CryptoExperts

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The relevance and challenges of random probing security for post-quantum algorithms

Application to Raccoon Signature Scheme

Mélissa Rossi

Journées du GDR-Sécurité, Caen, 24/06/2025

Based on the paper *New Techniques for Random Probing Security and Application to Raccoon Signature Scheme*
S. Belaïd, M. Rivain and M. Rossi, published in Eurocrypt 2025, https://eprint.iacr.org/2025/278

1) The relevance of the random probing model

2) Scaling up is a big challenge

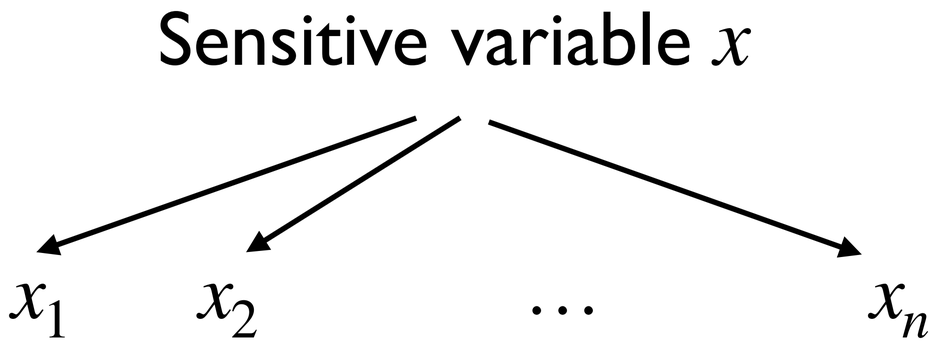
3) Random-probing Raccoon

1) The relevance of the random probing model

2) Scaling up is a big challenge

3) Random-probing Raccoon

Masking



Each strict subset of $(x_i)_{1 \leq i \leq n}$ is independent from x

$$x_1, x_2, \ldots, x_{n-1} \leftarrow \$$$

$$x_n \leftarrow x - (x_1 + x_2 + \ldots + x_{n-1})$$

Masking in Practice

- Masking linear operations

$$x = x_1 + x_2 + \ldots + x_n$$
$$y = y_1 + y_2 + \ldots + y_n$$

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- Masking non linear operations
  - Cannot be done share by share
  - Example of multiplication for $n = 2$

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$$x = x_1 + x_2 \qquad z_1 \leftarrow x_1 y_1 + x_1 y_2$$
$$y = y_1 + y_2 \qquad z_2 \leftarrow x_2 y_2 + x_2 y_1$$

Masking in Practice

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- Masking non linear operations
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  - Example of multiplication for $n = 2$

$$x = x_1 + x_2 \qquad z_1 \leftarrow x_1 y_1 + r + x_1 y_2$$
$$y = y_1 + y_2 \qquad z_2 \leftarrow x_2 y_2 - r + x_2 y_1$$

From a gadget to a circuit

x_1 x_2 k_1 k_2

A Multiplication gadget

$$z_1 + z_2 = (x_1 + x_2) \cdot (k_1 + k_2)$$

$$r \leftarrow \$$$
$$z_1 \leftarrow x_1 k_1 + r$$
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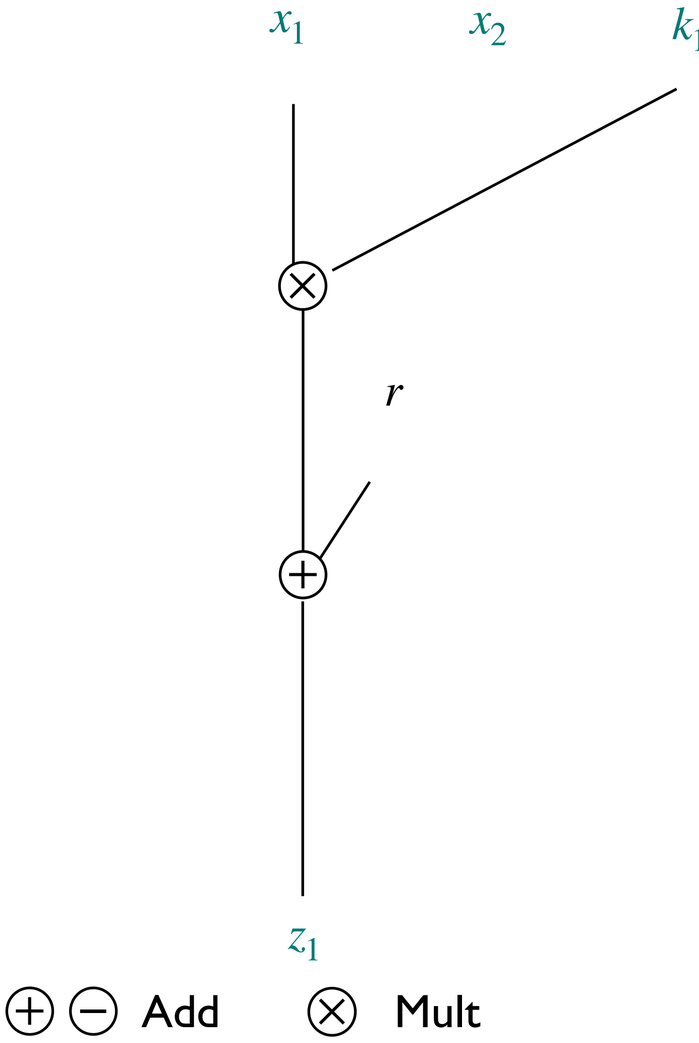

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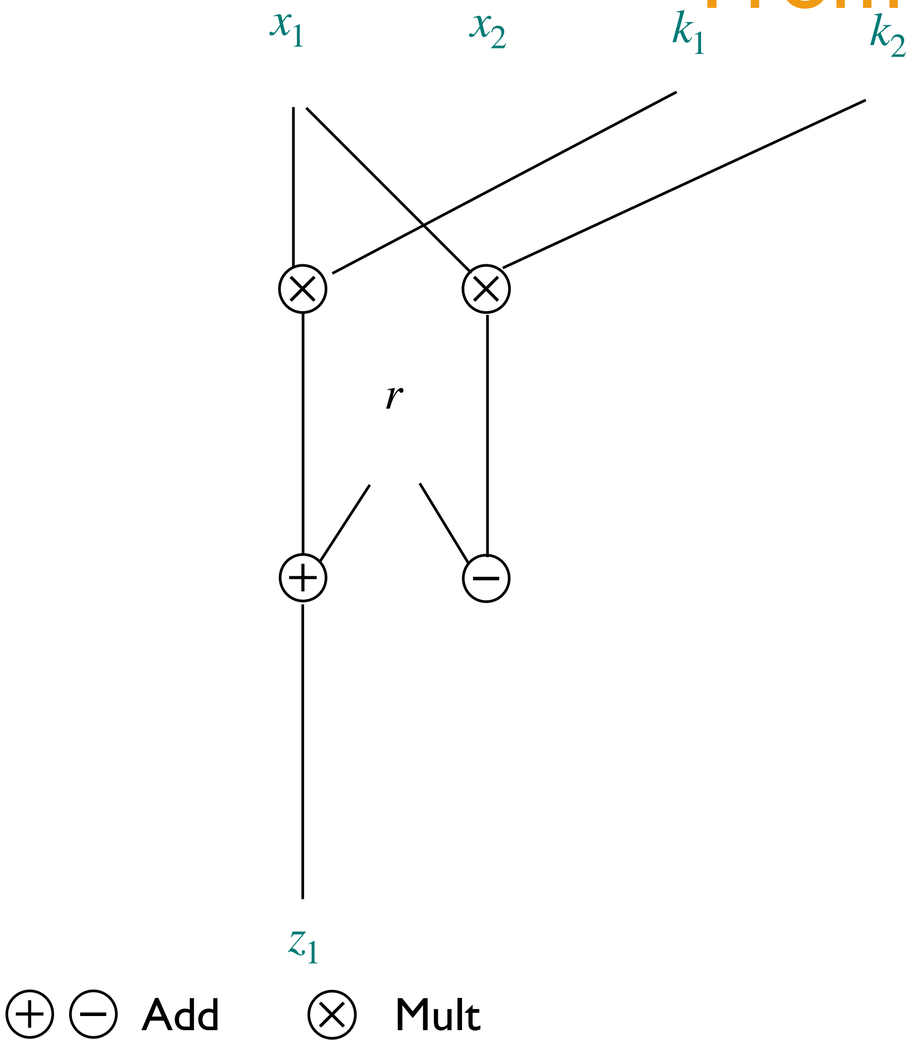

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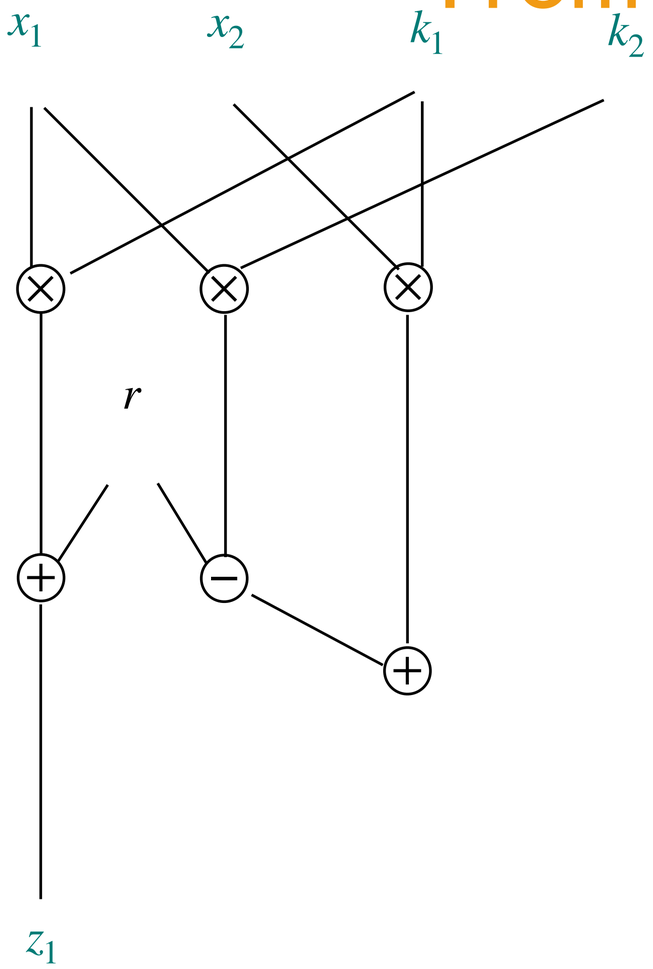

