



Bitslice Masking and Improved Shuffling: How and When to Mix Them in Software?

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Contents

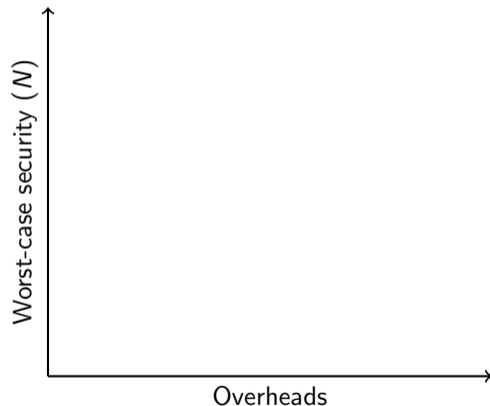
Introduction

Linear layers

Non-linear layers

Perf. vs security

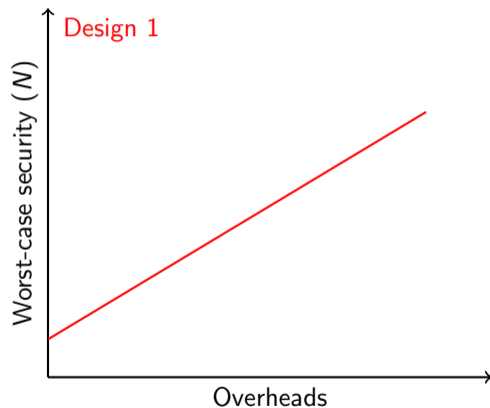
Design space for side-channel countermeasures



Countermeasures compared on:

- ▶ Run time overheads.
- ▶ Worst-case security (N).

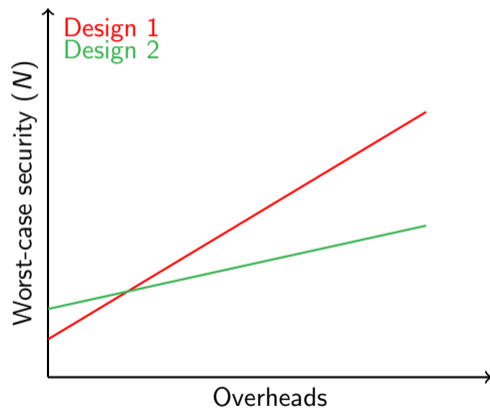
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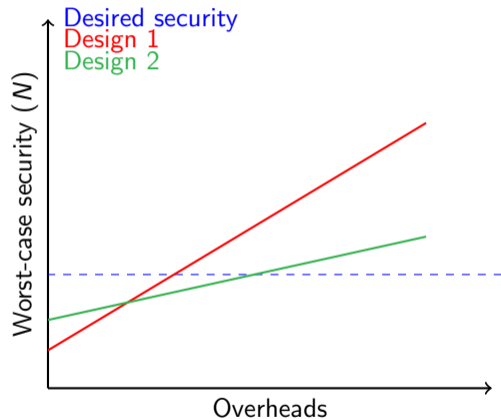
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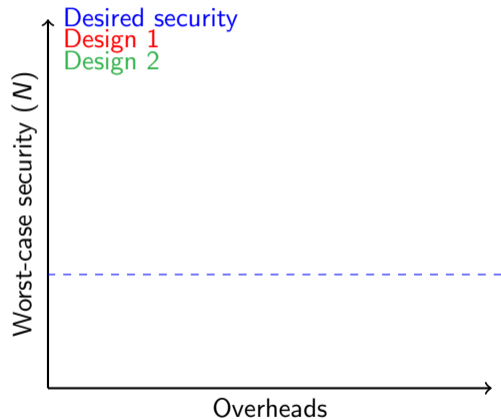


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→ Best design depends on desired security.

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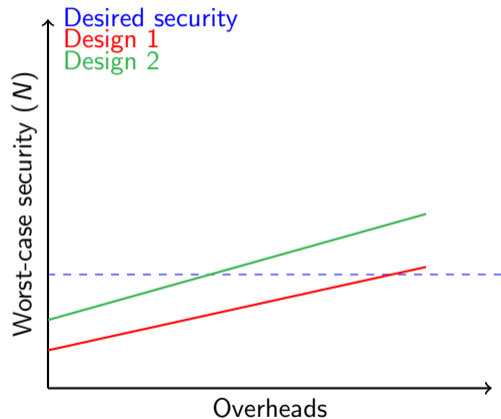
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Best design is device dependent:

- ▶ Noise level.
- ▶ Platform architecture.

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Existing side-channel countermeasures

$(MI(X; L) < 1)$

Masking:

- ▶ Randomized the data processed.
- ▶ Sharing of $x := (x^0, x^1, \dots, x^{d-1})$
- ▶ Noise amplification:

$$N \approx \frac{c}{\prod_i MI(X^i; L)} \approx \frac{c}{MI(X^i; L)^d}$$

- ▶ Data Layout:

0-th share	x^0
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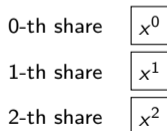
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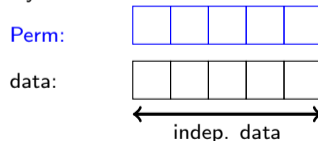
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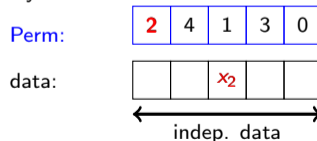
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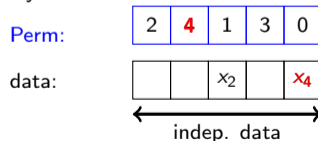
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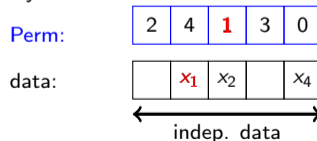
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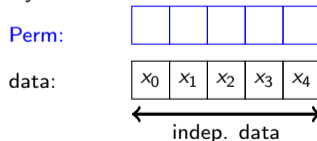
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→ **How to amplify shuffling thanks to masking ? (η^d)**

Design space for side-channel countermeasures

1. Security:

- ▶ Explore design space for shuffling + masking.
- ▶ Evaluate the security:
 - ▶ Paper & pencil.
 - ▶ Confirmed with simulations.

Rivain et al. [RPD09]:

- ▶ Linear layers: $\binom{d \cdot \eta}{d}$
- ▶ Non-linear layers: η

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- ▶ Benchmarks on Cortex-M4.

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3. Performances vs. security:

- ▶ Pertinence of masking and shuffling combination.

