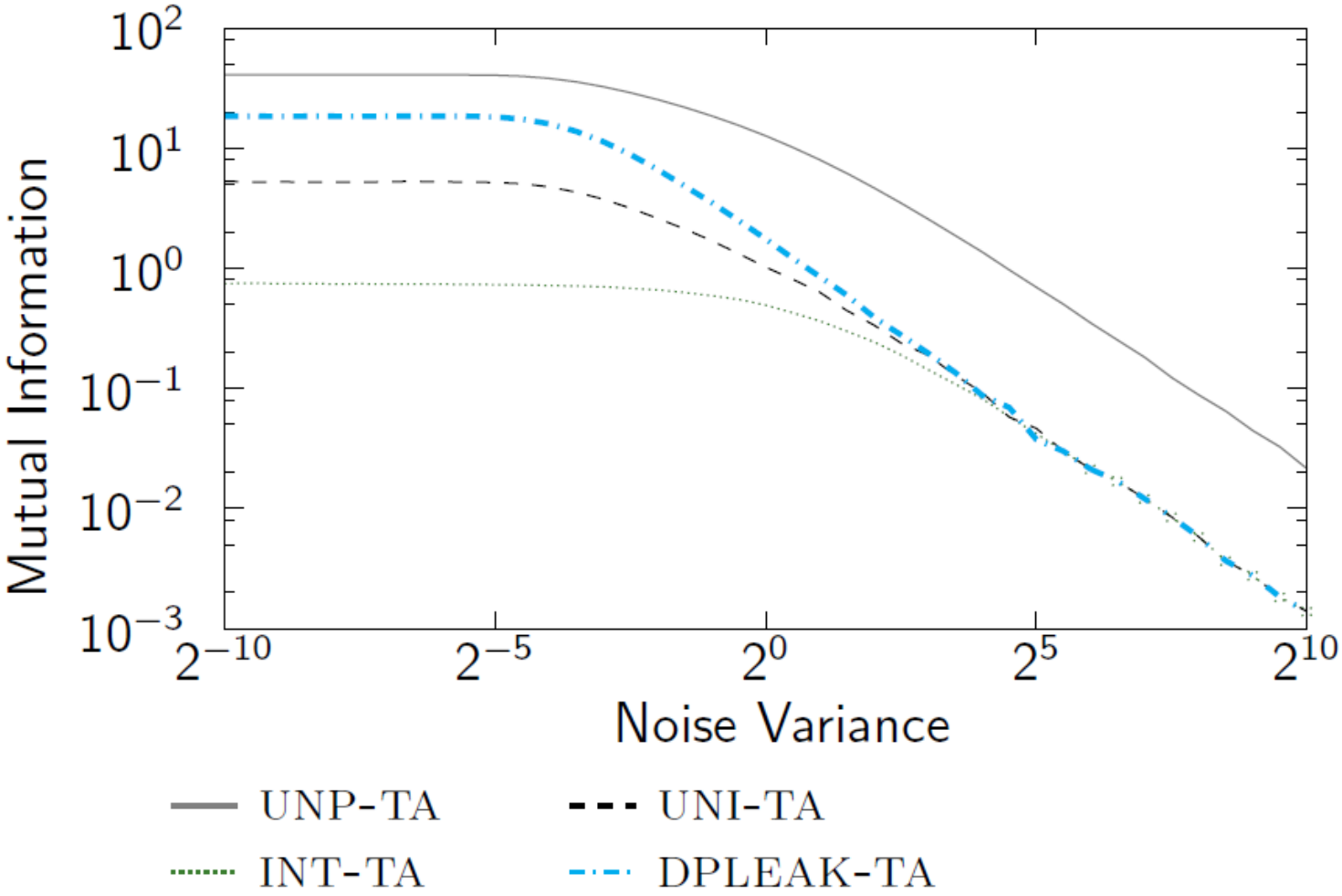