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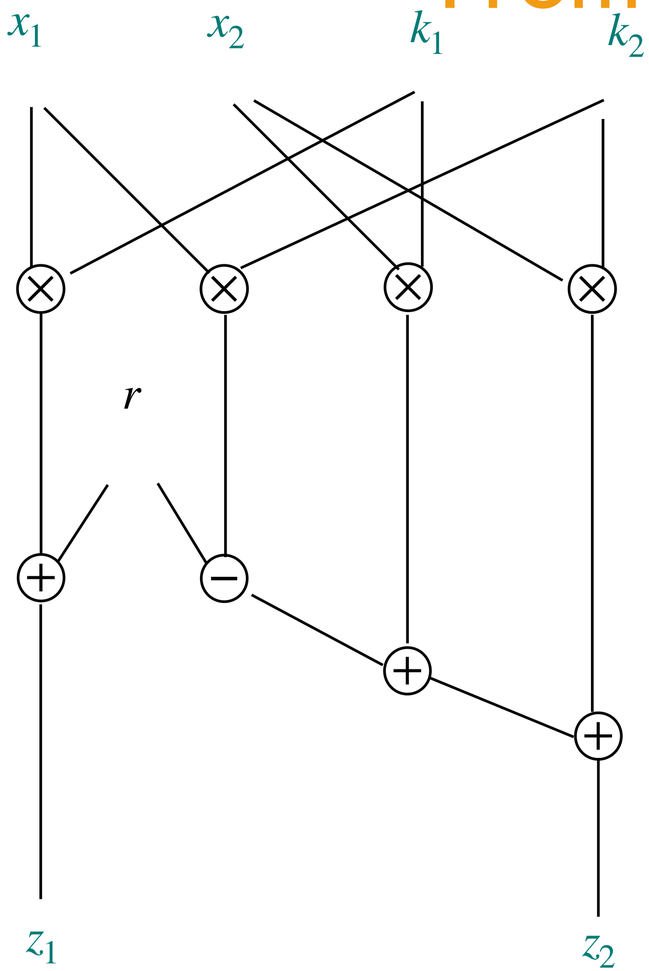

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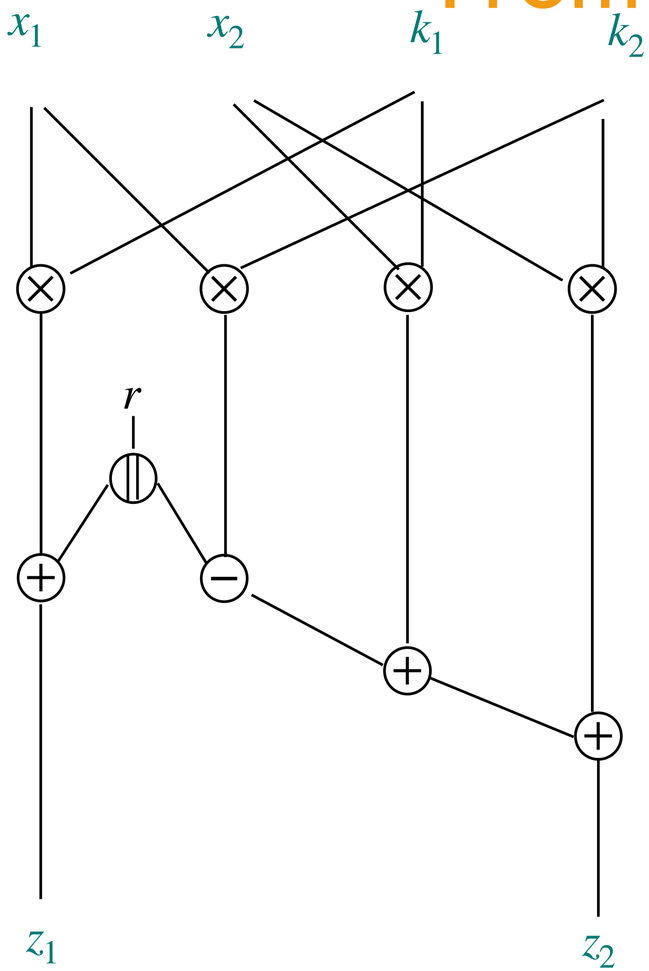

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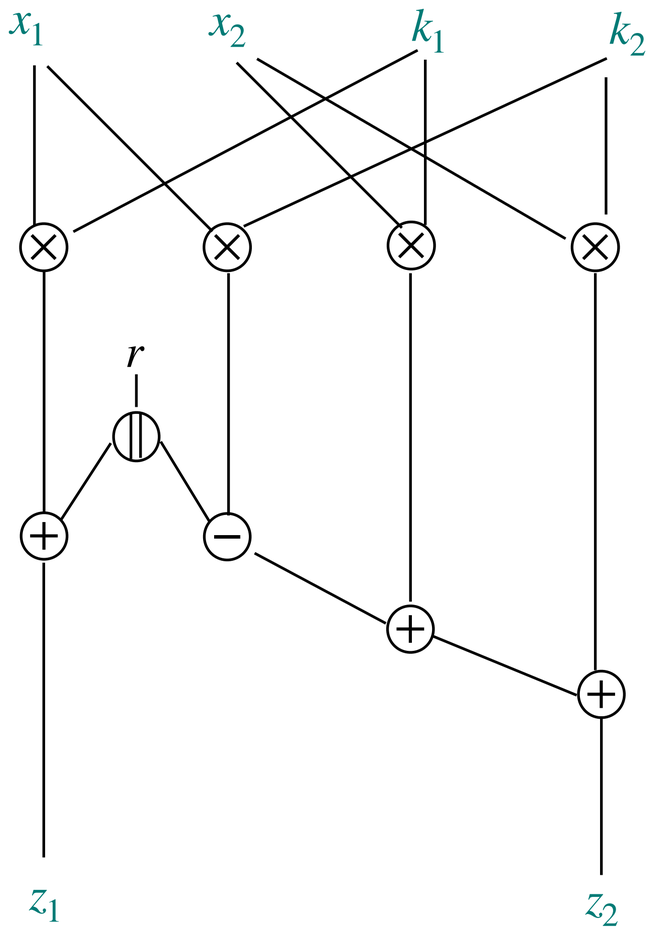
Leakage Models

Attacker view



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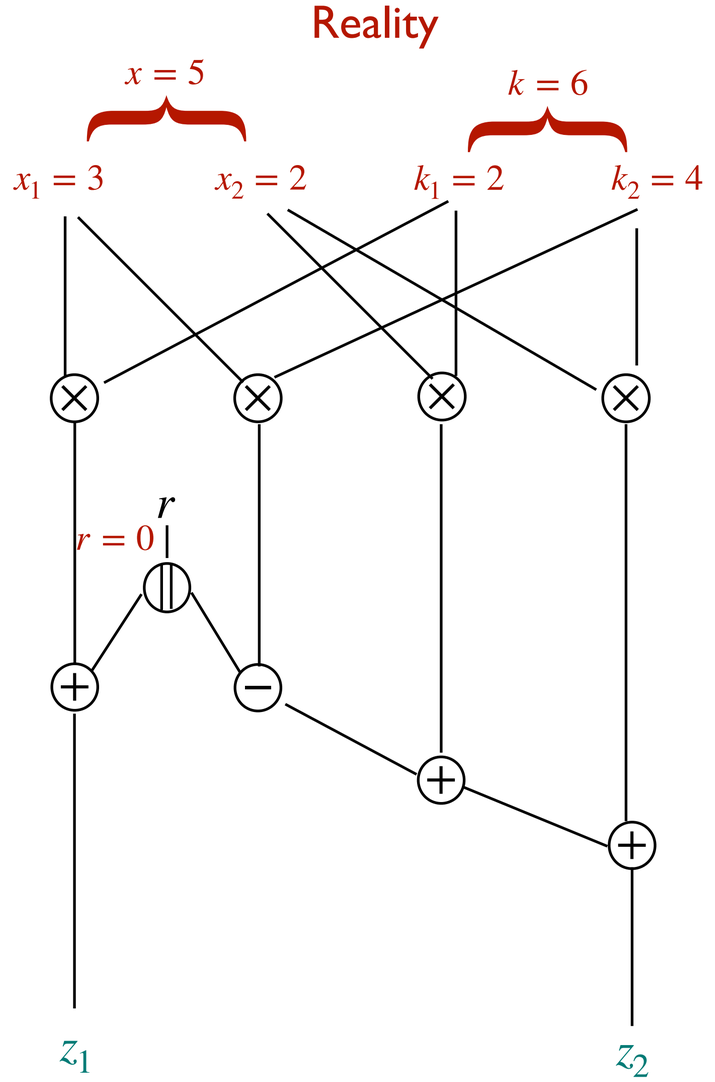

