Low Randomness ~~Masking~~ and Shulfifgn:

An Evaluation Using Mutual Information

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connecting innovators

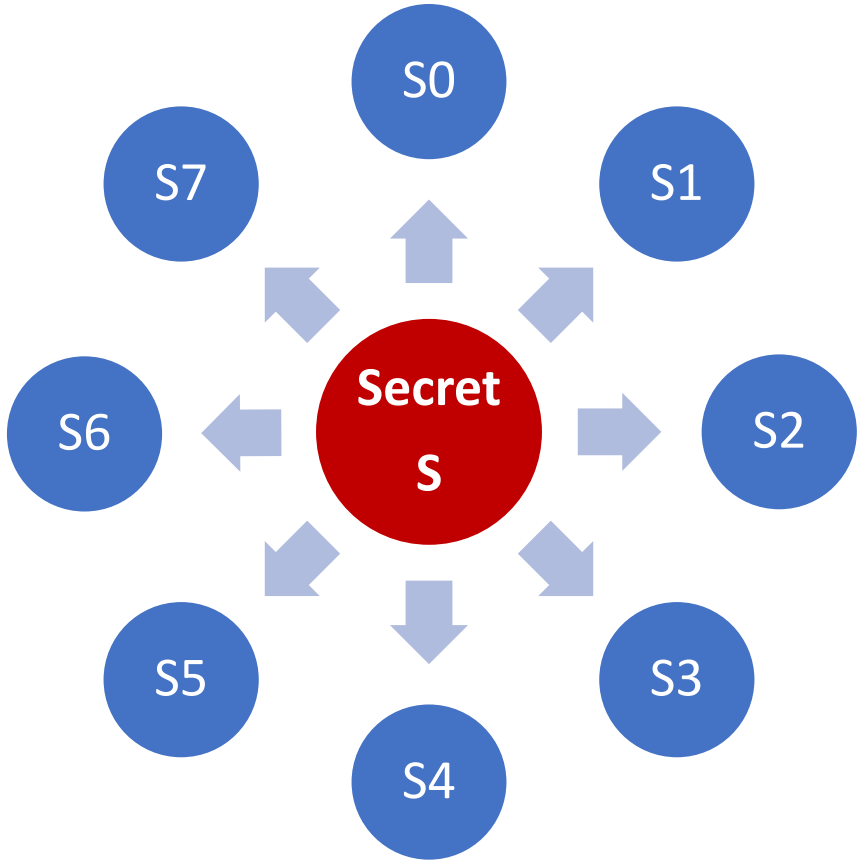
Overview

- Masking, shuffling and the cost of RNG
- New countermeasure variants that recycle randomness
- Pitfalls in formal security and noise amplification

Introduction

Masking and Shuffling Schemes Against Side-Channel Analysis

Introduction: Masking Schemes



- One of the most popular countermeasures against SCA
- Forces the adversary to recombine shares
- Performs noise amplification [1]

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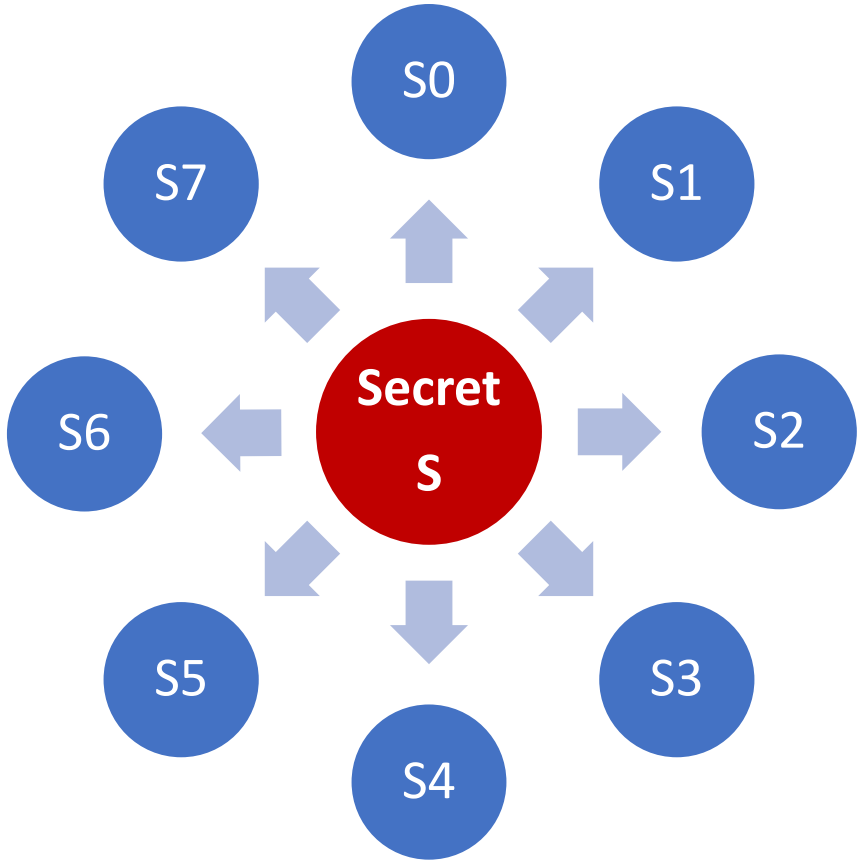

- One of the most popular countermeasures against SCA
- Forces the adversary to recombine shares
- Performs noise amplification [1]

- Computationally demanding in operations and RNG, $O(n^2)$ random elements for ISW multiplication with n shares [2]

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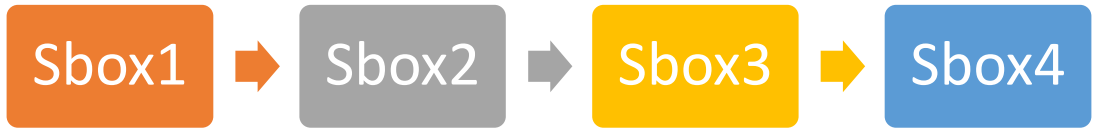

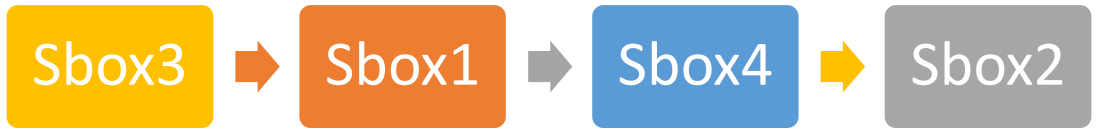

- Widely deployed countermeasure
- Permutes blocks
- Performs noise amplification [3]

[3] Nicolas Veyrat-Charvillon, Marcel Medwed, Stéphanie Kerckhof, and François-Xavier Standaert. Shuffling against side-channel attacks: A comprehensive study with cautionary note
[4] Donald E. Knuth. The Art of Computer Programming, Volume 2 (3rd Ed.): Seminumerical Algorithms

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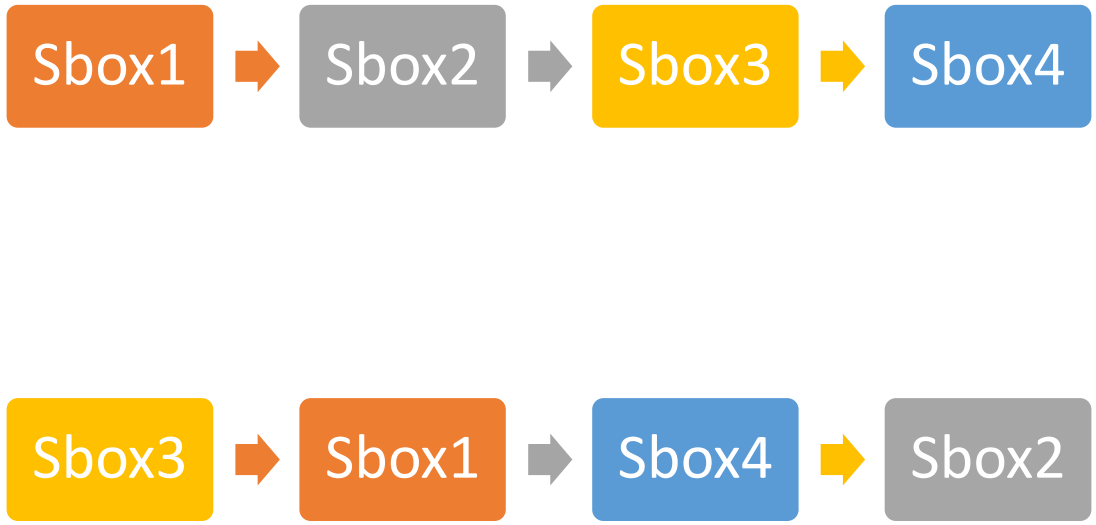

- Widely deployed countermeasure
- Permutes blocks
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- Computationally demanding in RNG, approx. $\mathrm{k} * \mathrm{ceil}(log_2 \mathrm{k})$ random bits, for k operations shuffled [4]