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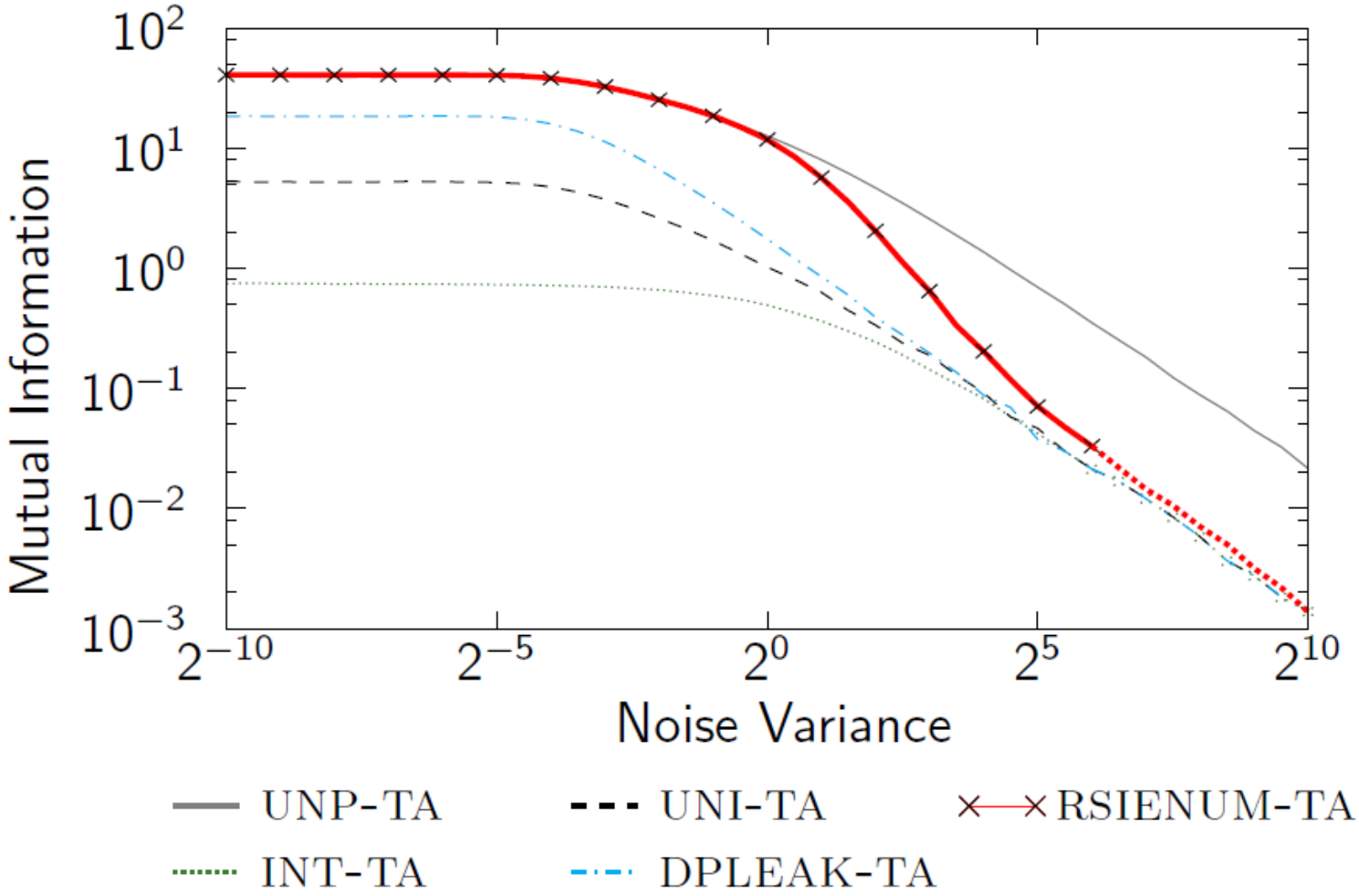