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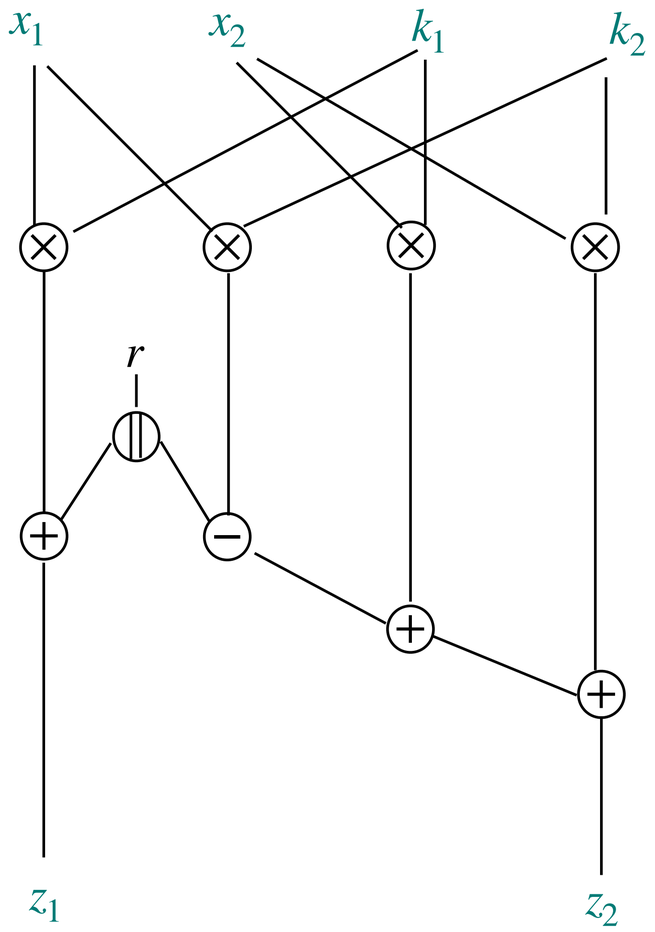

Attacker model

The attacker ← circuit + leakage

He/she must not recover any information about $x = \sum x_i$ and $k = \sum k_i$.

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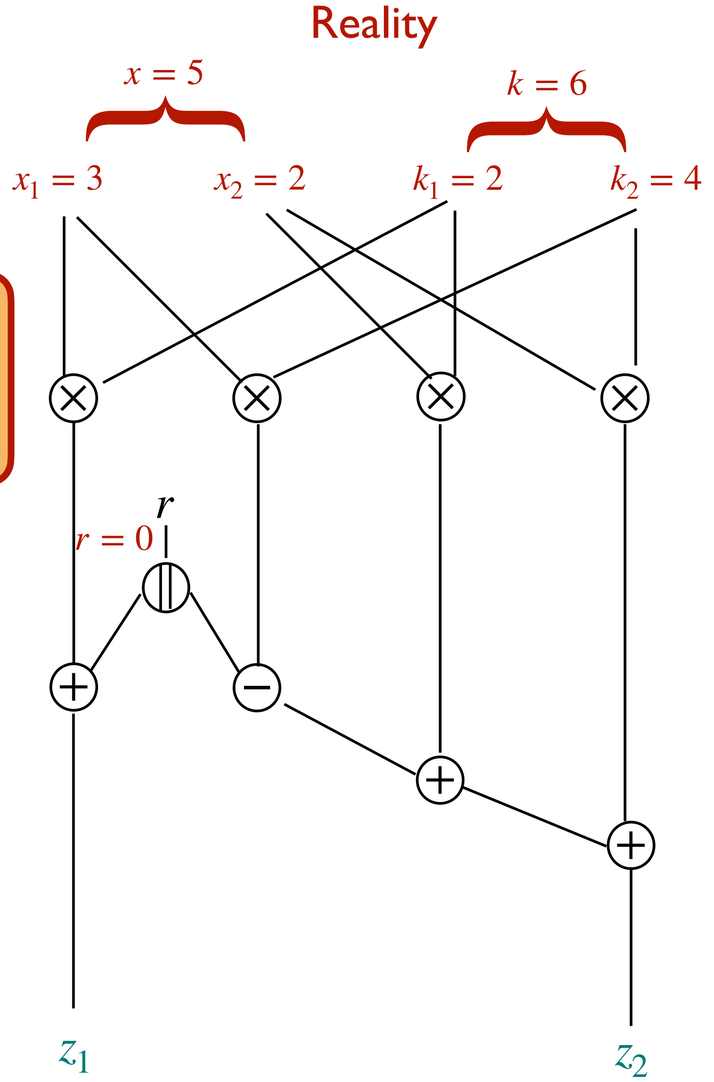

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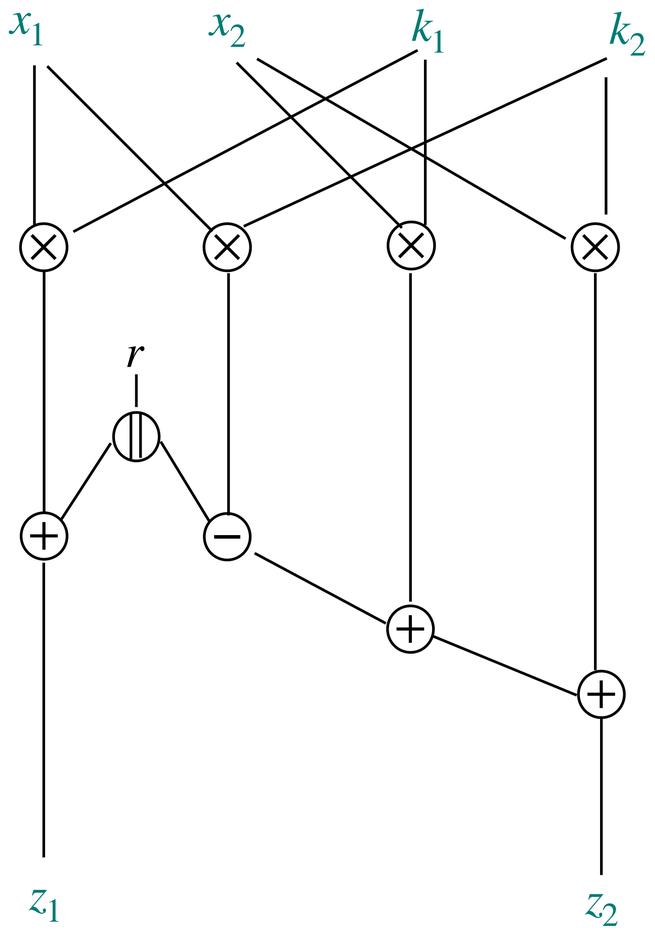

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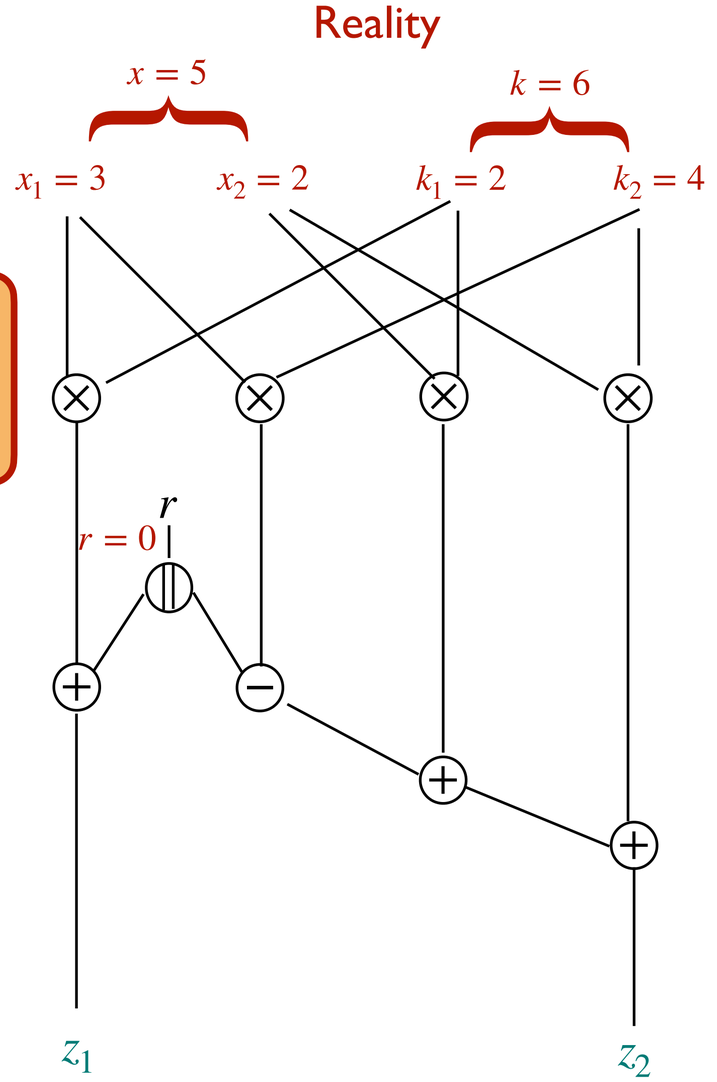