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Introduction: RNG Overhead

- The RNG constitutes a considerable performance overhead

[5] Josep Balasch, Sebastian Faust, Benedikt Gierlichs, Clara Paglialonga, and François-Xavier Standaert. Consolidating inner product masking
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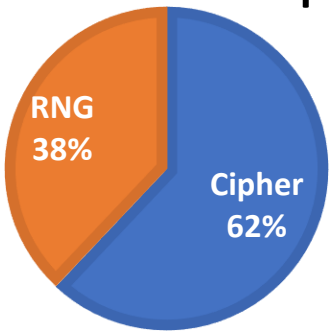

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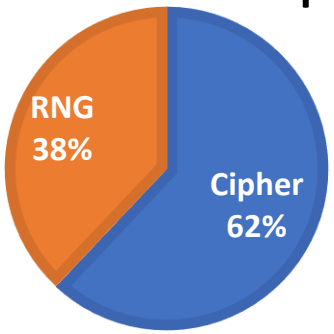

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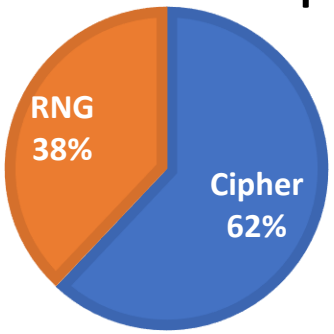

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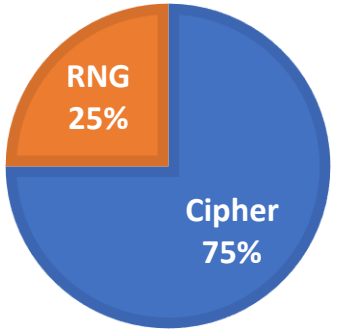

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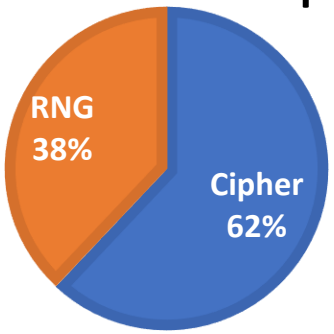

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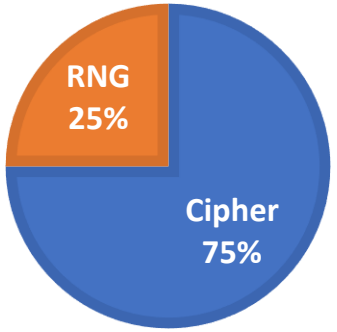

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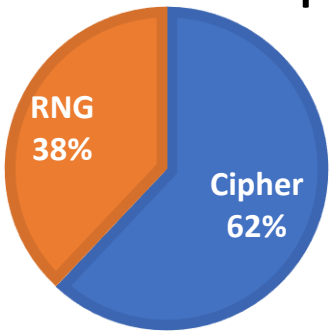

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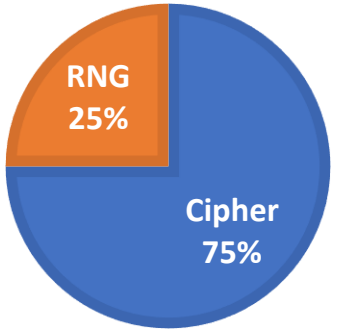

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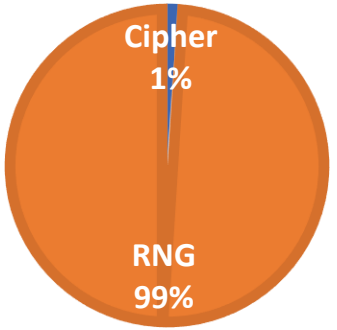

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Recycled Randomness Masking

Reducing the RNG overhead in masking with RRM

RRM: Example

- Assume two 2nd-order secure, independent ISW mult. gadgets $z = xy, c = ab$

$$z_0 = x_0y_0 \oplus w_0 \oplus w_1$$
$$z_1 = x_1y_1 \oplus ((w_0 \oplus x_0y_1) \oplus x_1y_0) \oplus w_2$$
$$z_2 = x_2y_2 \oplus ((w_1 \oplus x_0y_2) \oplus x_2y_0) \oplus ((w_2 \oplus x_1y_2) \oplus x_2y_1)$$

$$c_0 = a_0b_0 \oplus t_0 \oplus t_1$$
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RRM: Example

- **Recycle some random numbers** from the first to the second gadget

$$z_0 = x_0 y_0 \oplus w_0 \oplus w_1$$
$$z_1 = x_1 y_1 \oplus ((w_0 \oplus x_0 y_1) \oplus x_1 y_0) \oplus w_2$$
$$z_2 = x_2 y_2 \oplus ((w_1 \oplus x_0 y_2) \oplus x_2 y_0) \oplus ((w_2 \oplus x_1 y_2) \oplus x_2 y_1)$$

$$c_0 = a_0 b_0 \oplus w_0 \oplus w_1$$
$$c_1 = a_1 b_1 \oplus ((w_0 \oplus a_0 b_1) \oplus a_1 b_0) \oplus t_2$$
$$c_2 = a_2 b_2 \oplus ((w_1 \oplus a_0 b_2) \oplus a_2 b_0) \oplus ((t_2 \oplus a_1 b_2) \oplus a_2 b_1)$$

Reduced Randomness cost by 2 random numbers

RRM: Example

- **Formal security verification** [8] : the 2-multiplication gadget is 2-NI

$$z_0 = x_0y_0 \oplus w_0 \oplus w_1$$
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[8] Jean-Sebastien Coron. Formal Verification of Side-channel Countermeasures via Elementary Circuit Transformations.

RRM: Example

- **Recycle more!**

$z_0 = x_0y_0 \oplus w_0 \oplus w_1$
$z_1 = x_1y_1 \oplus ((w_0 \oplus x_0y_1) \oplus x_1y_0) \oplus w_2$
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$c_0 = a_0b_0 \oplus w_0 \oplus w_1$
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Reduced Randomness cost by 3 random numbers

RRM: Example

- **Formal security verification** : INSECURE, check $z_2 \oplus c_2$

$z_0 = x_0y_0 \oplus w_0 \oplus w_1$
$z_1 = x_1y_1 \oplus ((w_0 \oplus x_0y_1) \oplus x_1y_0) \oplus w_2$
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- Recycling excessively can hurt probing security even between independent gadgets

RRM: Efficient Gadgets

- Search for 2-multiplication, NI gadgets that recycle randomness

Recycling	2-mult ISW gadgets [2]			2-mult BBP gadgets [9]		
	Security Order			Security Order		
	1	2	3	1	2	3
Yes	1	4	8	1	2	6
No	2	6	12	2	4	8

Randomness Cost Table

[2] Yuval Ishai, Amit Sahai, and David Wagner. Private circuits: Securing hardware against probing attacks
[9] Sonia Belaïd, Fabrice Benhamouda, Alain Passelègue, Emmanuel Prouff, Adrian Thillard, and Damien Vergnaud. Randomness complexity of private circuits for multiplication.

RRM: Noise Amplification Pitfall

- **Central Limit Theorem:**
  Let m occurrences of random number, emitting leakages $L_1, L_2, \ldots, L_m \sim N(\mu, \sigma)$

- Averaging leakages gives: $L_{avg} = \frac{1}{m}\sum_{i=1}^{m} L_i \sim N(\mu, \frac{\sigma}{\sqrt{m}})$,
  i.e. exploiting the recycling can de-noise the signal [10]

[10] Alberto Battistello, Jean-Sébastien Coron, Emmanuel Prouff, and Rina Zeitoun. Horizontal side-channel attacks and countermeasures on the ISW masking scheme
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- Let 2 types of adversaries and we perform an information-theoretic analysis [11]
  C1: naive, doesn't see recycling