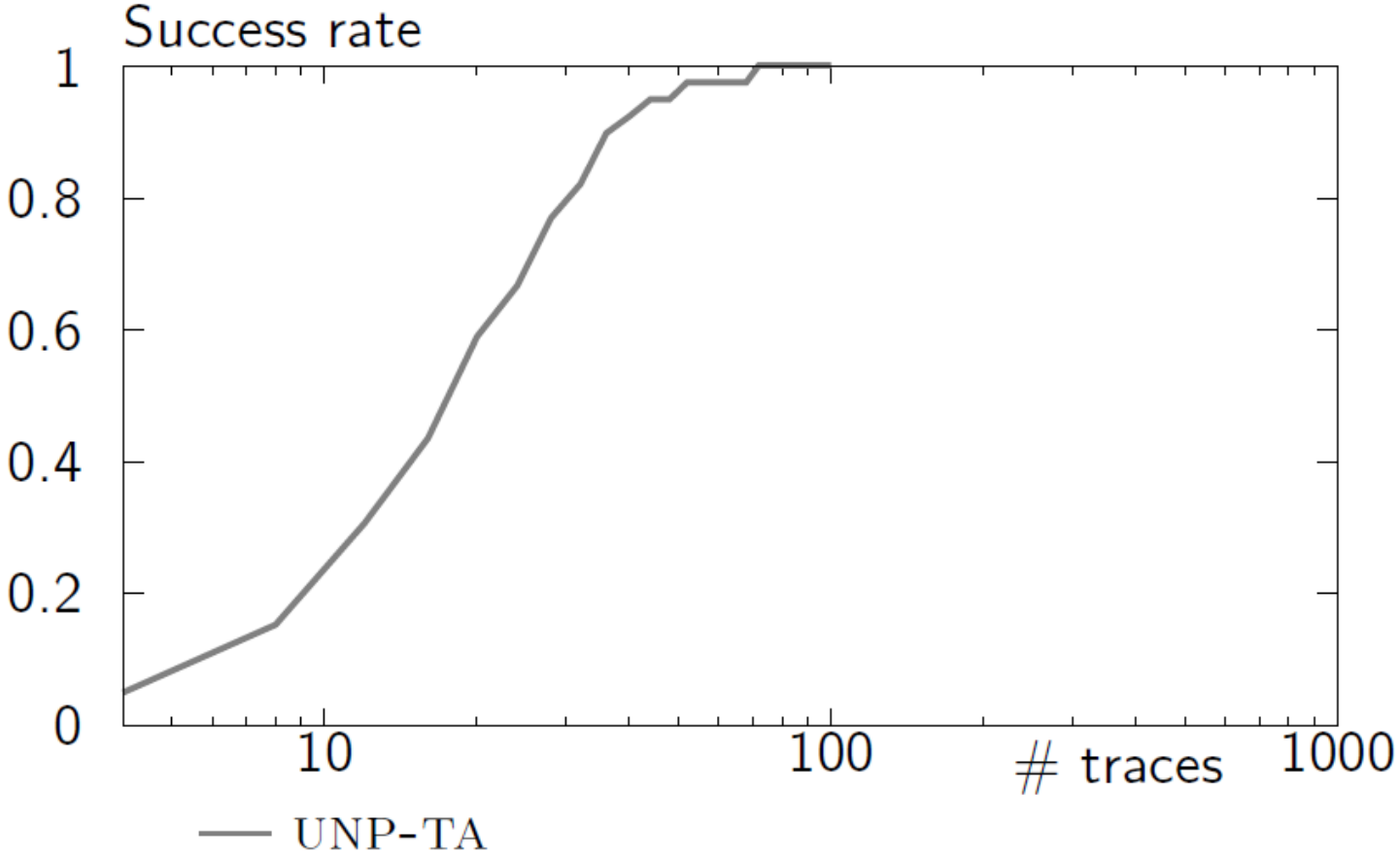