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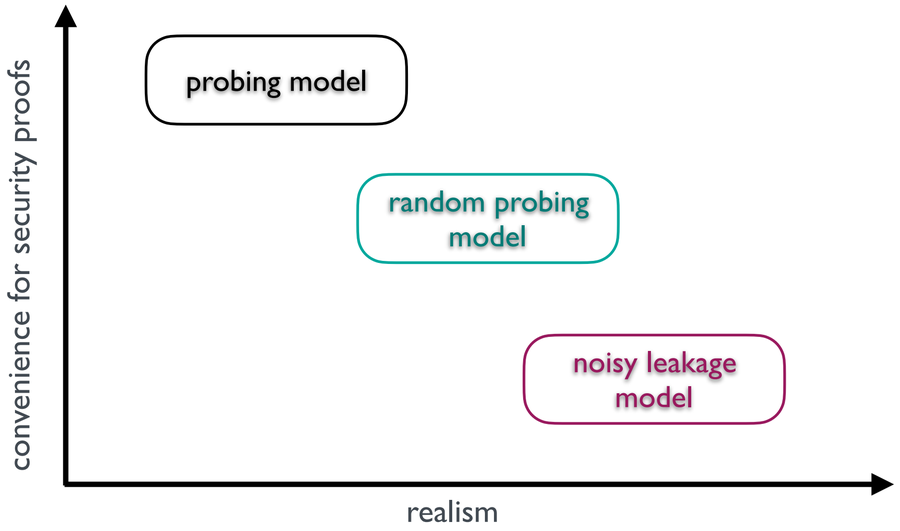

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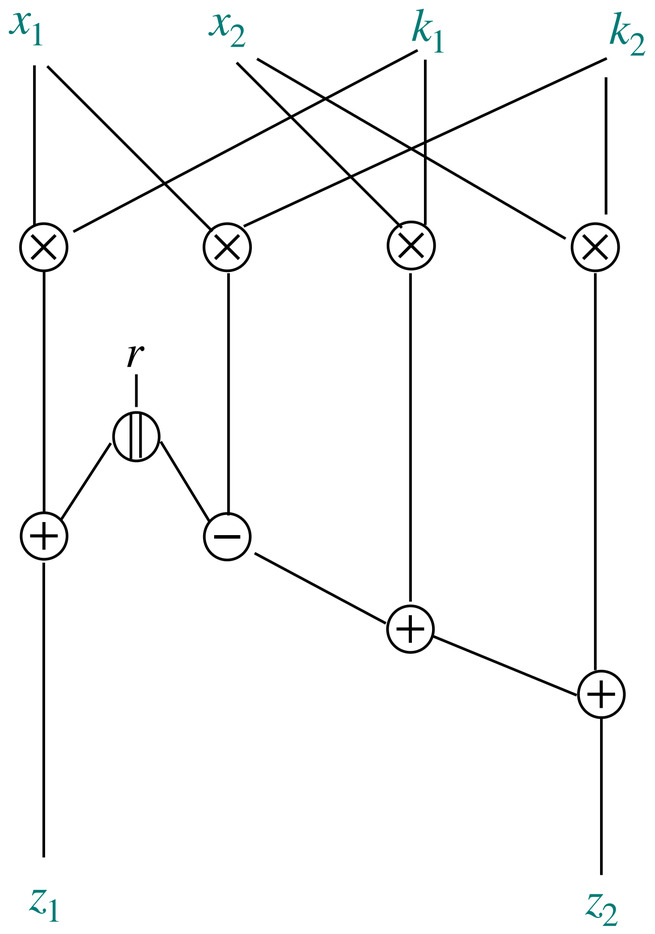

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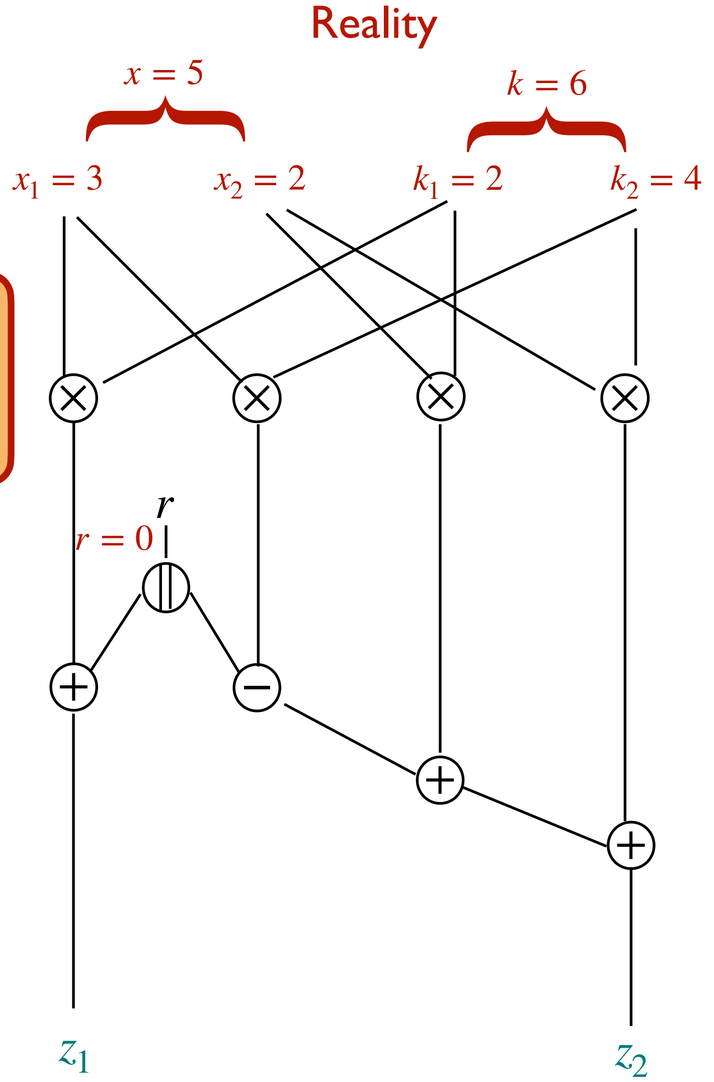

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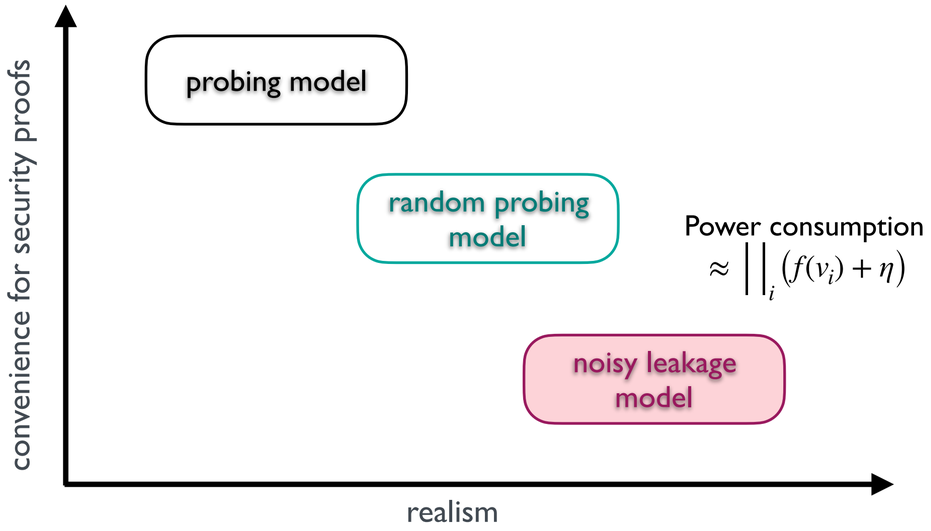

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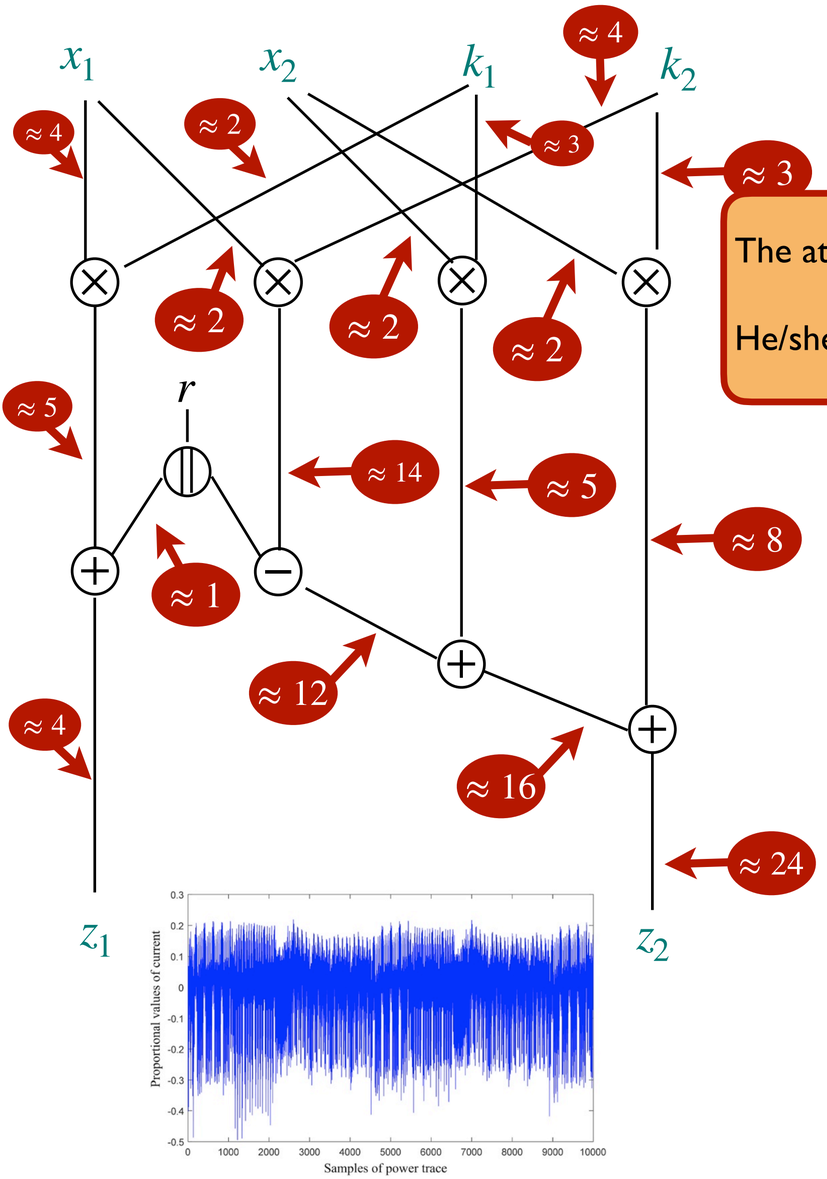