  C2: smart, can see leakages from recycling

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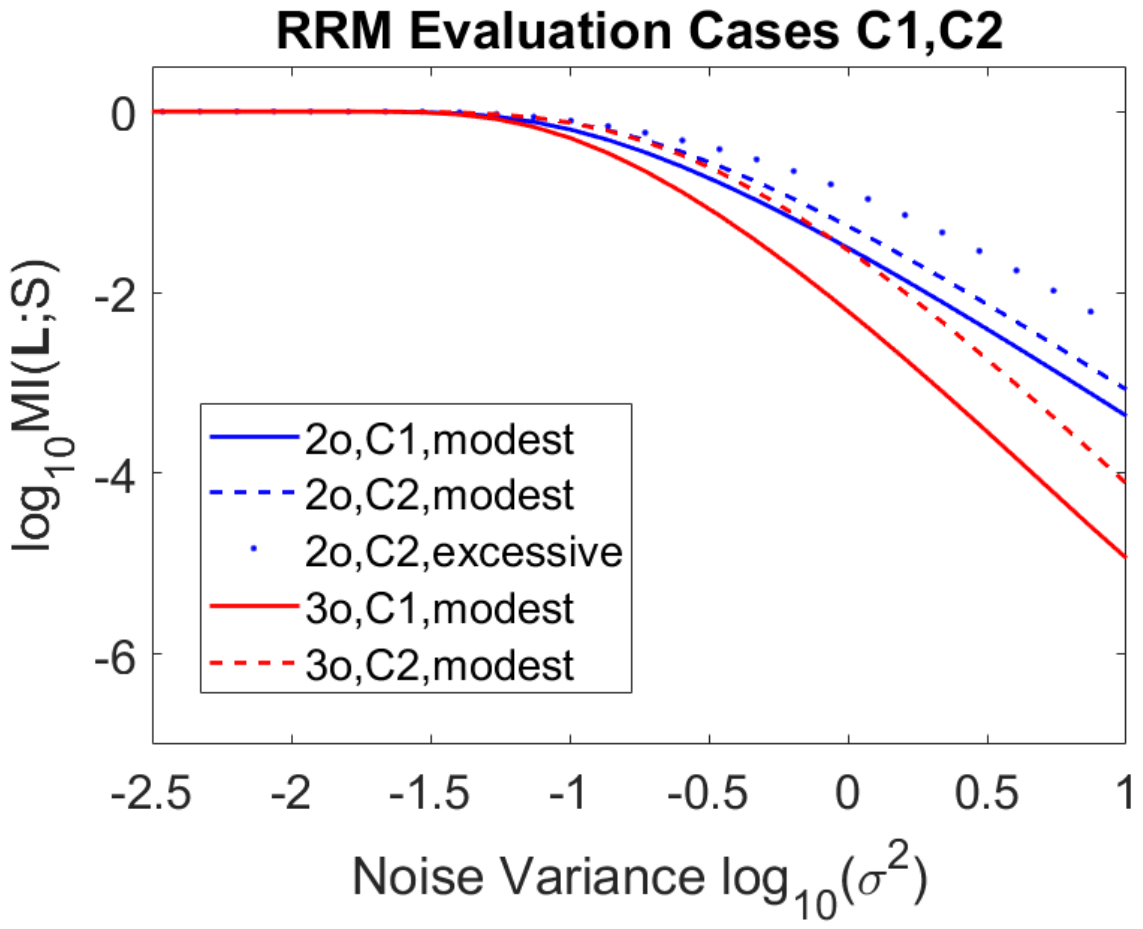

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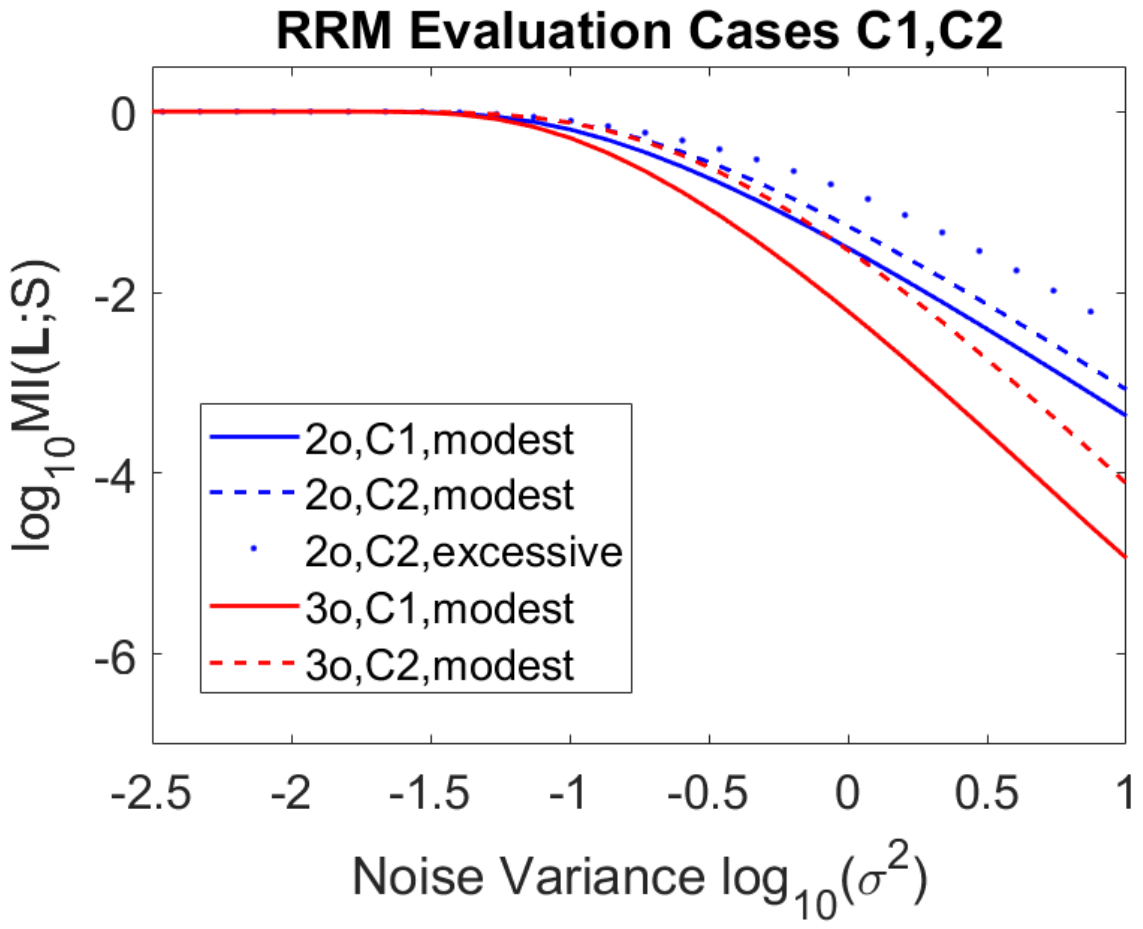

1. The naive adversary C1 cannot take advantage of recycling

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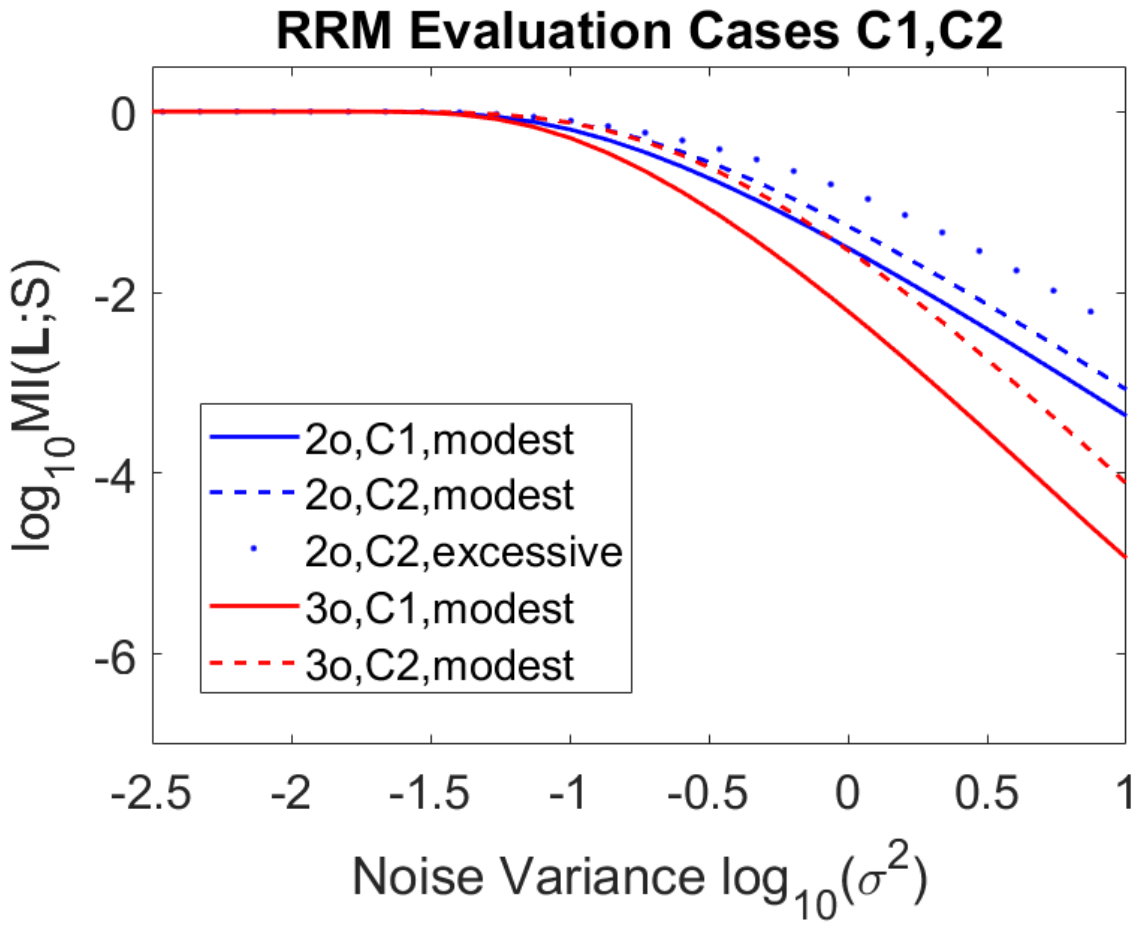