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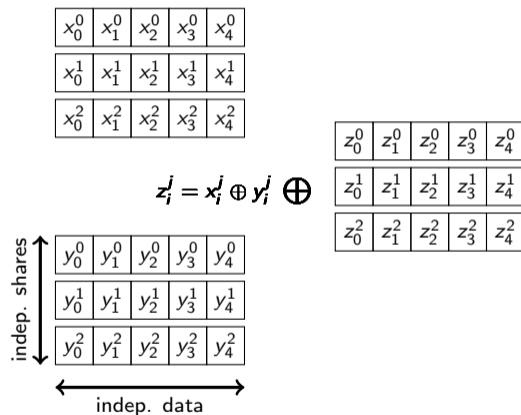
x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
x_0^2	x_1^2	x_2^2	x_3^2	x_4^2

Setting:

- ▶ $\eta = 5$ independent data x_j and y_j
- ▶ $d = 3$ shares x^i and y^i .

indep. shares ↑ ↓	y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
	y_0^1	y_1^1	y_2^1	y_3^1	y_4^1
	y_0^2	y_1^2	y_2^2	y_3^2	y_4^2
	← indep. data →				

Protecting masked linear layers



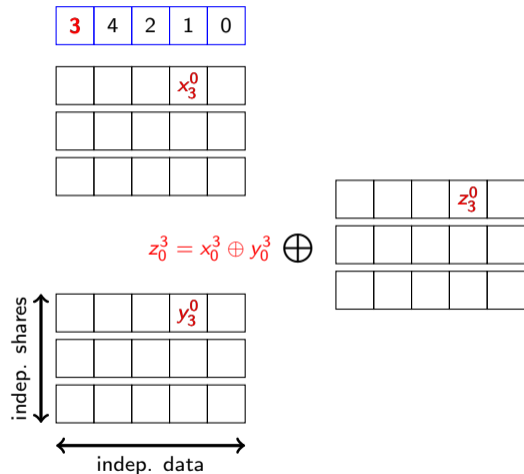
Setting:

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Goal:

- ▶ Compute all: $z_j^i = x_j^i \oplus y_j^i$

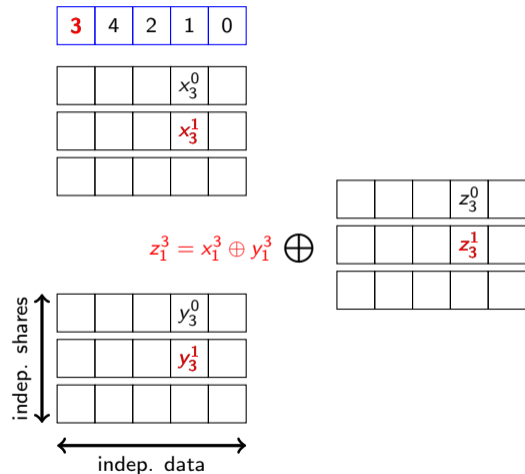
Shuffling-tuples on linear layers: description



Description:

- ▶ Shuffle between variables
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: η .

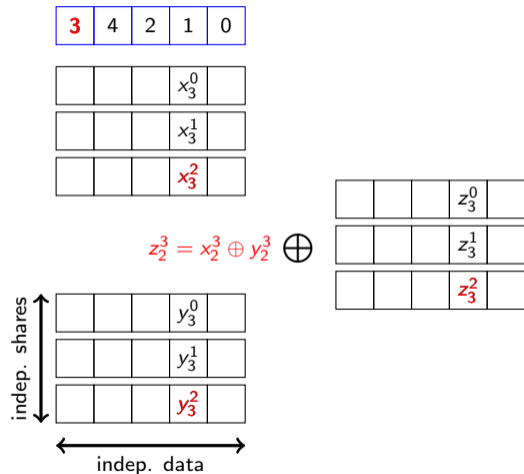
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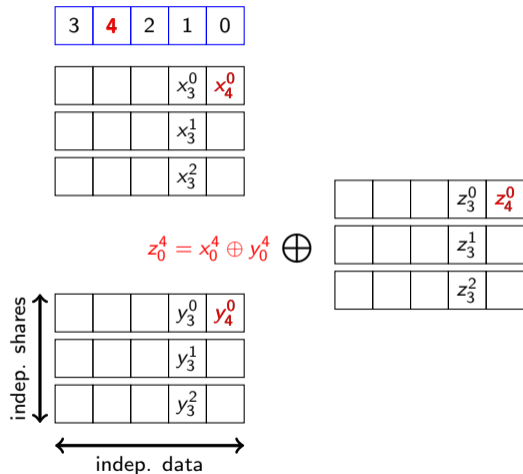
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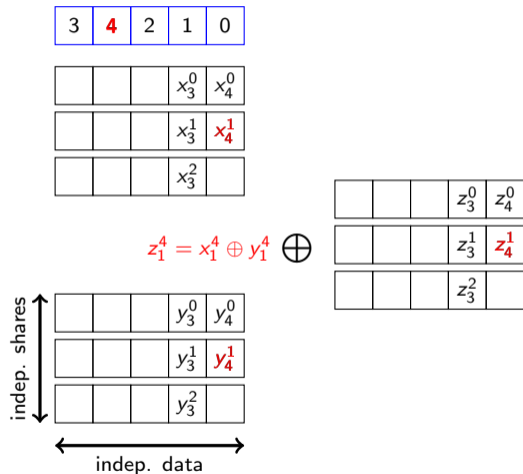
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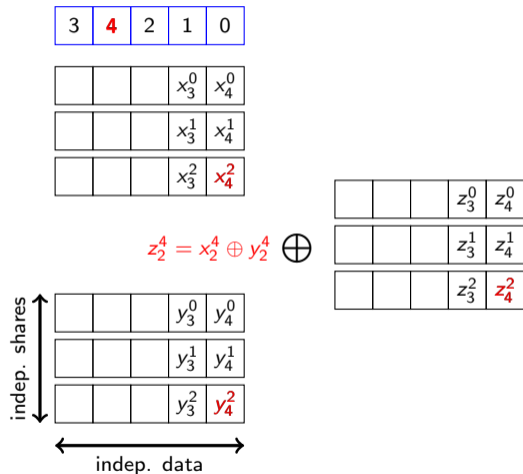
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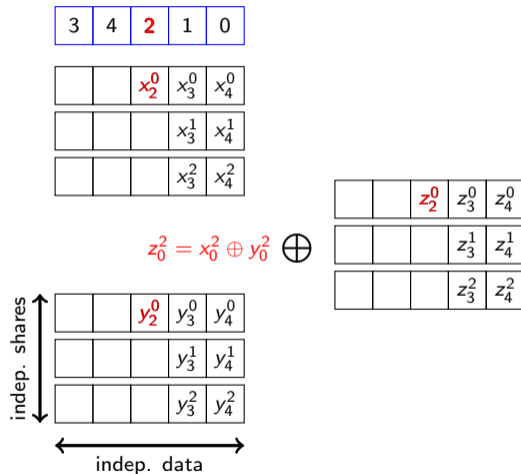
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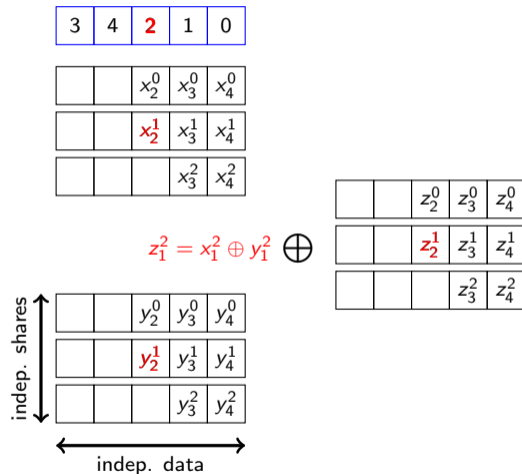
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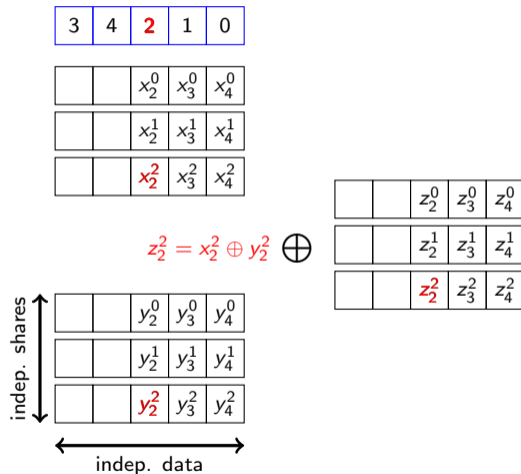
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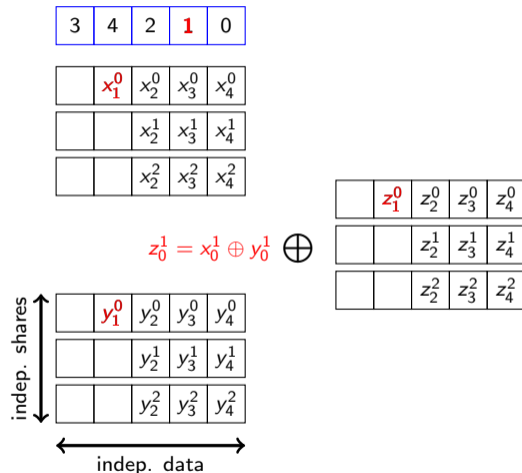
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Shuffling-tuples on linear layers: description