Talk outline

1. Implementation: how to shuffle efficiently?
   (Permutation generation - see paper)
   a. Double indexing
   b. (new) Randomized execution path
   c. (new) Randomized program memory

2. Security evaluation: “better than integrating”
   a. Information theoretic analysis
   b. Actual chip measurements

EC09 security analysis (Atmel AVR)



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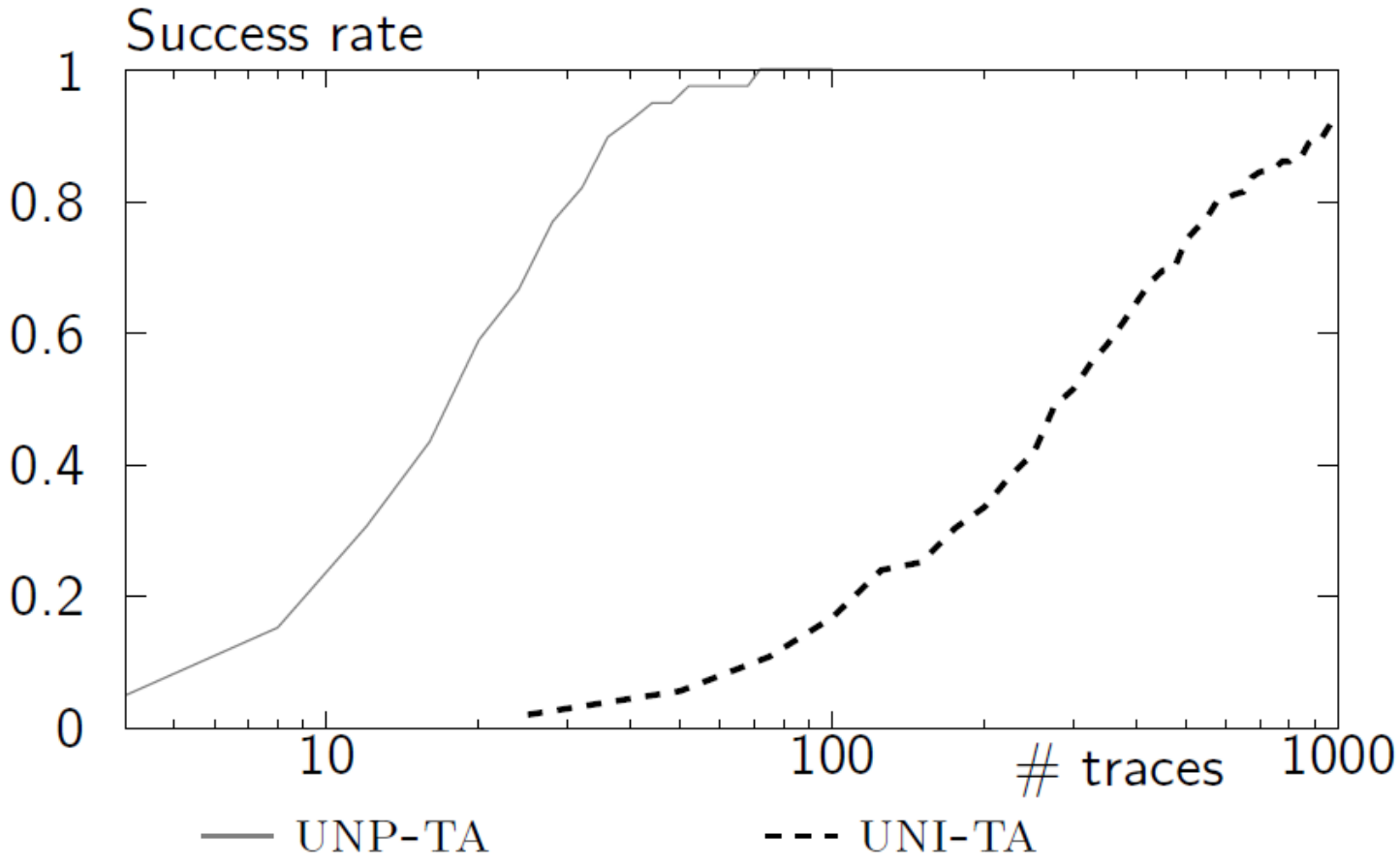