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2. The smart adversary C2 can shift the curve to the right

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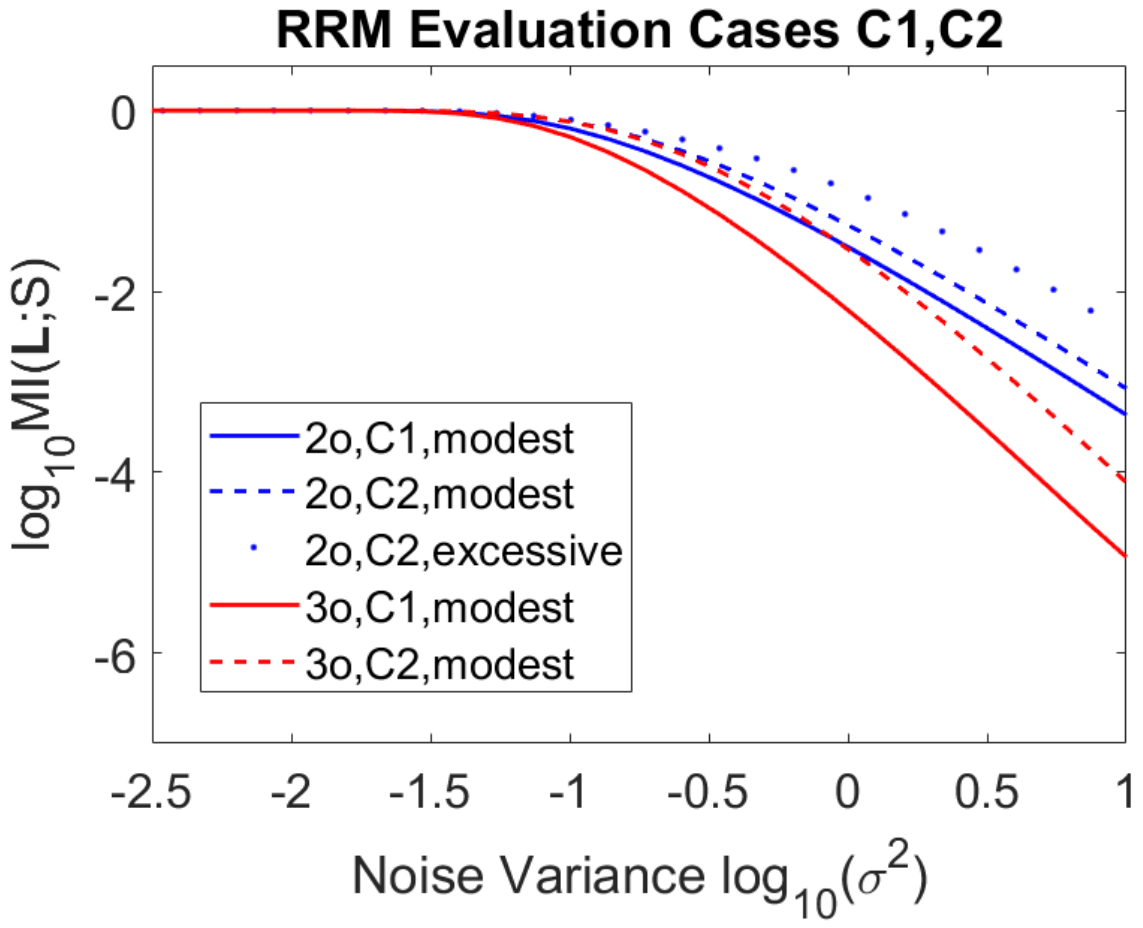

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3. Excessive recycling can damage the security

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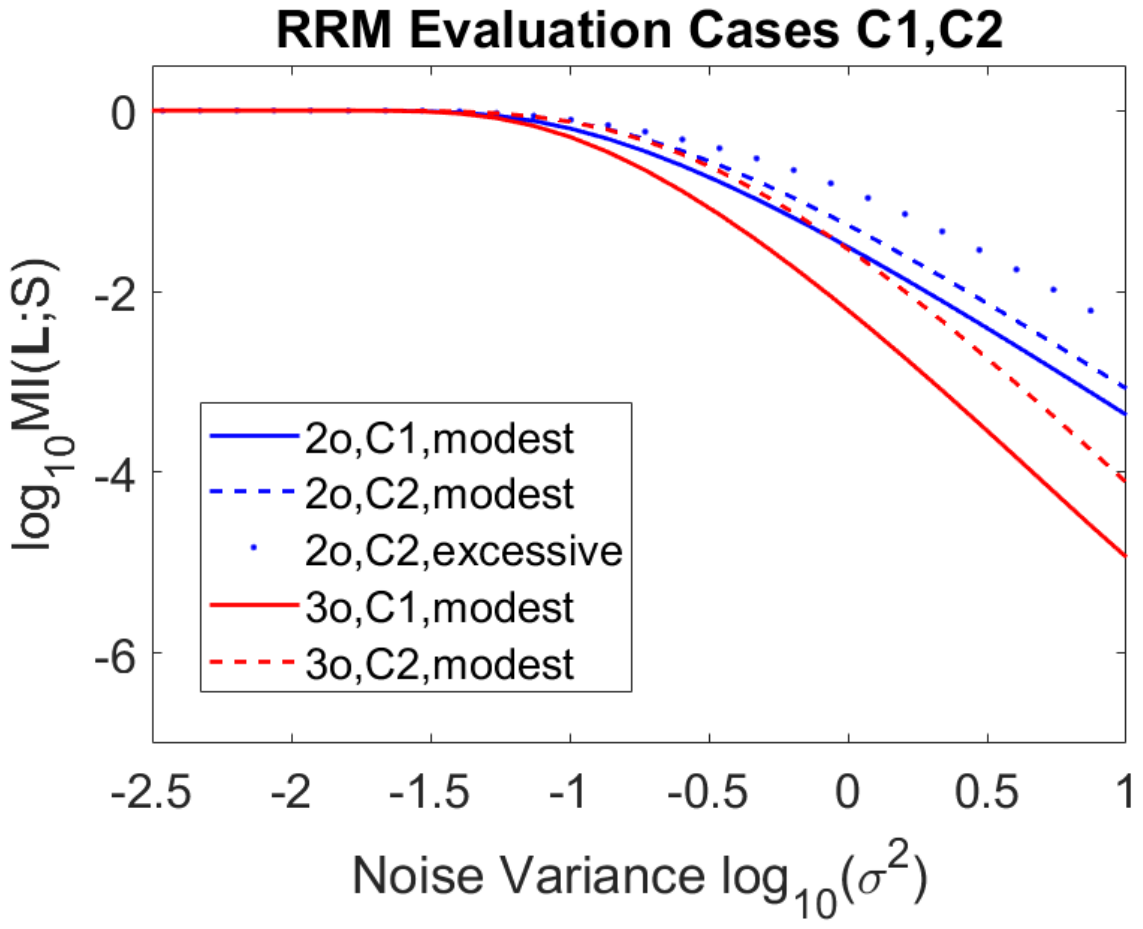
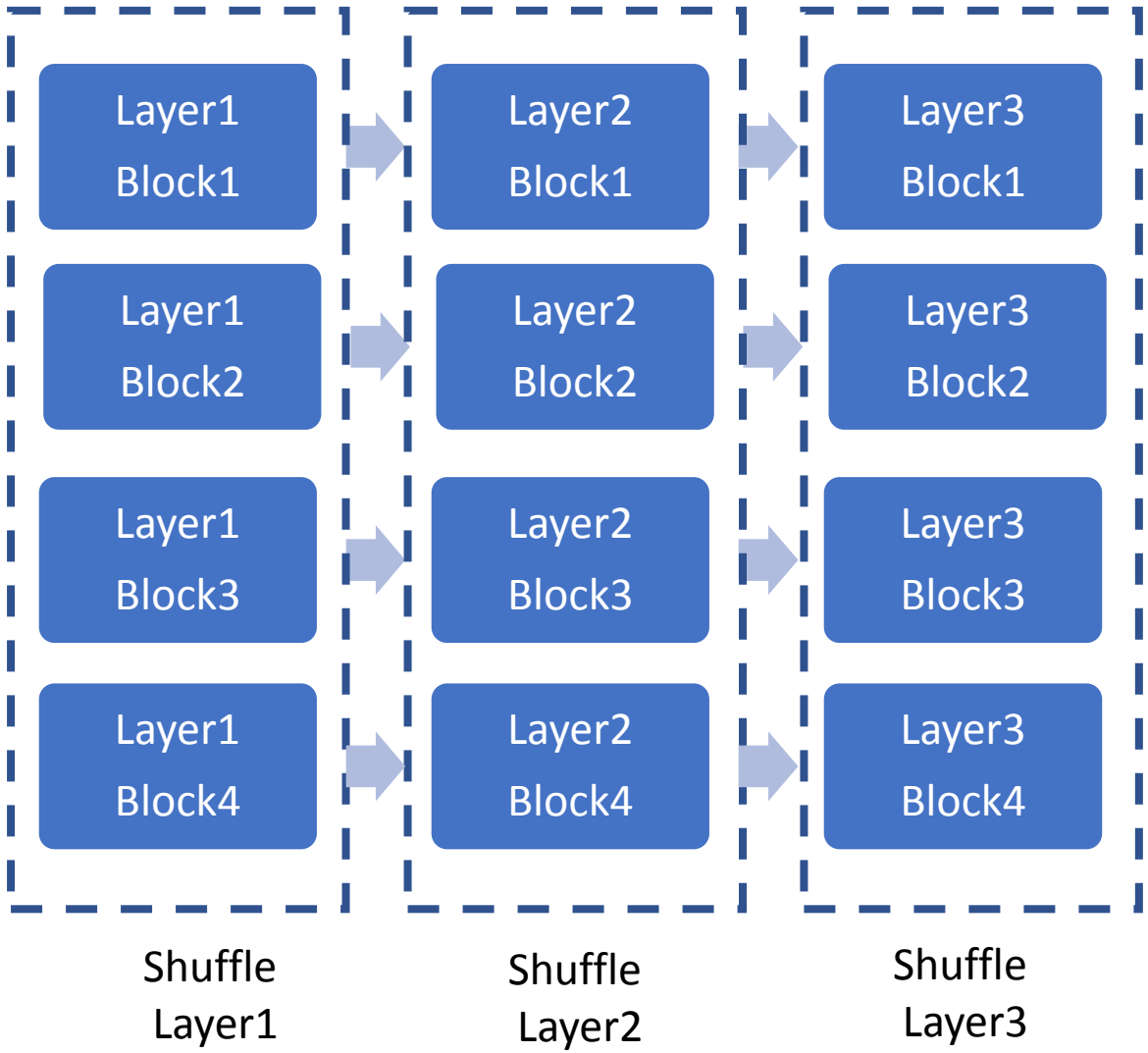