3	4	2	1	0
---	---	---	----------	---

	x_1^0	x_2^0	x_3^0	x_4^0
--	---------	---------	---------	---------

	x_1^1	x_2^1	x_3^1	x_4^1
--	---------------------------	---------	---------	---------

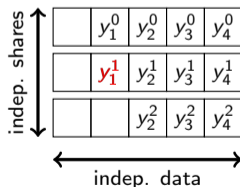
		x_2^2	x_3^2	x_4^2
--	--	---------	---------	---------

$$z_1^1 = x_1^1 \oplus y_1^1 \oplus$$

	z_1^0	z_2^0	z_3^0	z_4^0
--	---------	---------	---------	---------

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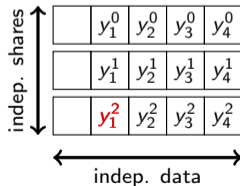
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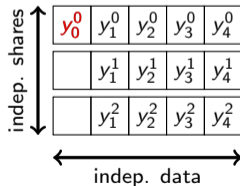
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$$z_0^0 = x_0^0 \oplus y_0^0 \oplus \bigoplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
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	z_1^1	z_2^1	z_3^1	z_4^1
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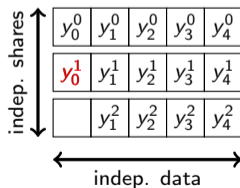
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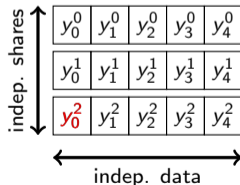
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Decrease $\text{MI}(X; L)$ by a factor η .

$$N \approx \frac{c \cdot \eta}{\prod_i \text{MI}(X^i; L)}$$

→ **Masking does not amplify shuffling.**

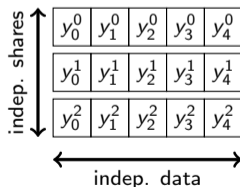
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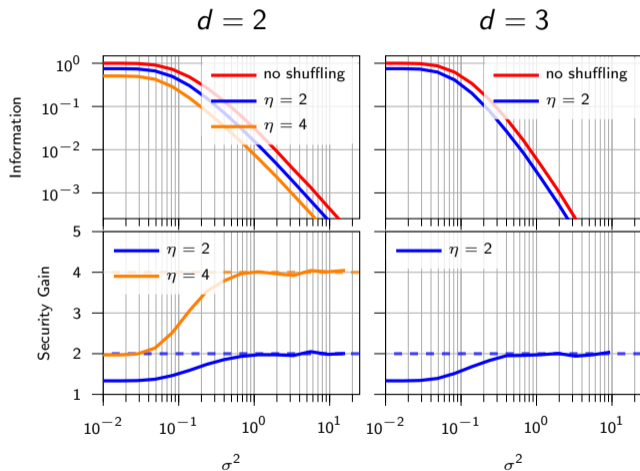
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$$N \approx \frac{c \cdot \eta}{\prod_i \text{MI}(X^i; L)}$$

→ **Masking does not amplify shuffling.**

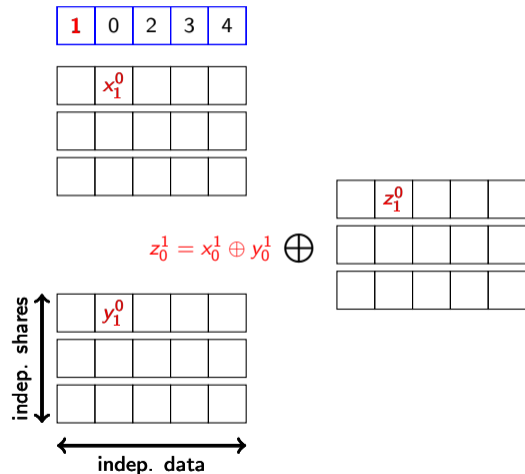
Shuffling-shares on linear layers: simulations