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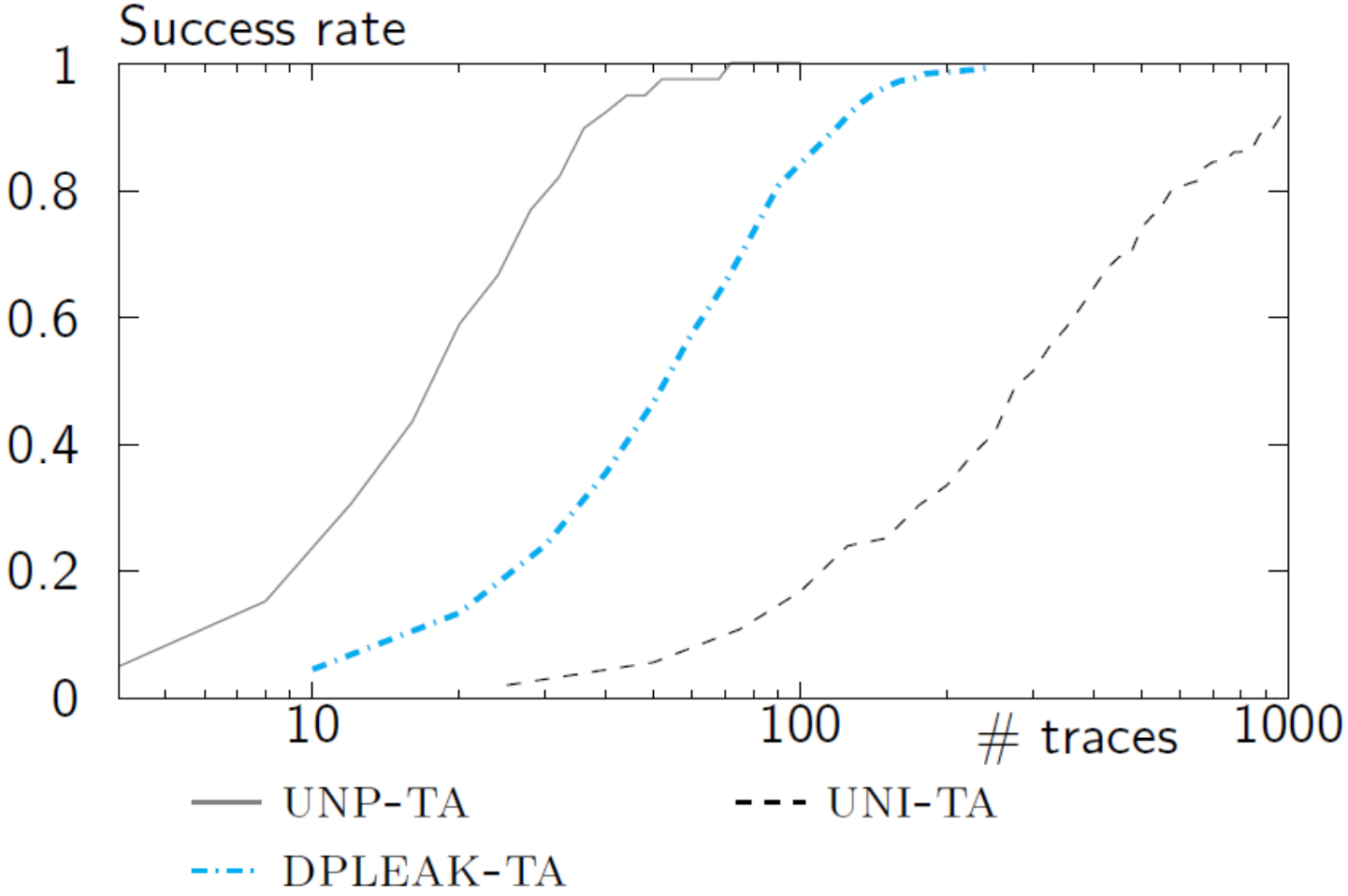