1. The naive adversary C1 cannot take advantage of recycling
2. The smart adversary C2 can shift the curve to the right
3. Excessive recycling can damage the security
4. **RRM is a tradeoff between security and randomness cost**

Reduced Randomness Shuffling

Reducing the RNG overhead in shuffling with RRS

RRS: Original Shuffling



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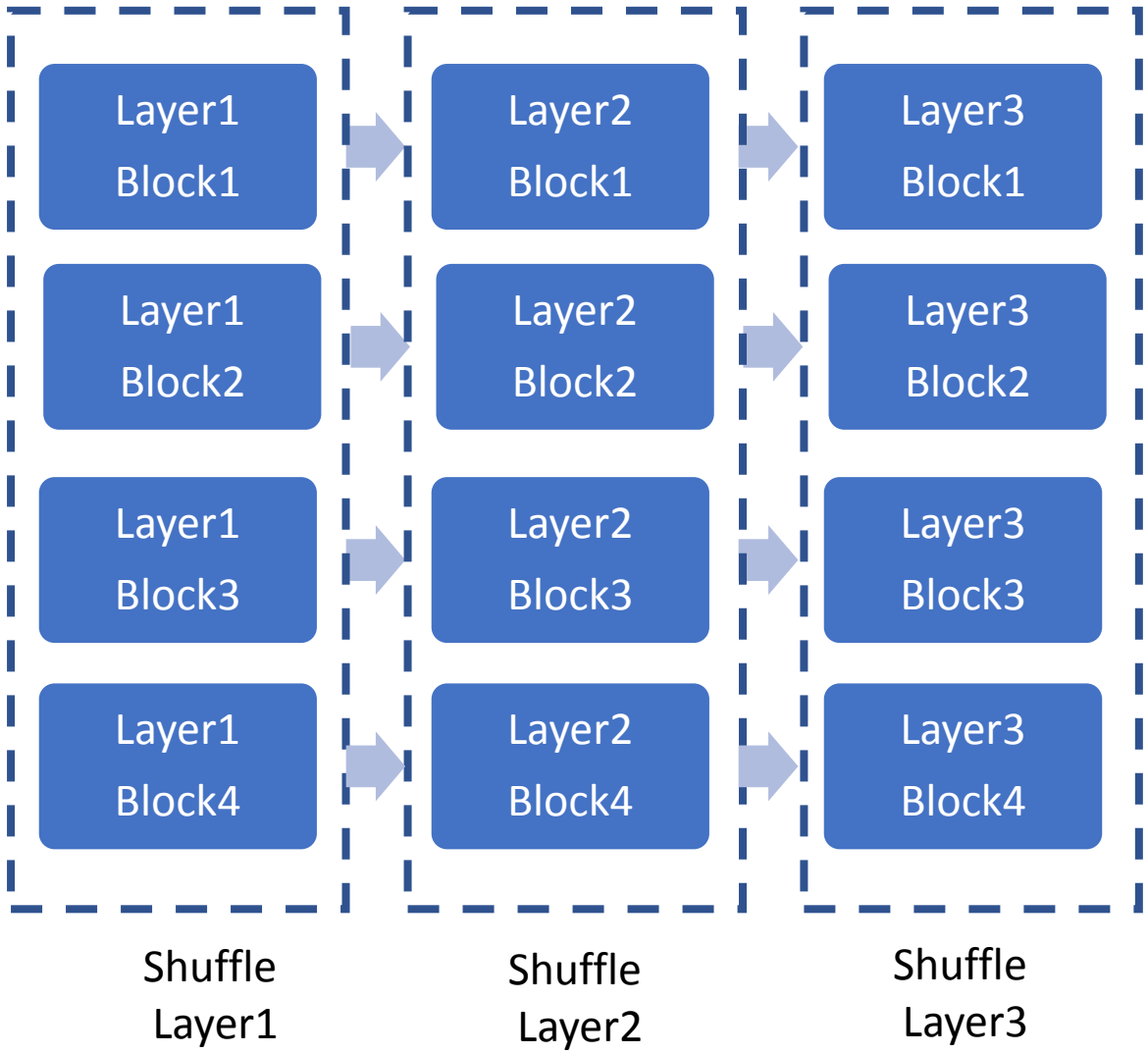
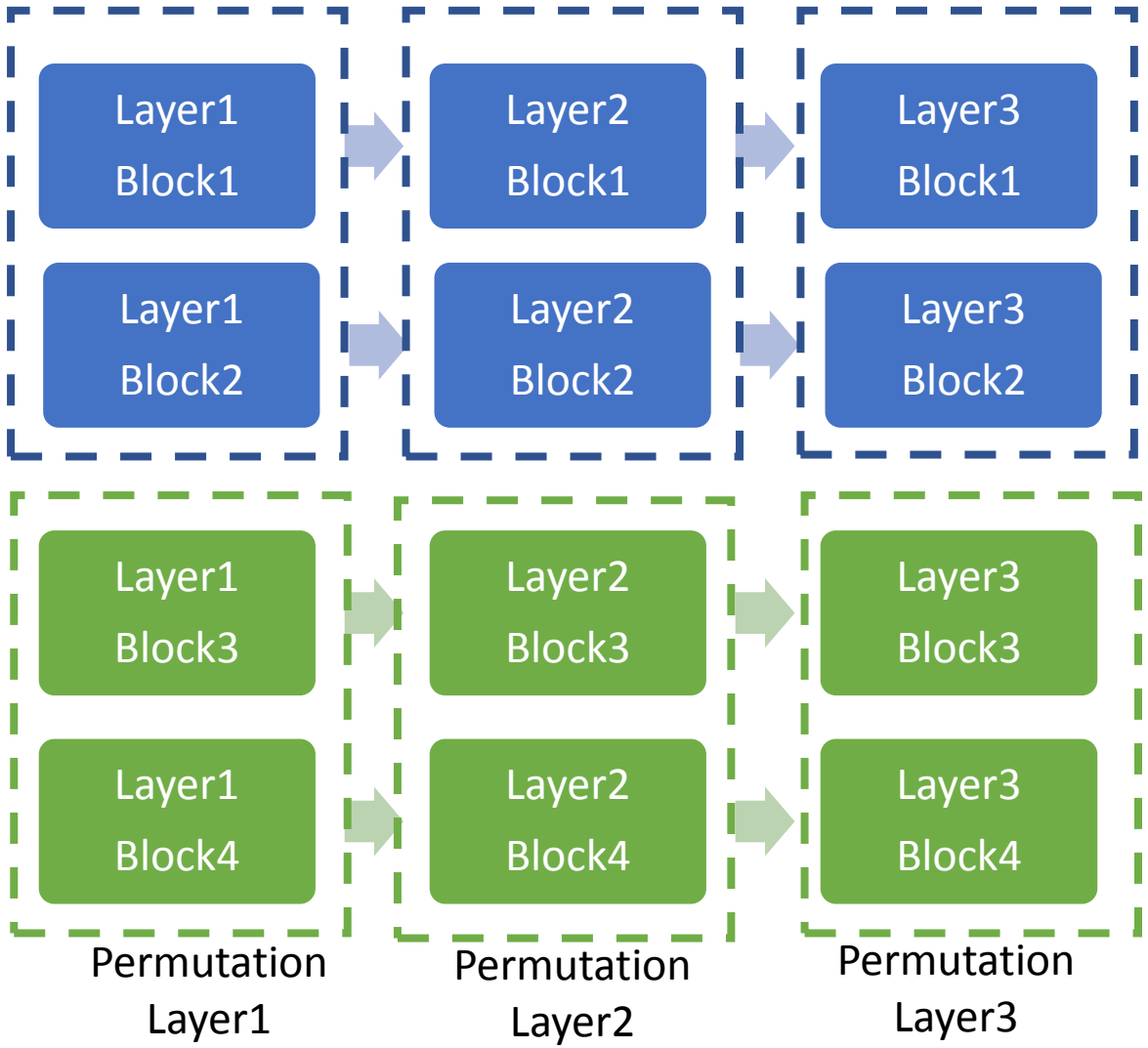