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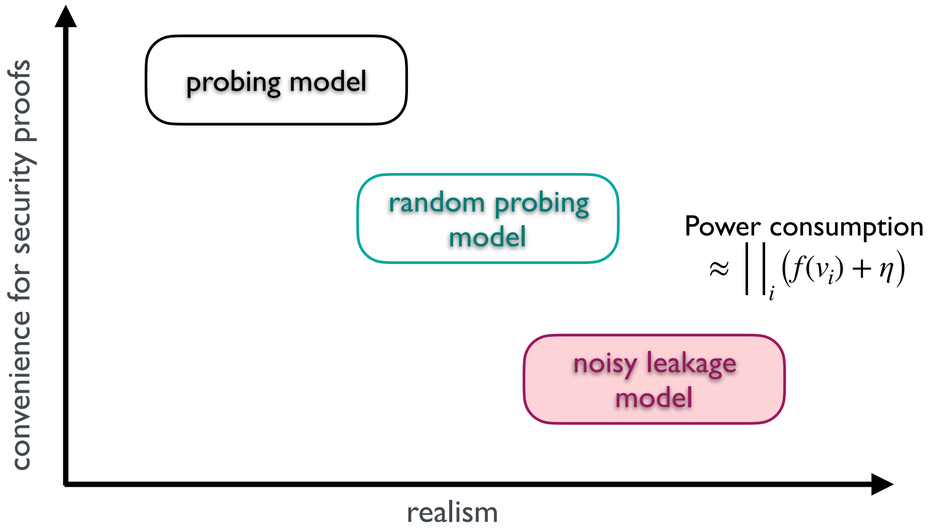

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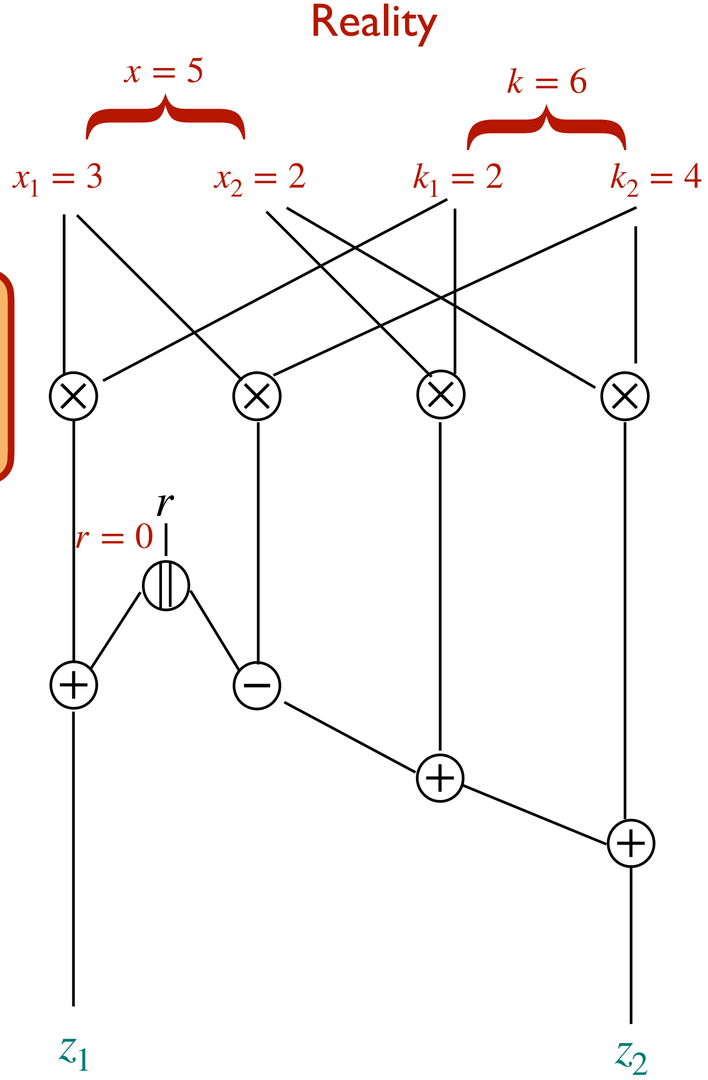

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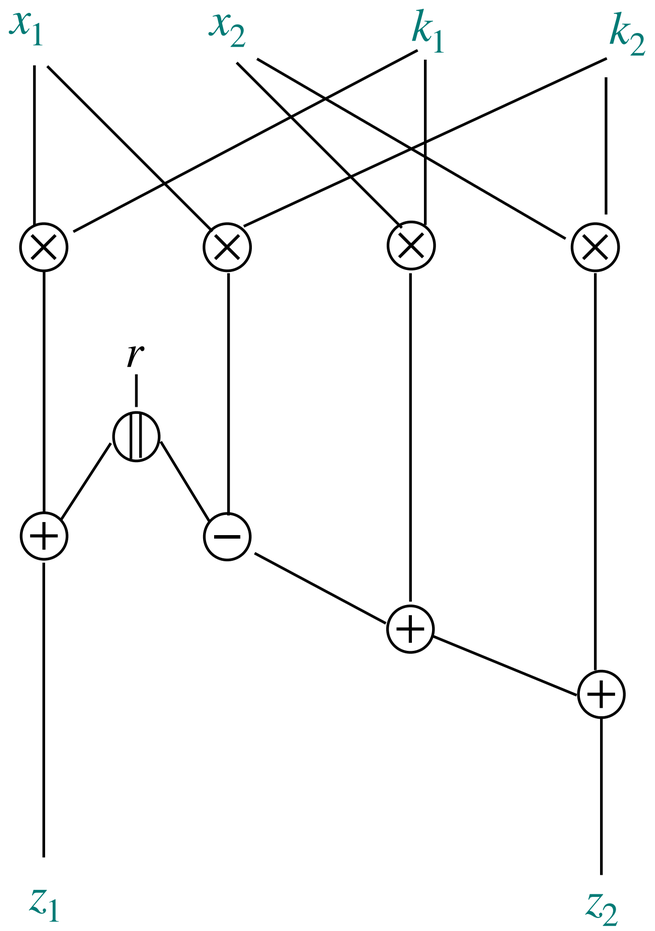

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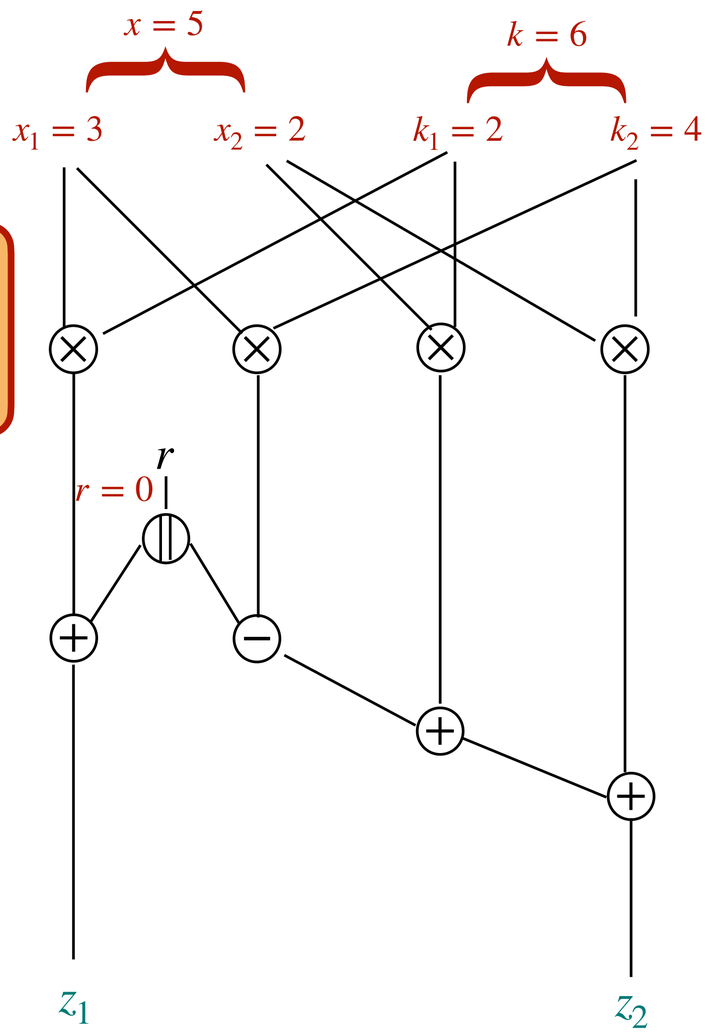