Expected security:

$$N \approx \frac{c \cdot \eta}{\prod_i \text{MI}(X^i; L)}$$

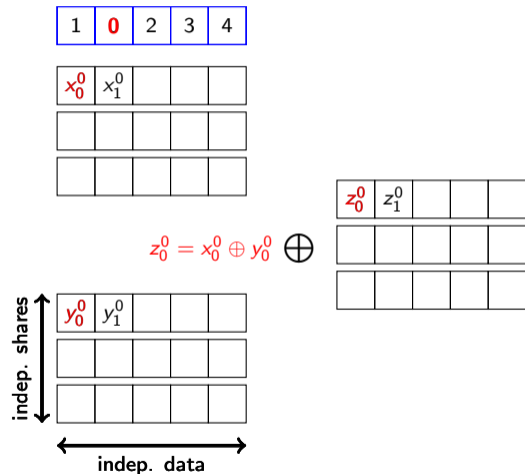
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

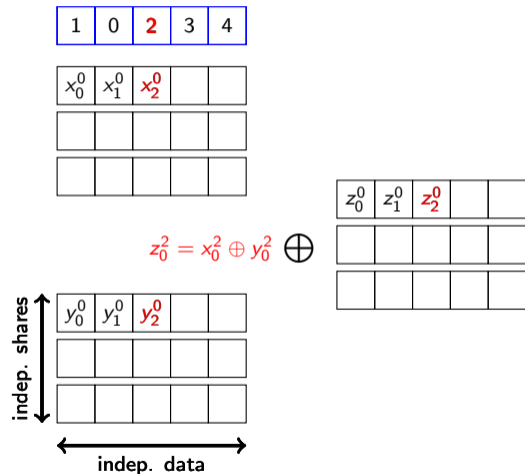
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

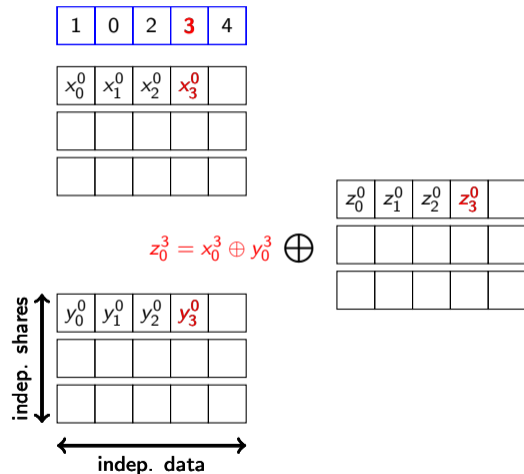
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

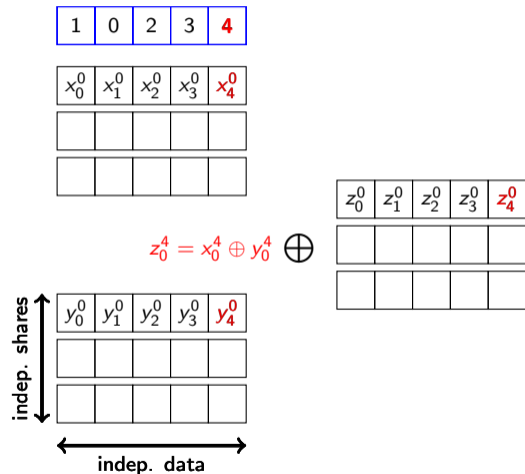
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

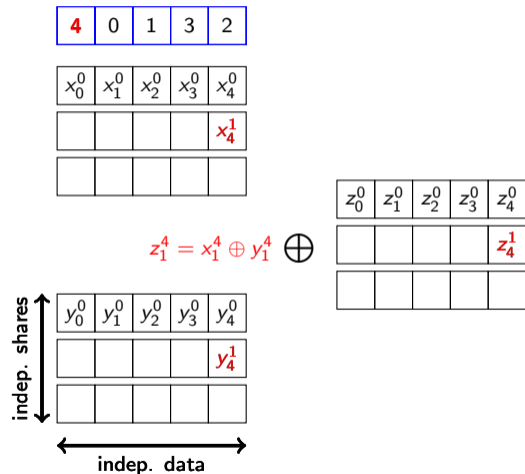
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

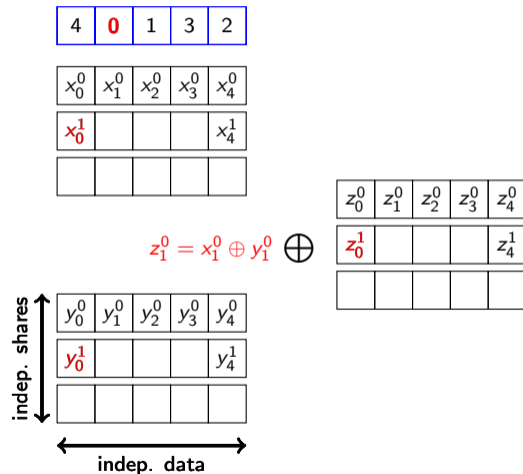
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

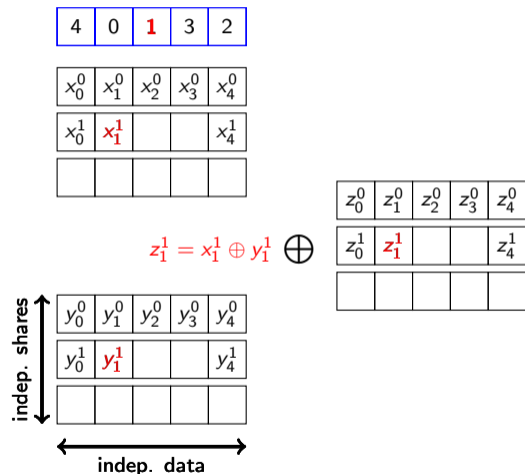
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

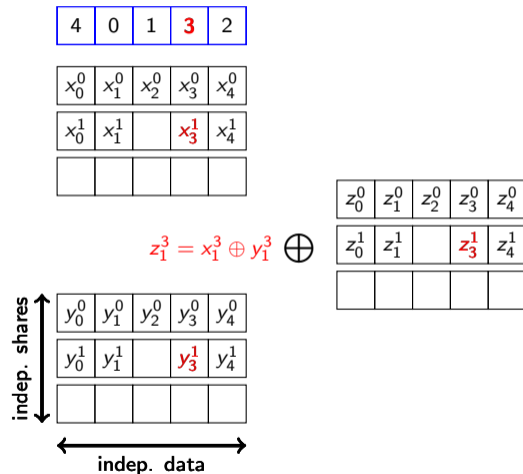
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