Randomness cost:

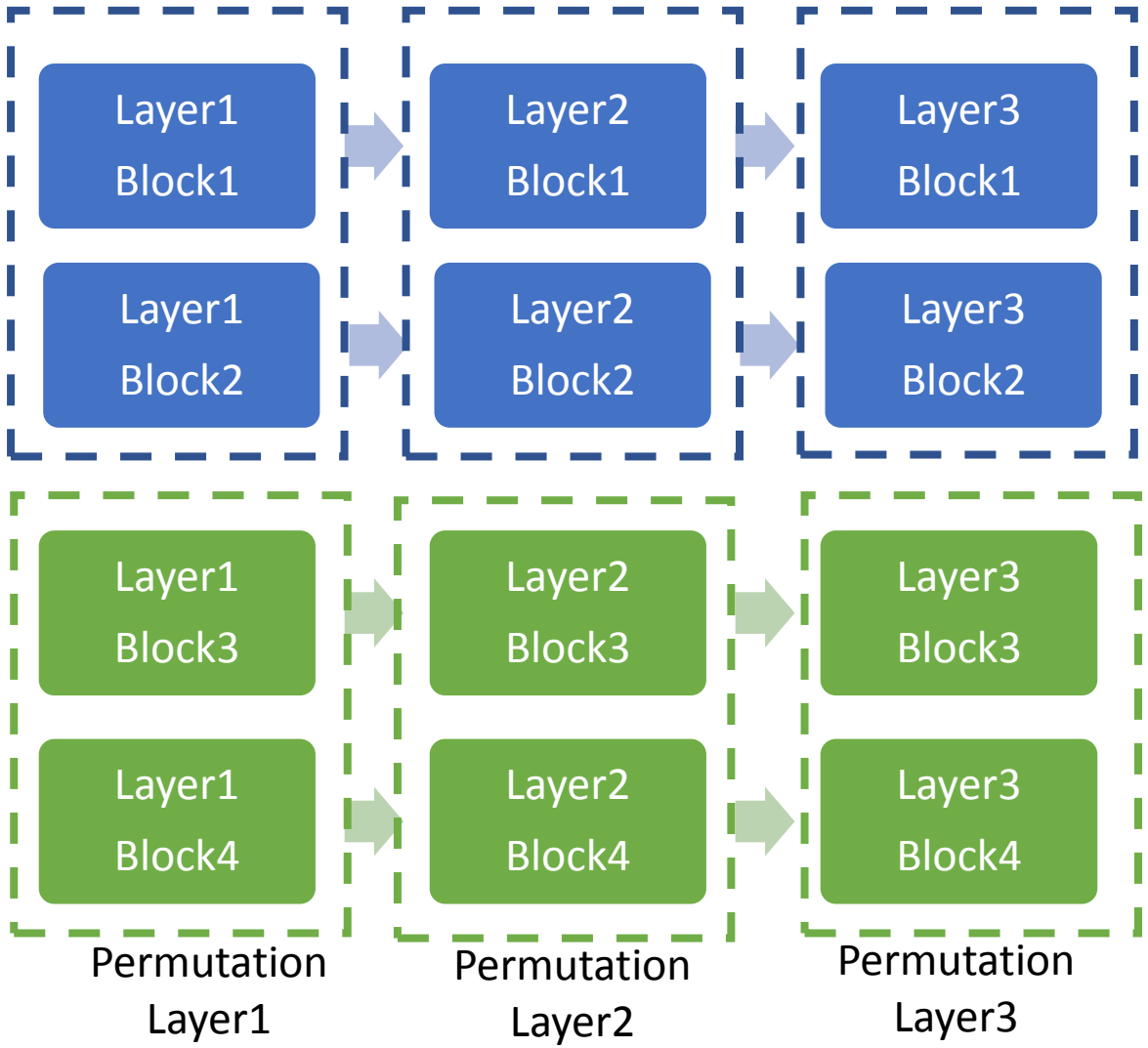
- Shuffle 3 layers independently
- Each layer must shuffle 4 blocks
- $3 * 4 * log_2 4 = 24\ bits$

RRS: Partitioned Shuffling



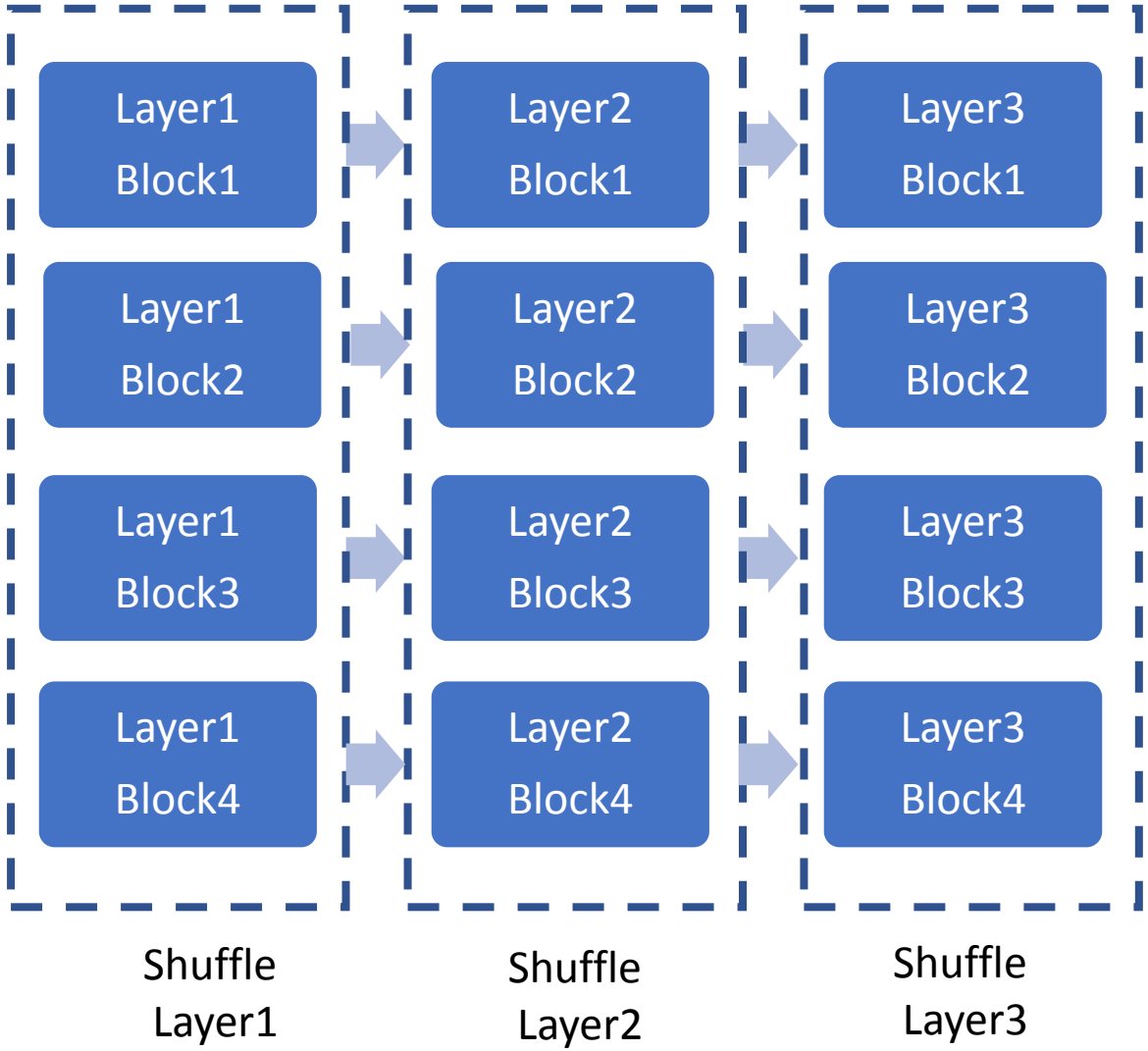
- **Partition** the layers in two, i.e. partition factor $f_p = 2$