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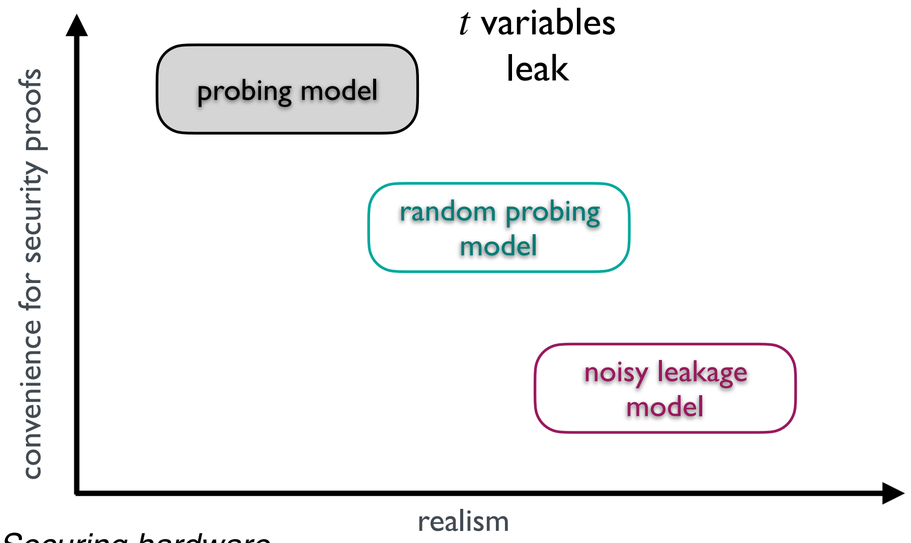

[ISW03] Y. Ishai, A. Sahai, and D. Wagner. *Private circuits: Securing hardware against probing attacks*. CRYPTO 2003

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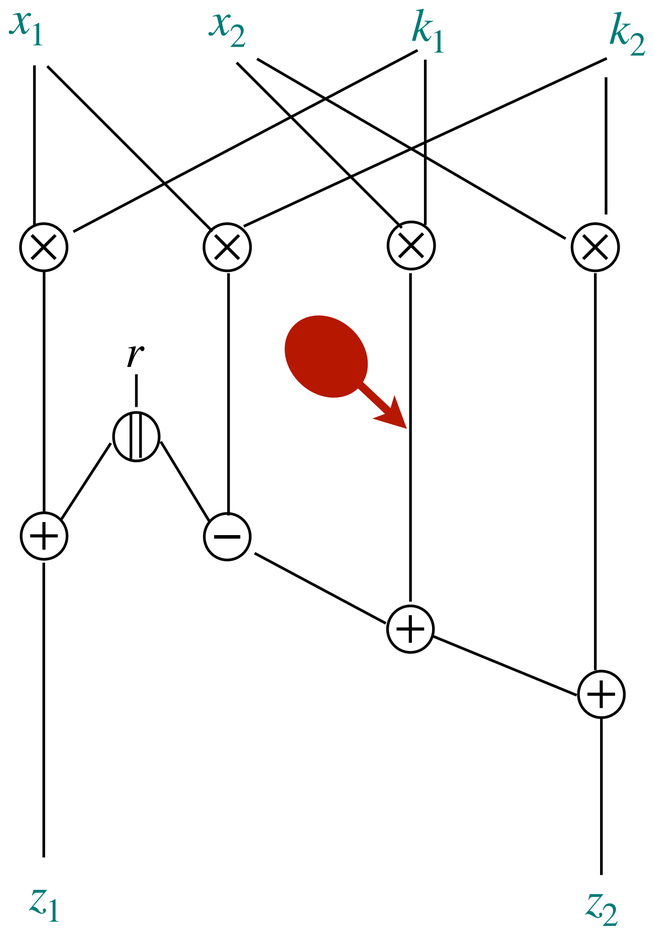

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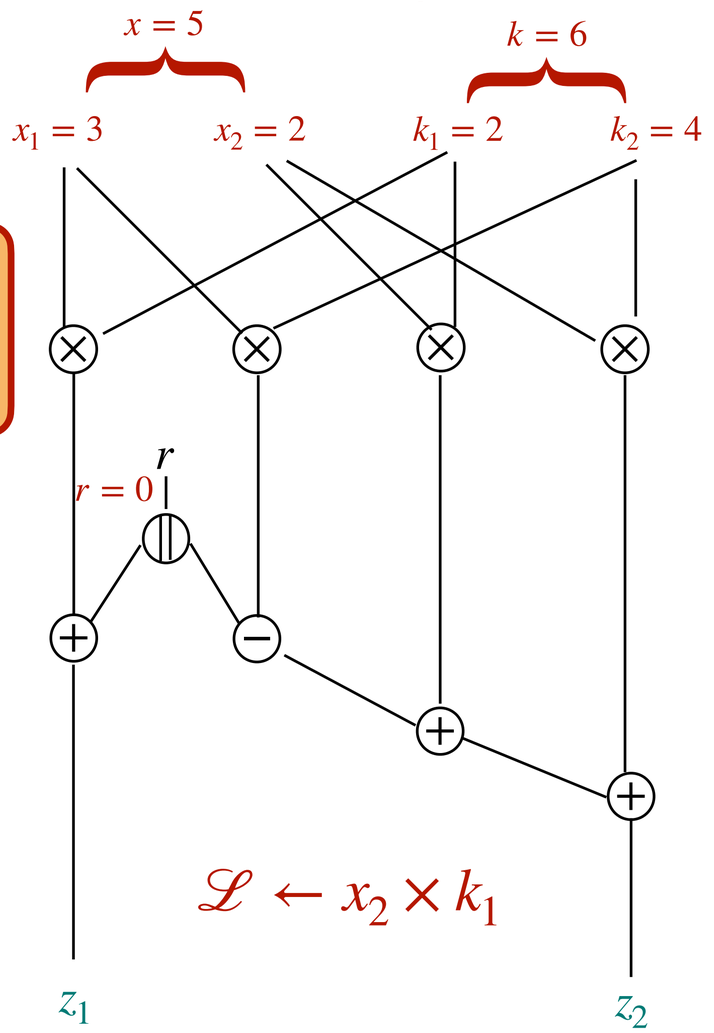

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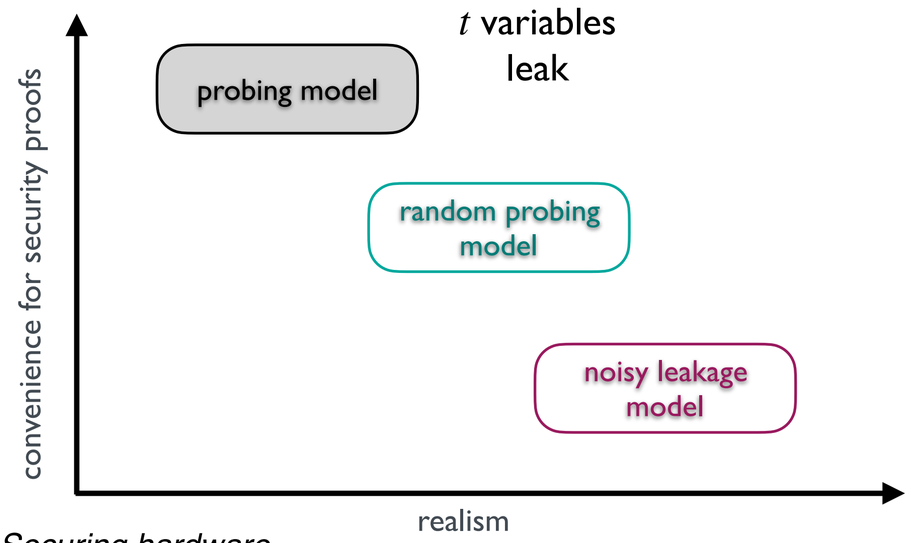

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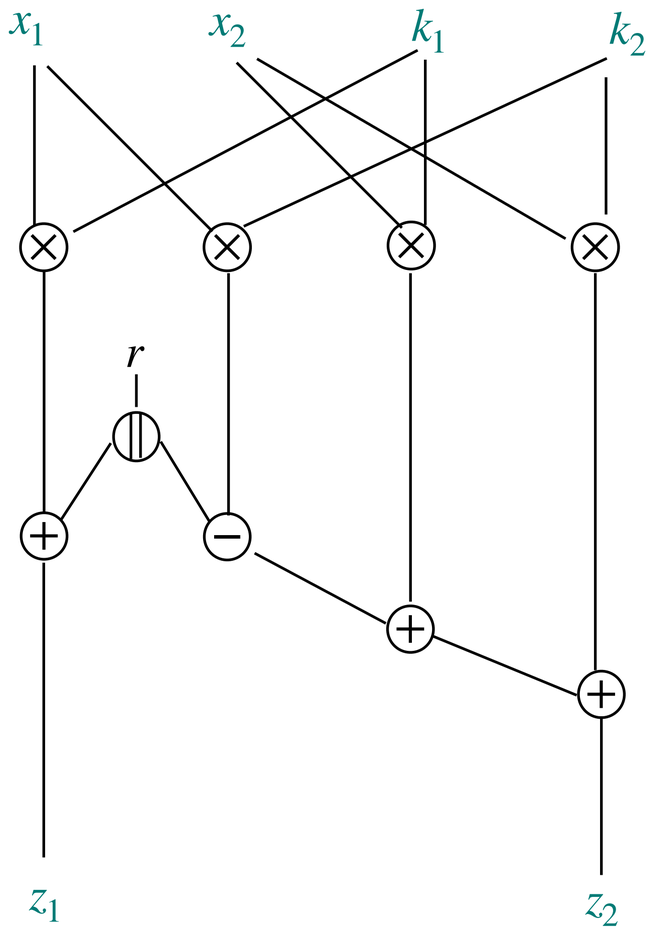
Random probing model