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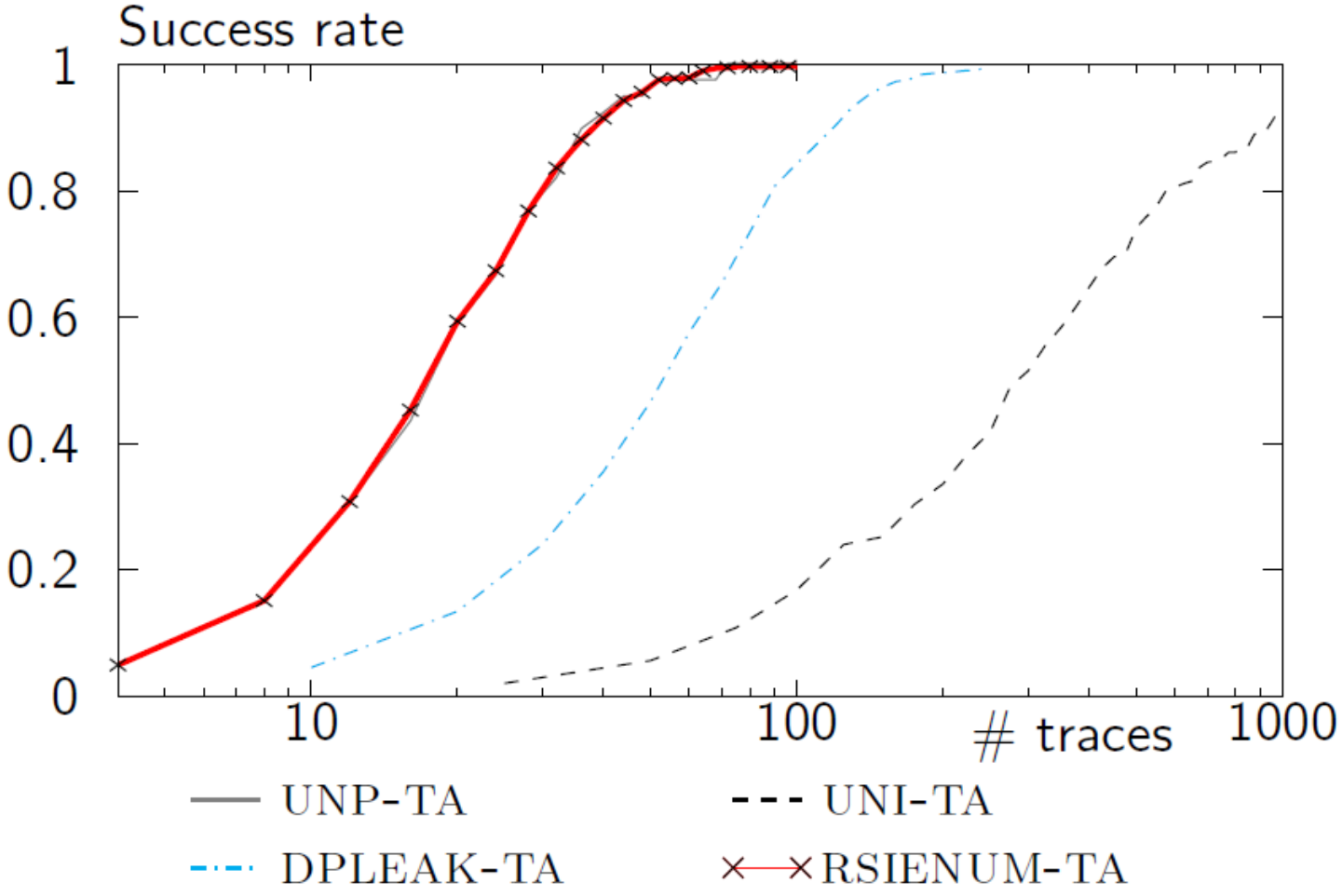