RRS: Partitioned Shuffling

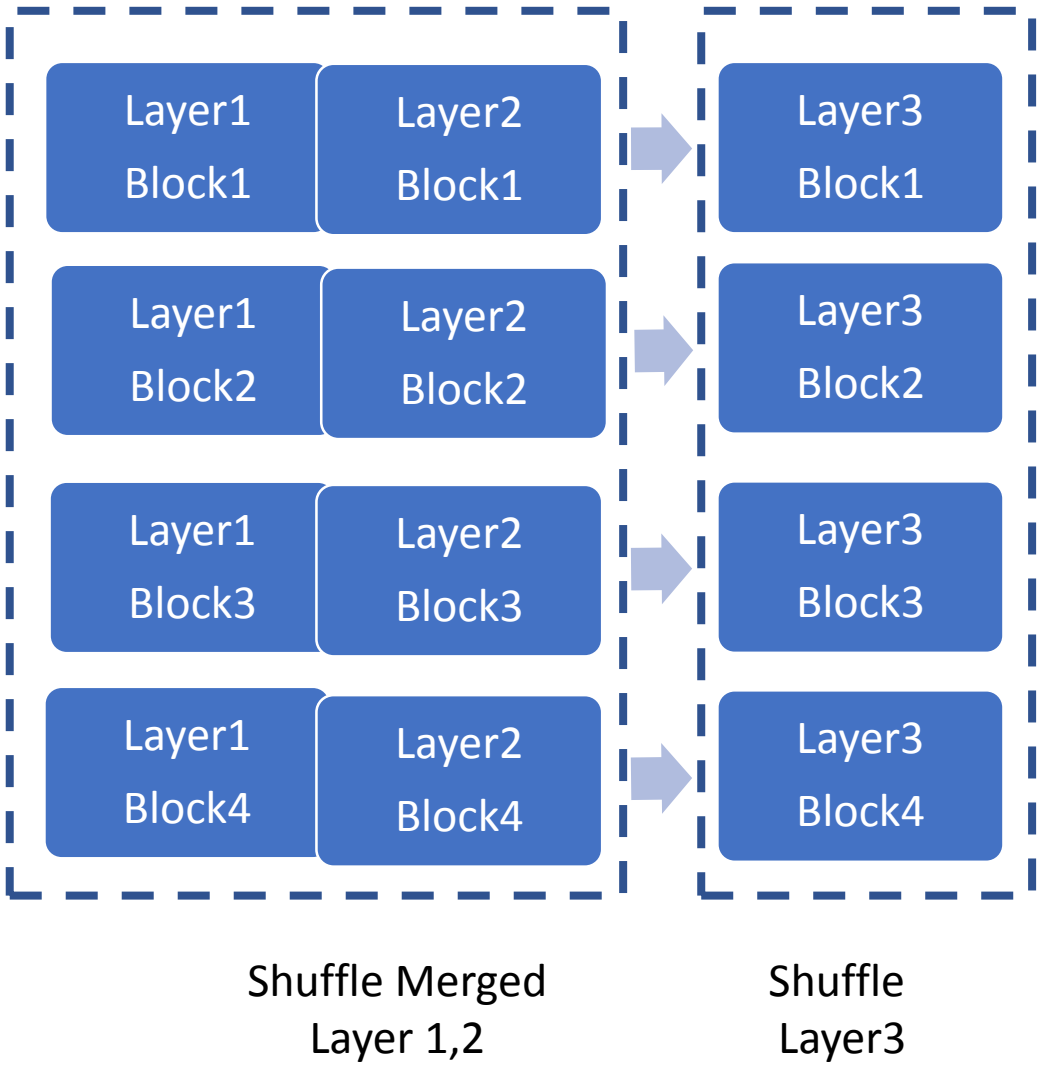


- **Partition** the layers in two, i.e. partition factor $f_p = 2$
- **Randomness cost:**
  - Shuffle 6 layers independently
  - Each partitioned layer shuffles 2 blocks
  - $6 * 2 * log_2 2 = 12\ bits < 24\ bits$

RRS: Original Shuffling



RRS: Merged Shuffling



- **Merge** the 2 layers and shuffle them together, i.e. merge factor $f_m = 2$

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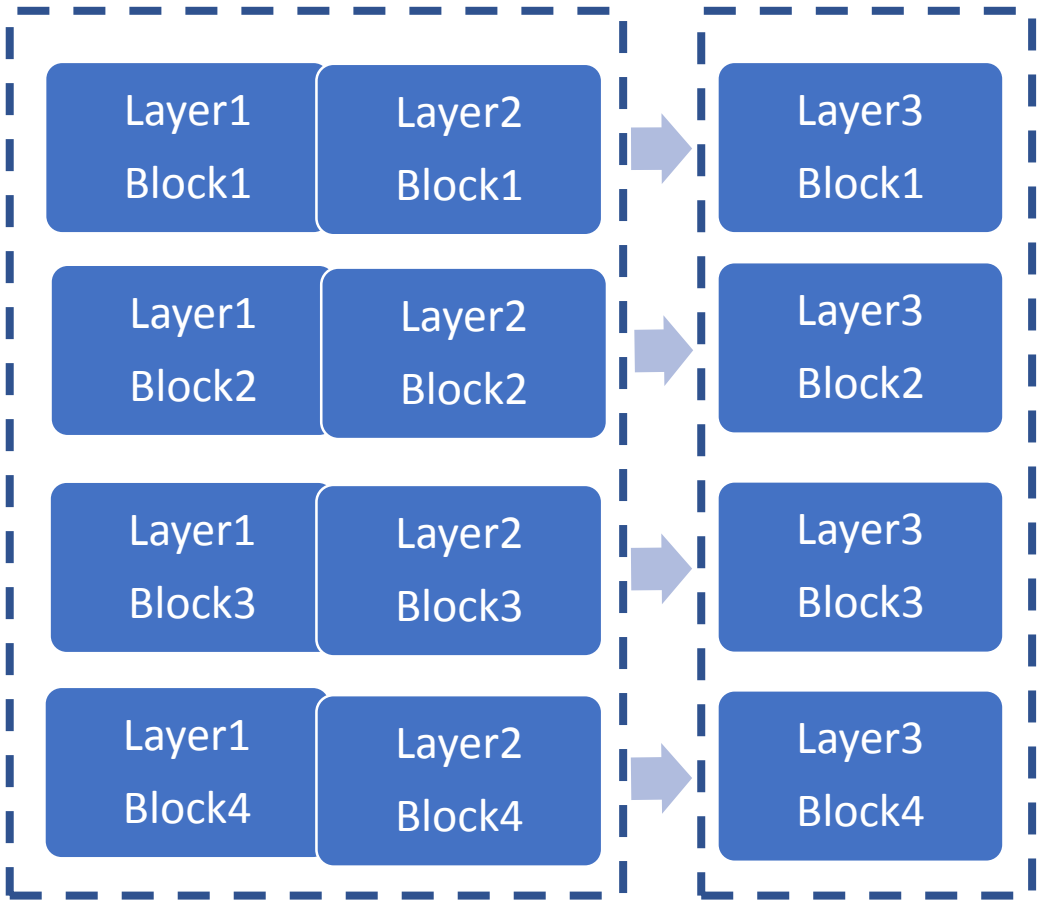

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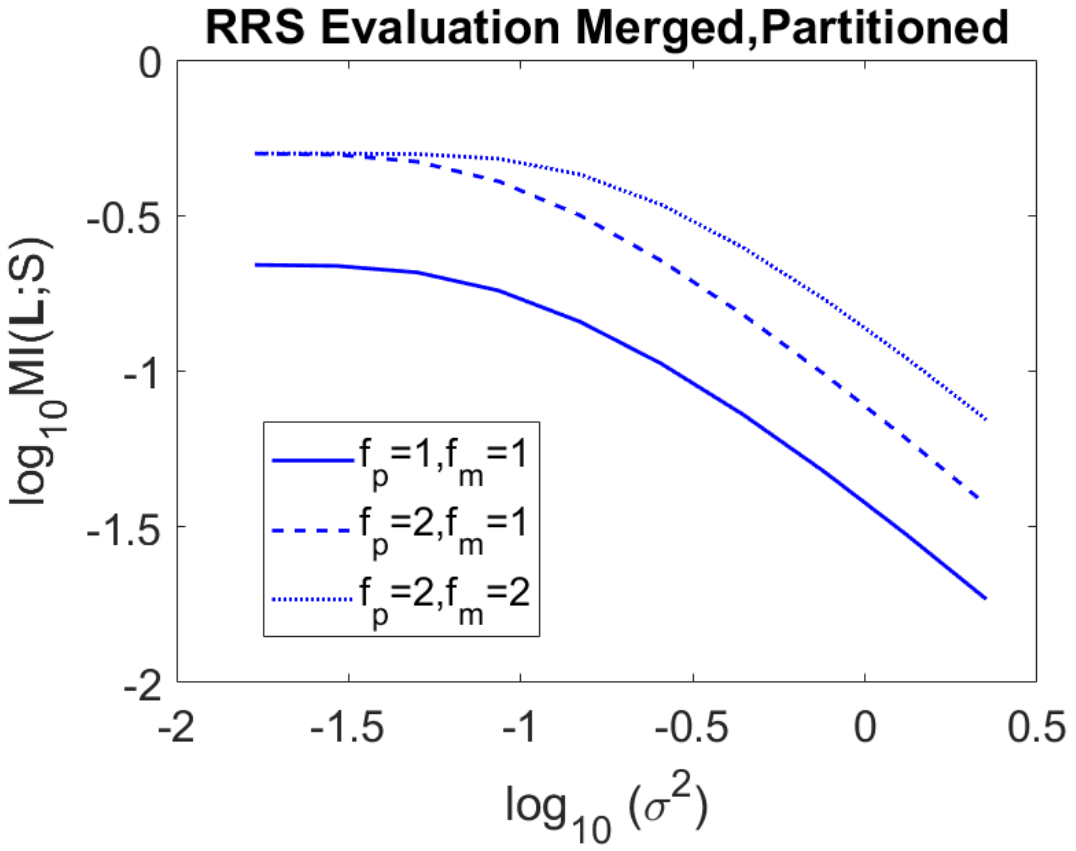
- **Randomness cost:**
  - Shuffle 2 layers:
    - Merged layer 1,2
    - Layer 3
  - Merged layer 1,2 has 4 blocks
  - Non-merged layer 3 has 4 blocks
  - $4 * log_2 4 + 4 * log_2 4 = 16\ bits < 24\ bits$