Attacker view



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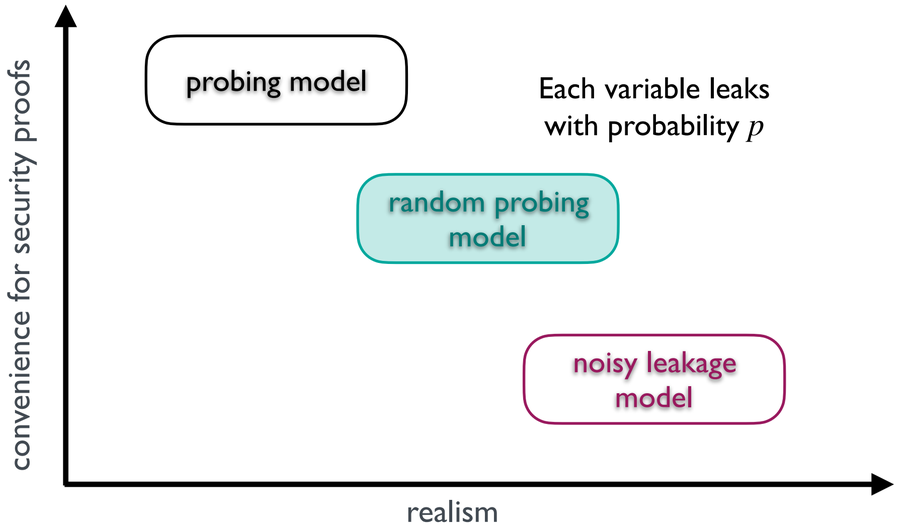

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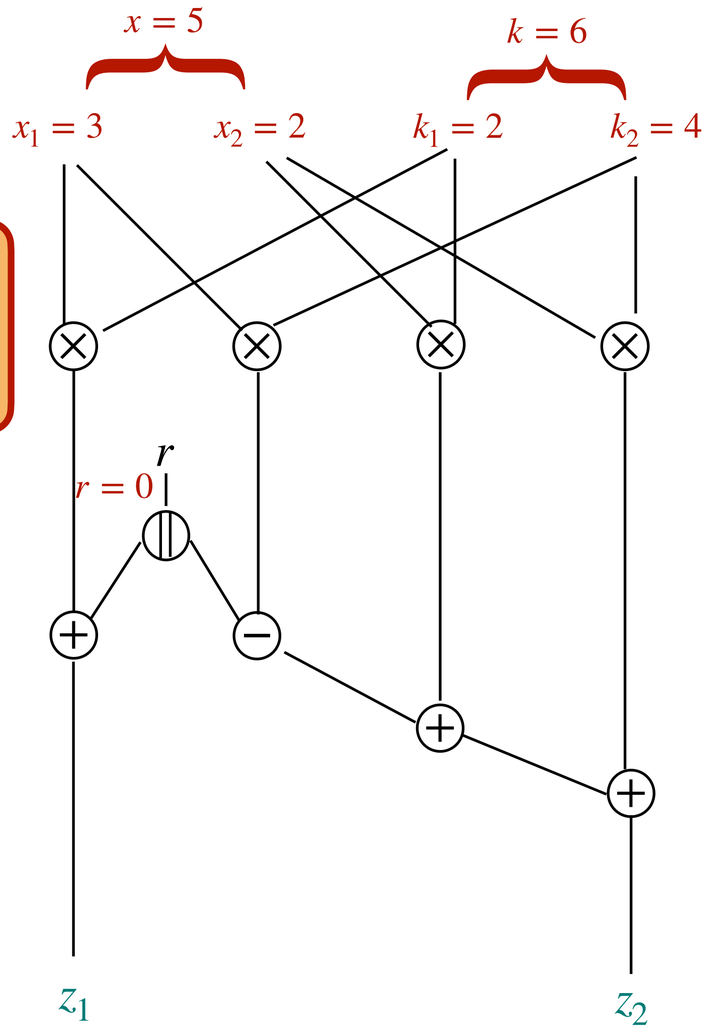

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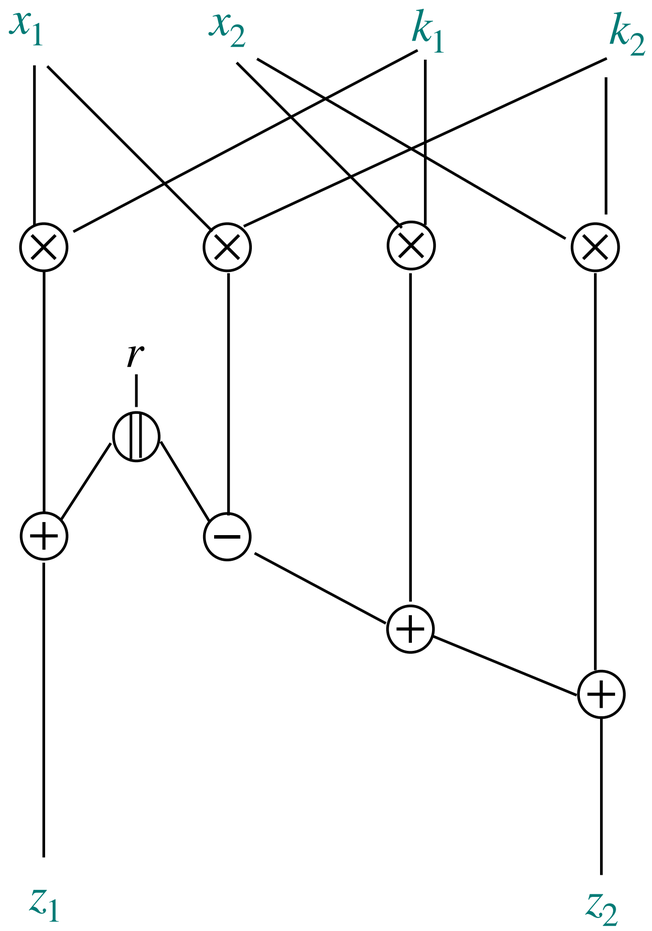

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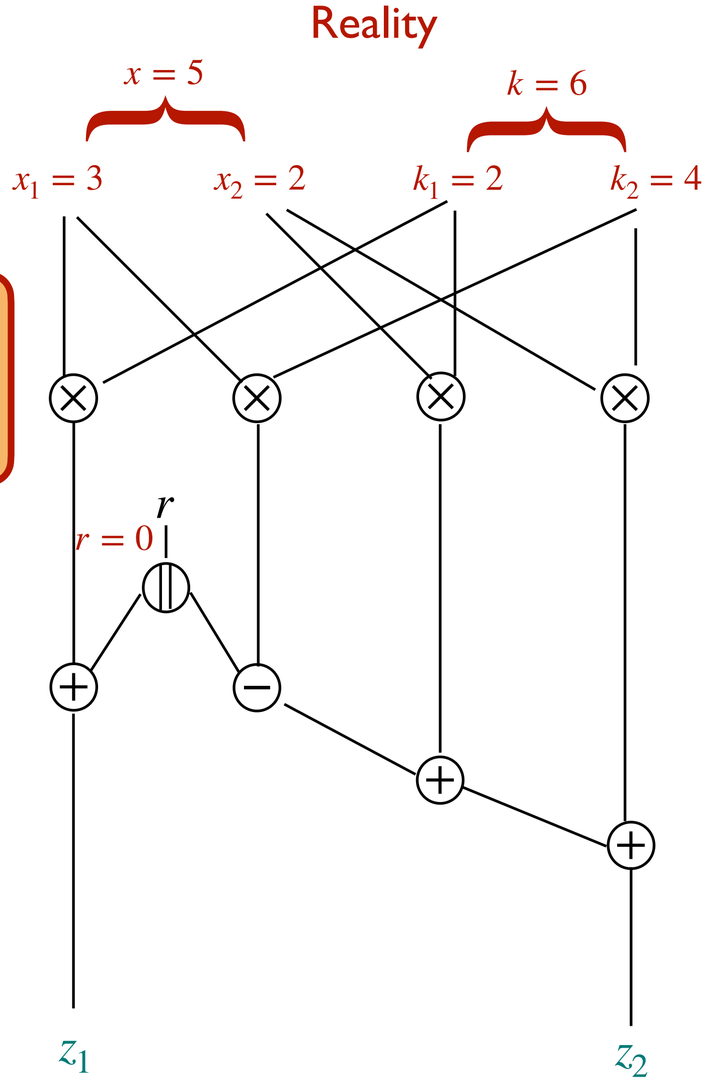

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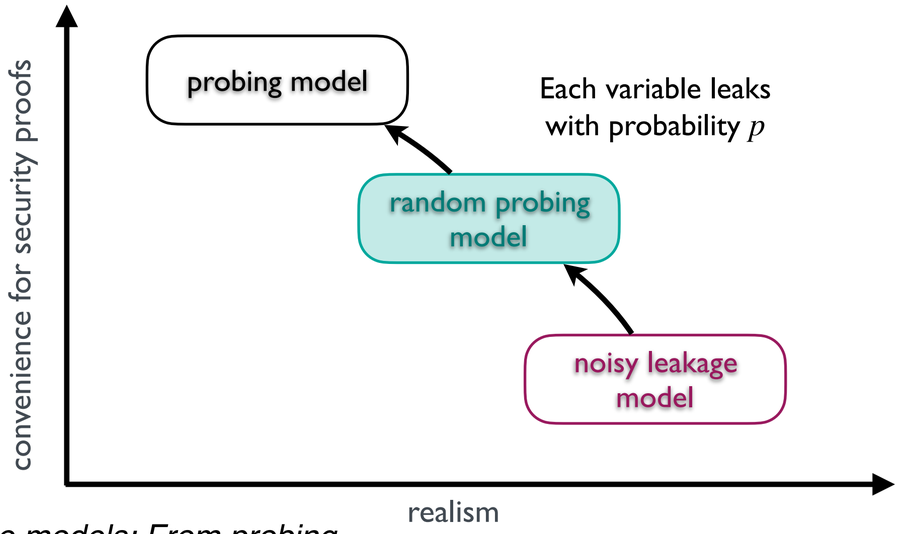