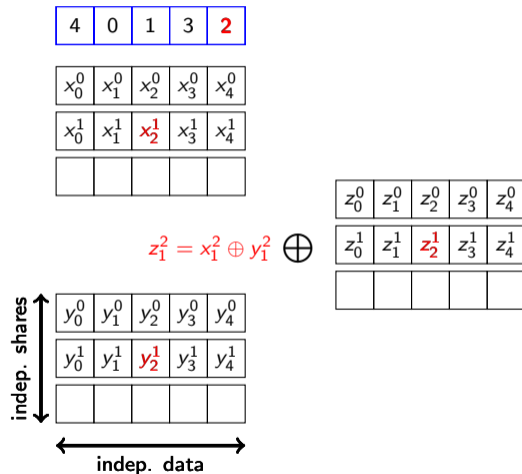
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

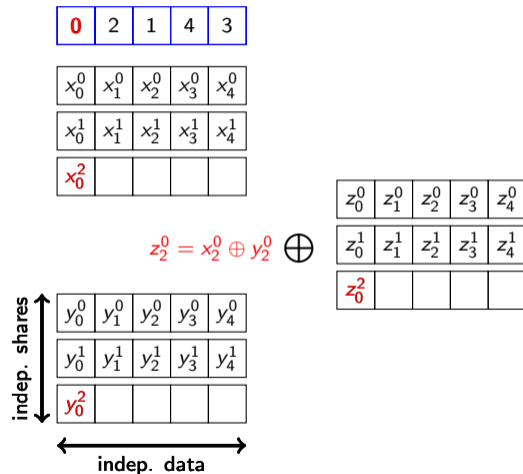
Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Shuffling-shares on linear layers: description



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Shuffling-shares on linear layers: description

0	2	1	4	3
---	---	---	---	---

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

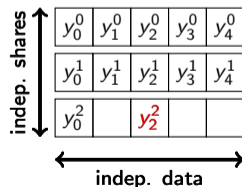
x_0^2		x_2^2		
---------	--	---------	--	--

$$z_2^2 = x_2^2 \oplus y_2^2 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2		z_2^2		
---------	--	---------	--	--



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Shuffling-shares on linear layers: description

0	2	1	4	3
---	---	---	---	---

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

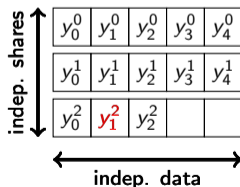
x_0^2	x_1^2	x_2^2		
---------	---------	---------	--	--

$$z_1^1 = x_2^1 \oplus y_2^1 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2	z_1^2	z_2^2		
---------	---------	---------	--	--



Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Shuffling-shares on linear layers: description

0	2	1	4	3
---	---	---	---	---

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

x_0^2	x_1^2	x_2^2		x_4^2
---------	---------	---------	--	---------

$$z_4^2 = x_2^2 \oplus y_2^2 \oplus \bigoplus$$

indep. shares	y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
	y_0^1	y_1^1	y_2^1	y_3^1	y_4^1
	y_0^2	y_1^2	y_2^2		y_4^2
	indep. data				

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2	z_1^2	z_2^2		z_4^2
---------	---------	---------	--	---------

Description:

- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Shuffling-shares on linear layers: description

0	2	1	4	3
---	---	---	---	---

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

x_0^2	x_1^2	x_2^2	x_3^2	x_4^2
---------	---------	---------	---------	---------

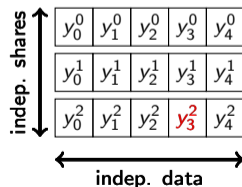
$$z_3^3 = x_3^2 \oplus y_2^3 \oplus$$



z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2	z_1^2	z_2^2	z_3^2	z_4^2
---------	---------	---------	---------	---------



Description:

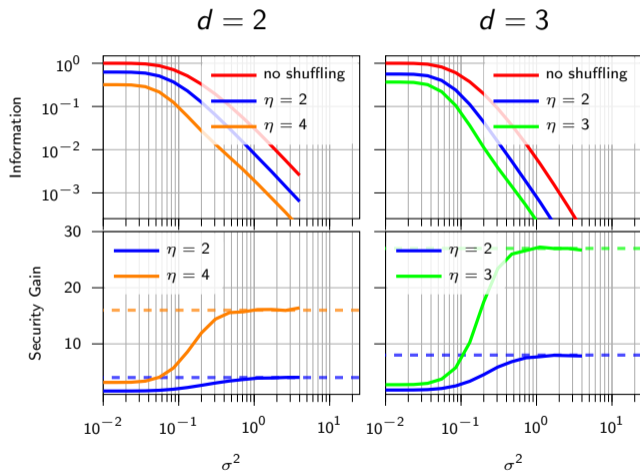
- ▶ Shuffle the i -th share of each x_j .
- ▶ Permutations:
 - ▶ Number: d .
 - ▶ Size: η .

Decrease $\text{MI}(X^i; L)$ by a factor η .

$$N \approx \frac{c}{\prod_i \text{MI}(X^i; L)/\eta} \approx \frac{c \cdot \eta^d}{\text{MI}(X^i; L)^d}$$

→ **Masking amplifies shuffling.**

Shuffling-shares on linear layers: simulations



Expected security:

$$N \approx \frac{c \cdot \eta^d}{\text{MI}(X^i; L)^d}$$

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

--	--	--	--	--

--	--	--	--	--

x_0^2				
---------	--	--	--	--

$$z_0^2 = x_0^2 \oplus y_0^2 \oplus$$

--	--	--	--	--

--	--	--	--	--

z_0^2				
---------	--	--	--	--

indep. shares

y_0^2				

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

	x_1^0			
--	---------	--	--	--

--	--	--	--	--

x_0^2				
---------	--	--	--	--

$$z_0^1 = x_0^1 \oplus y_0^1 \oplus$$

	z_1^0			
--	---------	--	--	--

--	--	--	--	--

z_0^2				
---------	--	--	--	--

indep. shares

	y_1^0			
y_0^2				

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

	x_1^0				x_4^0
--	---------	--	--	--	---------

--	--	--	--	--	--

x_0^2					
---------	--	--	--	--	--

$$z_0^4 = x_0^4 \oplus y_0^4 \oplus$$

	z_1^0				z_4^0
--	---------	--	--	--	---------

--	--	--	--	--	--

z_0^2					
---------	--	--	--	--	--

	y_1^0				y_4^0
y_0^2					

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

	x_1^0			x_4^0
--	---------	--	--	---------

				x_4^1
--	--	--	--	---------

x_0^2				
---------	--	--	--	--

$$z_1^4 = x_1^4 \oplus y_1^4 \oplus$$

	z_1^0			z_4^0
--	---------	--	--	---------

				z_4^1
--	--	--	--	---------

z_0^2				
---------	--	--	--	--

	y_1^0			y_4^0
				y_4^1
y_0^2				

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0			x_4^0
---------	---------	--	--	---------