RRS: Noise Amplification



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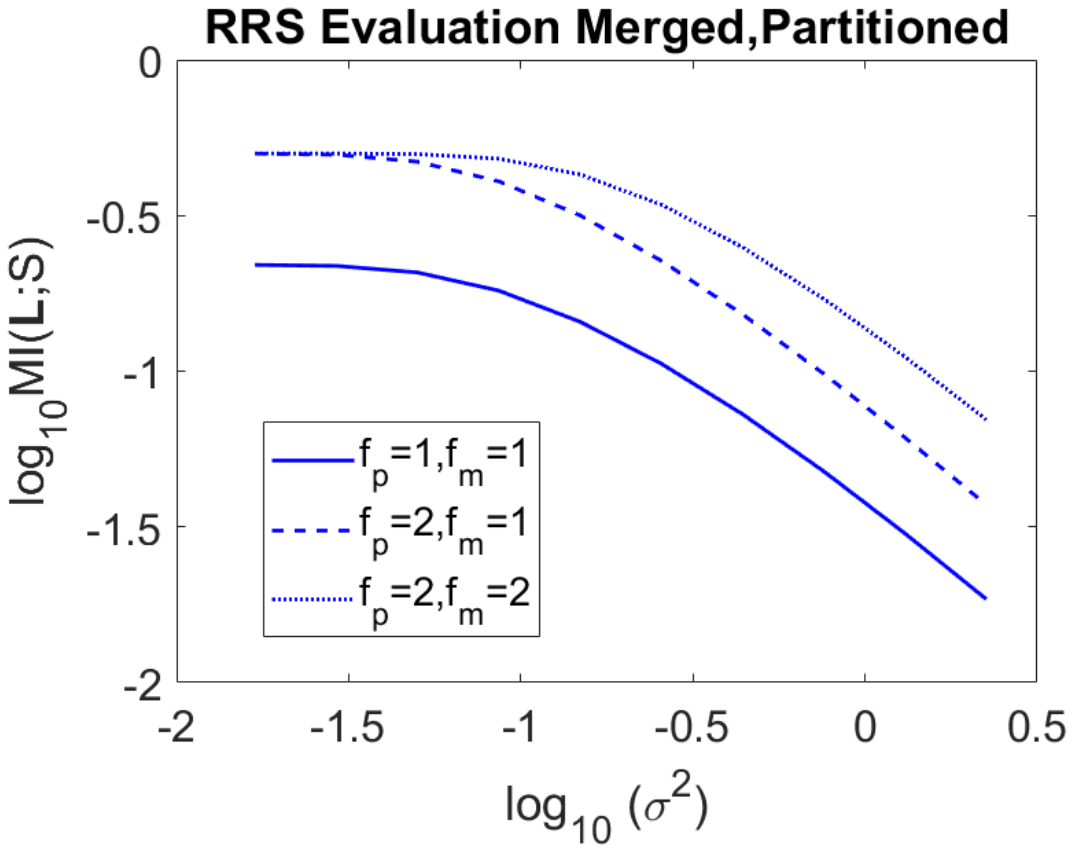

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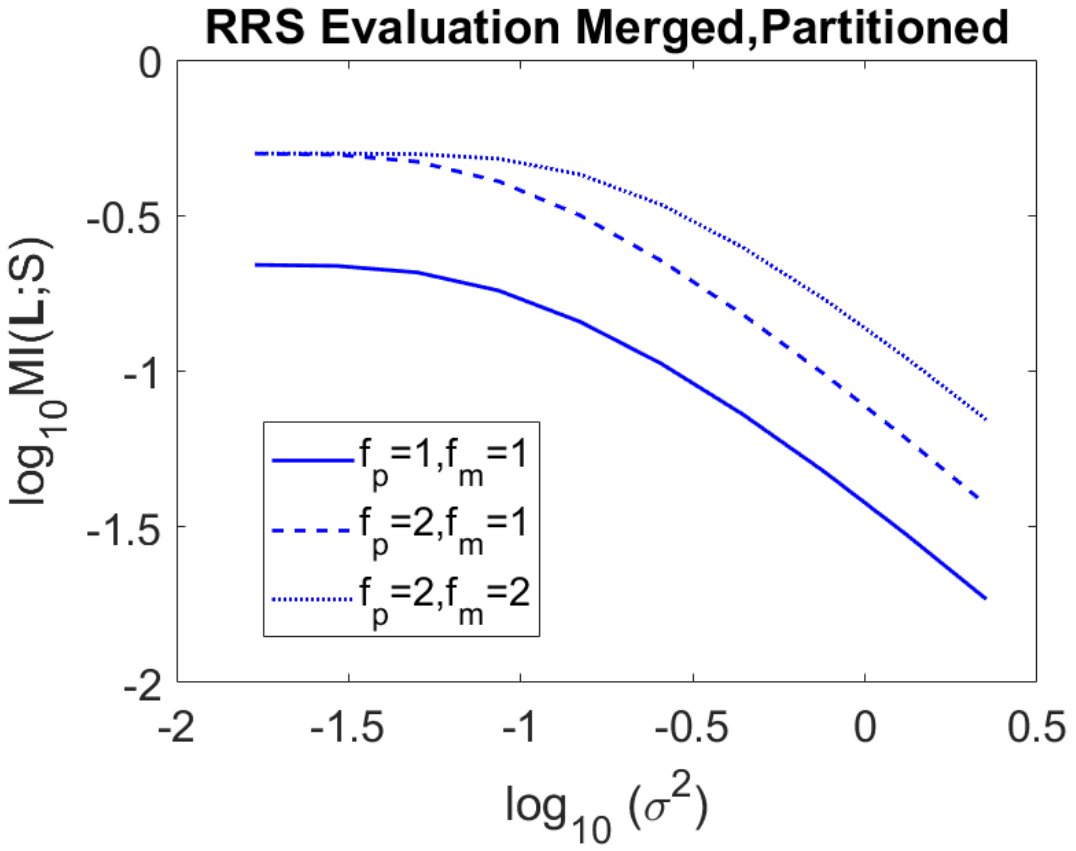

1. Partitioning or merging layers can reduce the randomness cost
2. Like RRM it damages the noise amplification stage of shuffling
3. **RRS is a tradeoff between security and randomness cost**

Future Directions

Towards parametric design for side-channel countermeasures

Future Directions: RNG

- We have demonstrated how to reduce the randomness cost in masking and shuffling

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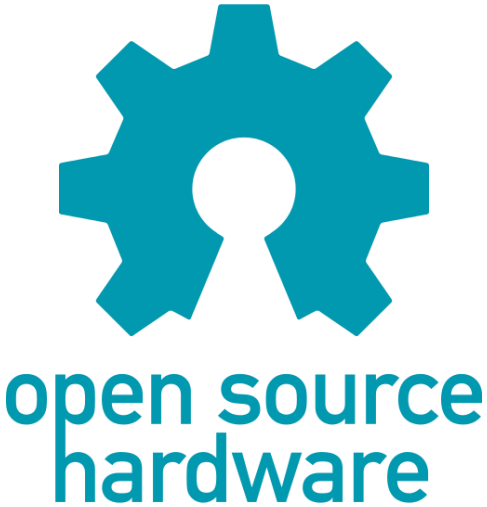
- Establish the required properties for a generator used in side-channel protection



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Athens Tower, 1971

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Athens Tower, 1971

Turning Torso Malmö, 2005