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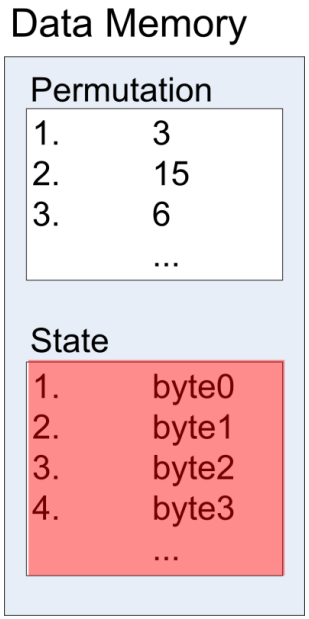

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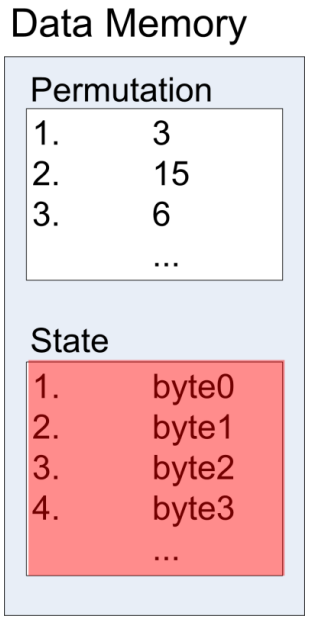

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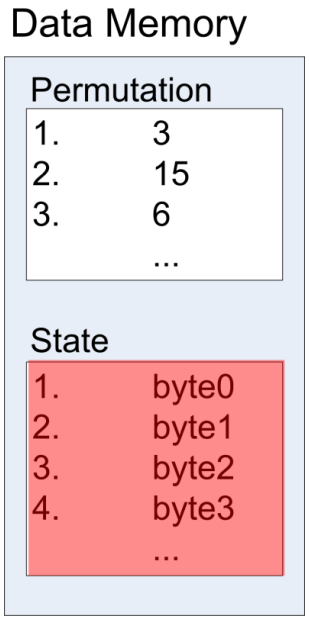

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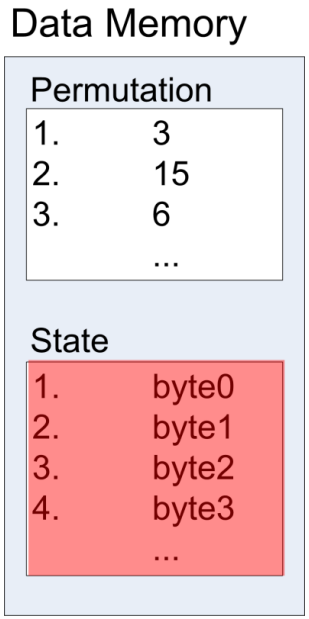

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  - Tradeoff between “online” and “offline” cycles
- Cautionary note: shuffling can be used as a noise amplifier – never as a noise generator!
- Computation matters: enumerable permutations lead to easier attacks => RSI should be avoided
  - (and all the operations in the block cipher should be permuted over at least 16!)
- Indirect leakages can appear!
  - Ideally, not only the order of operations should be shuffled, but also the resources used

THANKS

http://perso.uclouvain.be/fstandae/