				x_4^1
--	--	--	--	---------

x_0^2				
---------	--	--	--	--

$$z_0^0 = x_0^0 \oplus y_0^0 \oplus$$



z_0^0	z_1^0			z_4^0
---------	---------	--	--	---------

				z_4^1
--	--	--	--	---------

z_0^2				
---------	--	--	--	--

y_0^0	y_1^0			y_4^0
				y_4^1
y_0^2				

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0			x_4^0
---------	---------	--	--	---------

x_0^1				x_4^1
---------	--	--	--	---------

x_0^2				
---------	--	--	--	--

$$z_1^0 = x_1^0 \oplus y_1^0 \oplus$$

z_0^0	z_1^0			z_4^0
---------	---------	--	--	---------

z_0^1				z_4^1
---------	--	--	--	---------

z_0^2				
---------	--	--	--	--

y_0^0	y_1^0			y_4^0
y_0^1				y_4^1
y_0^2				

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0		x_4^0
x_0^1				x_4^1
x_0^2				

$$z_0^2 = x_0^2 \oplus y_0^2 \oplus$$

indep. shares

y_0^0	y_1^0	y_2^0		y_4^0
y_0^1				y_4^1
y_0^2				

indep. data

z_0^0	z_1^0	z_2^0		z_4^0
z_0^1				z_4^1
z_0^2				

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0		x_4^0
---------	---------	---------	--	---------

x_0^1				x_4^1
---------	--	--	--	---------

x_0^2				x_4^2
---------	--	--	--	---------

$$z_2^4 = x_2^4 \oplus y_2^4 \oplus$$

z_0^0	z_1^0	z_2^0		z_4^0
---------	---------	---------	--	---------

z_0^1				z_4^1
---------	--	--	--	---------

z_0^2				z_4^2
---------	--	--	--	---------

y_0^0	y_1^0	y_2^0		y_4^0
y_0^1				y_4^1
y_0^2				y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1				x_4^1
---------	--	--	--	---------

x_0^2				x_4^2
---------	--	--	--	---------

$$z_0^3 = x_0^3 \oplus y_0^3 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1				z_4^1
---------	--	--	--	---------

z_0^2				z_4^2
---------	--	--	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1				y_4^1
y_0^2				y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1			x_3^1	x_4^1
---------	--	--	---------	---------

x_0^2				x_4^2
---------	--	--	--	---------

$$z_1^3 = x_1^3 \oplus y_1^3 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1			z_3^1	z_4^1
---------	--	--	---------	---------

z_0^2				z_4^2
---------	--	--	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1			y_3^1	y_4^1
y_0^2				y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1			x_3^1	x_4^1
---------	--	--	---------	---------

x_0^2		x_2^2		x_4^2
---------	--	---------	--	---------

$$z_2^2 = x_2^2 \oplus y_2^2 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1			z_3^1	z_4^1
---------	--	--	---------	---------

z_0^2		z_2^2		z_4^2
---------	--	---------	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1			y_3^1	y_4^1
y_0^2		y_2^2		y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1		x_3^1	x_4^1
---------	---------	--	---------	---------

x_0^2		x_2^2		x_4^2
---------	--	---------	--	---------

$$z_1^1 = x_1^1 \oplus y_1^1 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1		z_3^1	z_4^1
---------	---------	--	---------	---------

z_0^2		z_2^2		z_4^2
---------	--	---------	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1	y_1^1		y_3^1	y_4^1
y_0^2		y_2^2		y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

x_0^2		x_2^2		x_4^2
---------	--	---------	--	---------

$$z_1^2 = x_1^2 \oplus y_1^2 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2		z_2^2		z_4^2
---------	--	---------	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1	y_1^1	y_2^1	y_3^1	y_4^1
y_0^2		y_2^2		y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

x_0^2	x_1^2	x_2^2		x_4^2
---------	---------	---------	--	---------

$$z_2^1 = x_2^1 \oplus y_2^1 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2	z_1^2	z_2^2		z_4^2
---------	---------	---------	--	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1	y_1^1	y_2^1	y_3^1	y_4^1
y_0^2	y_1^2	y_2^2		y_4^2

indep. shares

indep. data

Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

Shuffling-everything on linear layers: description

10	1	4	9	0		
	5	2	14	3	8	
		12	6	7	11	13

x_0^0	x_1^0	x_2^0	x_3^0	x_4^0
---------	---------	---------	---------	---------

x_0^1	x_1^1	x_2^1	x_3^1	x_4^1
---------	---------	---------	---------	---------

x_0^2	x_1^2	x_2^2	x_3^2	x_4^2
---------	---------	---------	---------	---------

$$z_2^3 = x_2^3 \oplus y_2^3 \oplus$$

z_0^0	z_1^0	z_2^0	z_3^0	z_4^0
---------	---------	---------	---------	---------

z_0^1	z_1^1	z_2^1	z_3^1	z_4^1
---------	---------	---------	---------	---------

z_0^2	z_1^2	z_2^2	z_3^2	z_4^2
---------	---------	---------	---------	---------

y_0^0	y_1^0	y_2^0	y_3^0	y_4^0
y_0^1	y_1^1	y_2^1	y_3^1	y_4^1
y_0^2	y_1^2	y_2^2	y_3^2	y_4^2

indep. shares

indep. data

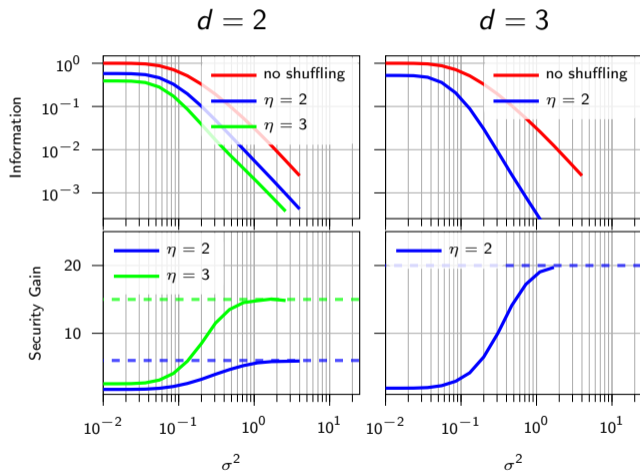
Description:

- ▶ Shuffle all the possible operations.
- ▶ Permutations:
 - ▶ Number: 1.
 - ▶ Size: $d \cdot \eta$.

$$N \approx \frac{c \cdot \binom{d \cdot \eta}{d}}{\prod_i \text{MI}(X^i; L)}$$

→ Masking amplifies shuffling.

Shuffling-everything on linear layers: simulations



Expected security:

$$N \approx \frac{c \cdot \binom{d \cdot \eta}{d}}{\prod_i \text{MI}(X^i; L)}$$

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Non-linear layers: summary of the results

For shuffled multiplications:

- ▶ Shuffling-shares and shuffling-tuples still apply with similar gain.
- ▶ Shuffling-everything could not be analyzed with paper & pencil:
 - ▶ Permutation on the output shares is not uniform.

	Linear layer			Non-linear layer		
	<i>Gain</i>	$\ \text{perm.}\ $	$\# \text{ perm.}$	<i>Gain</i>	$\ \text{perm.}\ $	$\# \text{ perm.}$
shuffling-tuples	η	η	1	η	η	1
shuffling-shares	η^d	η	d	η^d	η	d^2
shuffling-everything	$\binom{d \cdot \eta}{d}$	$d \cdot \eta$	1	?	?	?

Table: Summary of the shuffling + masking combinations.

Non-linear layers: summary of the results

For shuffled multiplications:

- ▶ Shuffling-shares and shuffling-tuples still apply with similar gain.
- ▶ Shuffling-everything could not be analyzed with paper & pencil:
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	Linear layer			Non-linear layer		
	<i>Gain</i>	$\ \text{perm.}\ $	$\# \text{ perm.}$	<i>Gain</i>	$\ \text{perm.}\ $	$\# \text{ perm.}$
shuffling-tuples	η	η	1	η	η	1
shuffling-shares	η^d	η	d	η^d	η	d^2
shuffling-everything	$\binom{d \cdot \eta}{d}$	$d \cdot \eta$	1	?	?	?

Table: Summary of the shuffling + masking combinations.

→ **Next focus on shuffling-shares.**

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Time versus security for shuffled ISW: open questions

Bitslice masking:

- ▶ Favors large #ANDs.
- ▶ Profits from parallelism.
- ▶ Randomness usage:

$$\#AND \cdot \frac{d \cdot (d - 1)}{2}$$

Time versus security for shuffled ISW: open questions

Bitslice masking:

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Shuffling:

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- ▶ Profits from serialization.
- ▶ Randomness usage:

$$d^2 \cdot \eta \cdot \log_2 \eta$$

Time versus security for shuffled ISW: open questions

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- ▶ Favors large #ANDs.
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- ▶ Favors large #ANDs.
- ▶ Profits from serialization.
- ▶ Randomness usage:

$$d^2 \cdot \eta \cdot \log_2 \eta$$

Challenges when protecting ISW:

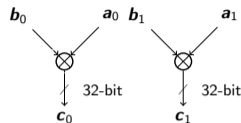
- ▶ Should we favor parallelism or serialization.
- ▶ Does it depend on the platform ?
- ▶ Does it depend on the primitive to protect ?

Time versus security for shuffled ISW: design space (#AND = 64)

Time versus security for shuffled ISW: design space (#AND = 64)

Option 1:

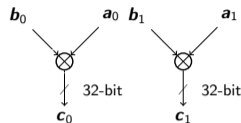
- ▶ Only bitsliced ISW.
- ▶ 32 bits per reg (full para.).



Time versus security for shuffled ISW: design space (#AND = 64)

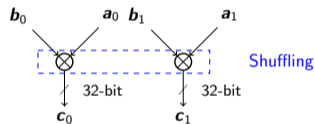
Option 1:

- ▶ Only bitsliced ISW.
- ▶ 32 bits per reg (full para.).



Option 2:

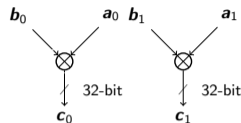
- ▶ Shuffled bitsliced ISW.
- ▶ 32 bits per reg (full para.).



Time versus security for shuffled ISW: design space (#AND = 64)

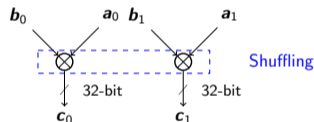
Option 1:

- ▶ Only bitsliced ISW.
- ▶ 32 bits per reg (full para.).



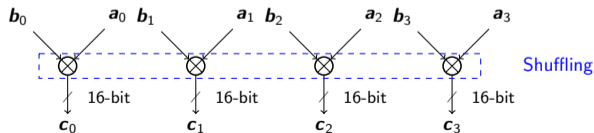
Option 2:

- ▶ Shuffled bitsliced ISW.
- ▶ 32 bits per reg (full para.).

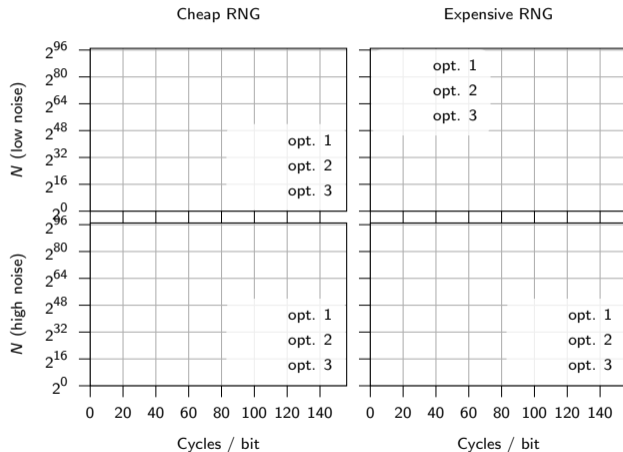


Option 3:

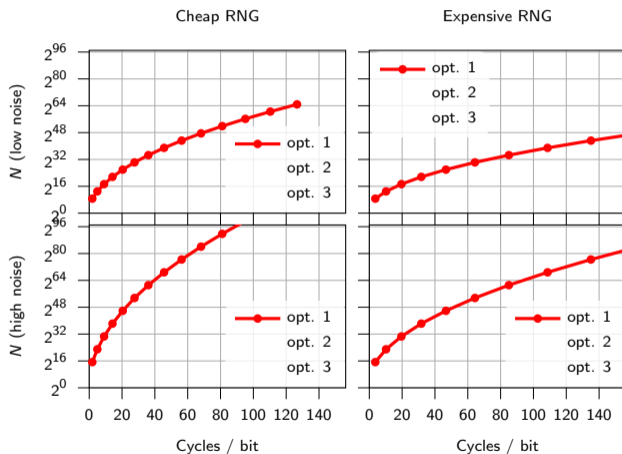
- ▶ Shuffled bitsliced ISW.
- ▶ 16 bits per reg (inc. ser.).



Time versus security: experimental results

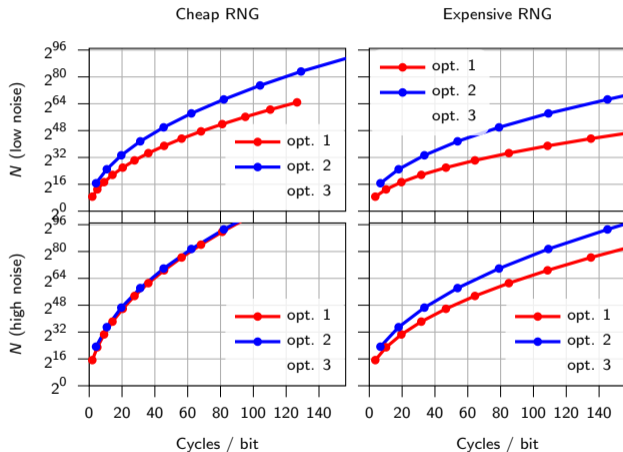


Time versus security: experimental results



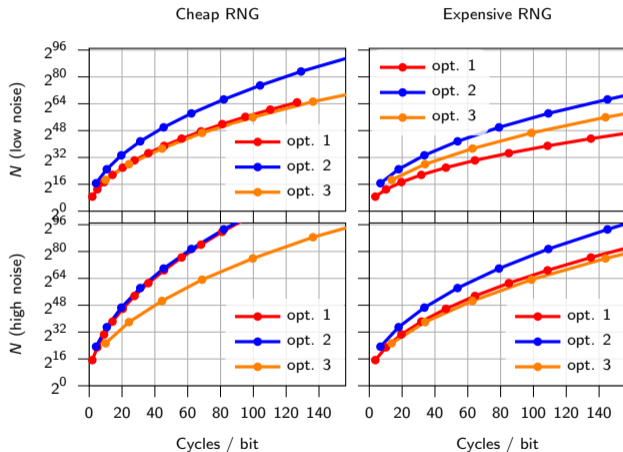
Opt 1: mask. only

Time versus security: experimental results



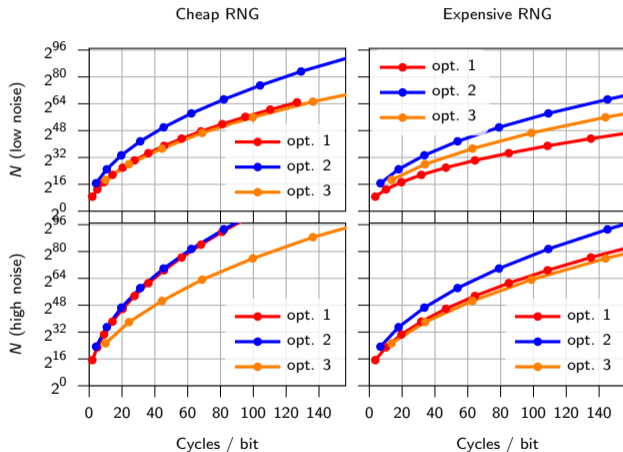
Opt 1: mask. only
 Opt 2: mask. & shuffl.

Time versus security: experimental results



Opt 1: mask. only
 Opt 2: mask. & shuffl.
 Opt 3: lager perm.

Time versus security: experimental results



Opt 1: mask. only
 Opt 2: mask. & shuffl.
 Opt 3: lager perm.

Take home:
 Use fully the registers
 and then shuffle.

General conclusion for masking and shuffling combination

General conclusion for masking and shuffling combination

General conclusion for masking and shuffling combination

Masking or Masking + shuffling:

- ▶ : masking is faster.
- ▶ : masking + shuffling is faster.

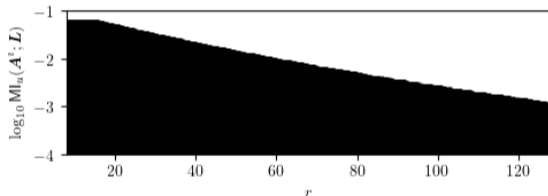


Figure: #AND=128, $N = 2^{64}$

General conclusion for masking and shuffling combination

Masking or Masking + shuffling:

- ▶ : masking is faster.
- ▶ : masking + shuffling is faster.

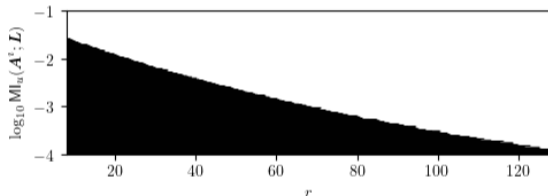


Figure: #AND=256, $N = 2^{64}$

General conclusion for masking and shuffling combination

Masking or Masking + shuffling:

- ▶ : masking is faster.
- ▶ : masking + shuffling is faster.

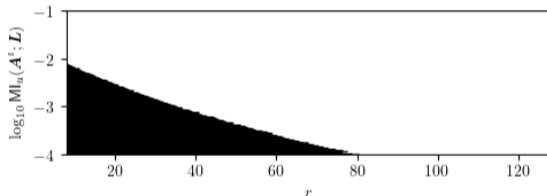


Figure: #AND=512, $N = 2^{64}$

General conclusion for masking and shuffling combination

Masking or Masking + shuffling:

- ▶ : masking is faster.
- ▶ : masking + shuffling is faster.

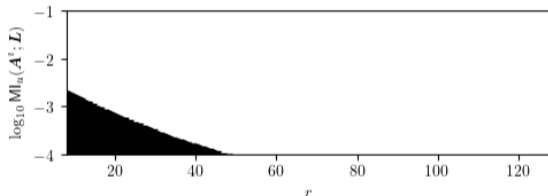


Figure: #AND=1024, $N = 2^{64}$

General conclusion for masking and shuffling combination

When to favor shuffling + masking:

- ▶ large of independent $\#AND$.
- ▶ expensive randomness r .
- ▶ relatively low noise.

Masking or Masking + shuffling:

- ▶ : masking is faster.
- ▶ : masking + shuffling is faster.

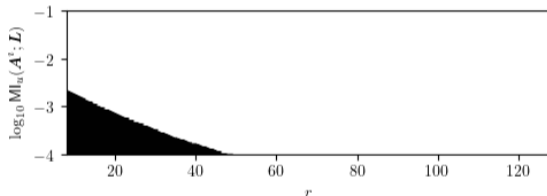


Figure: $\#AND=1024$, $N = 2^{64}$

General conclusion for masking and shuffling combination

When to favor shuffling + masking:

- ▶ large of independent $\#AND$.
- ▶ expensive randomness r .
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Thanks !

Masking or Masking + shuffling:

- ▶ \blacksquare : masking is faster.
- ▶ \square : masking + shuffling is faster.

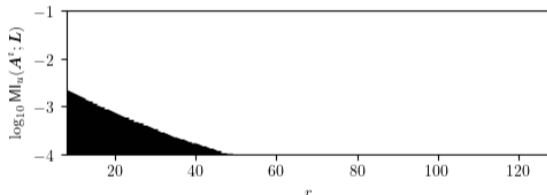


Figure: $\#AND=1024$, $N = 2^{64}$

https://github.com/uclcrypto/bitslice_masking_and_shuffling