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Random probing model

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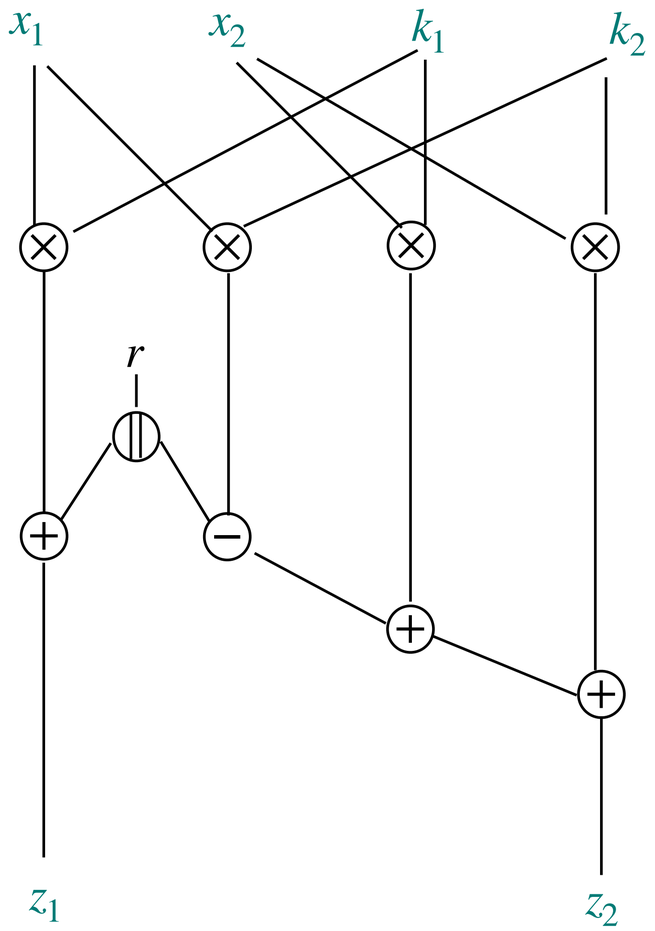
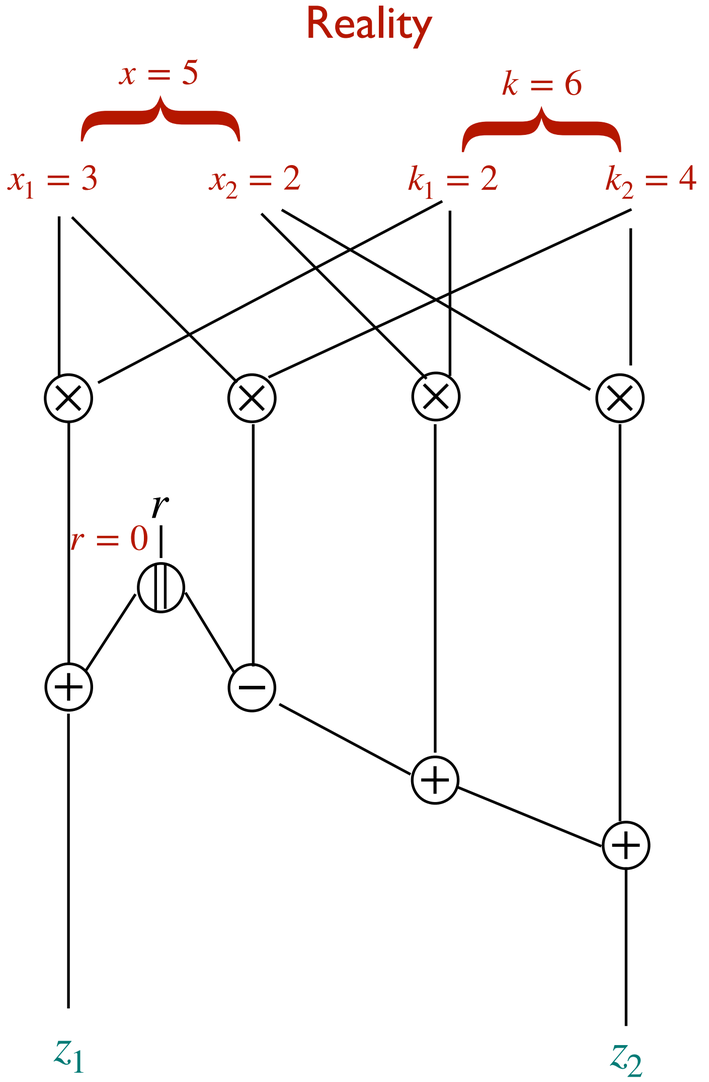


Attacker model

The attacker is given the value of each wire with probability p.

Reality



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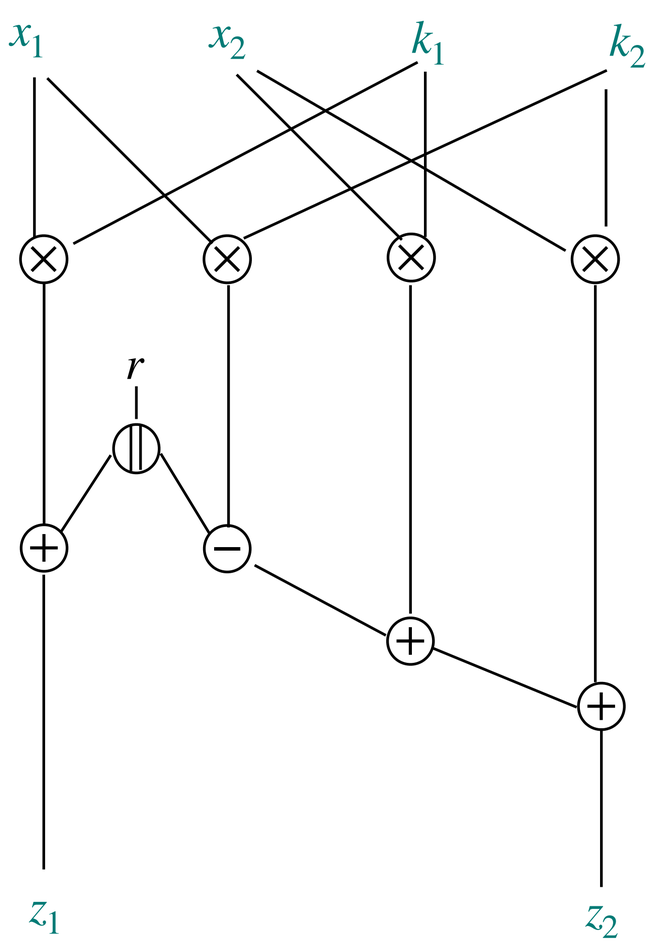

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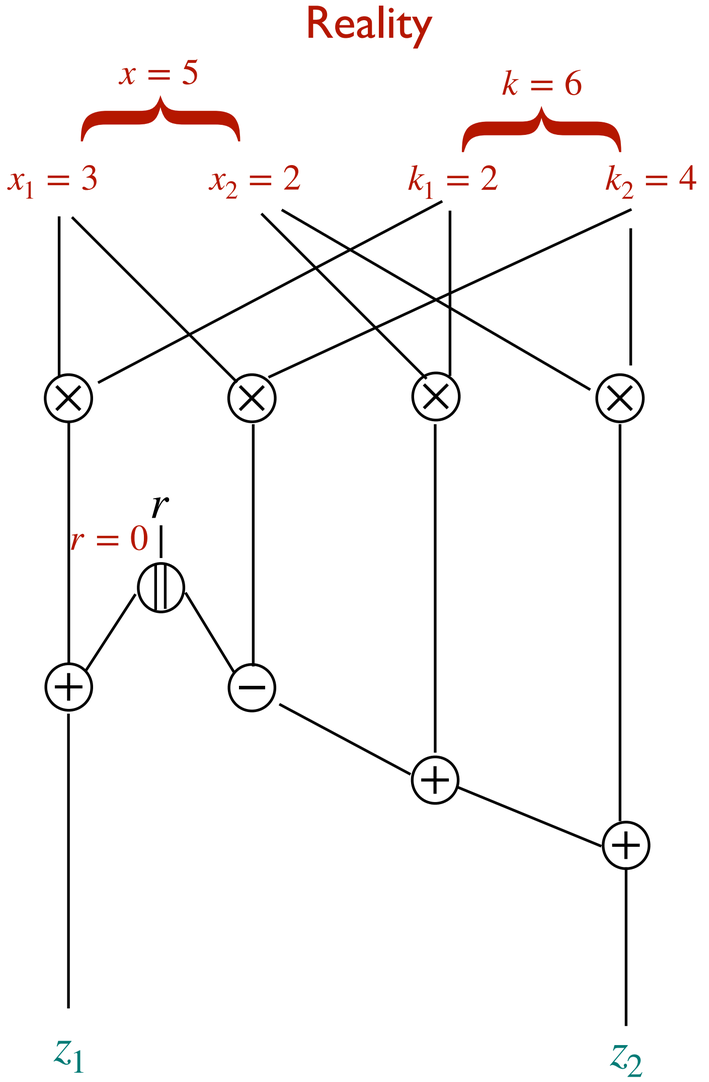
(p, ϵ)-random-probing security

Let $\mathscr{W}$ be a set of wires that are drawn with prob. p.
Given $\mathscr{W}$, the attacker cannot deduce the values of the secrets x and k.



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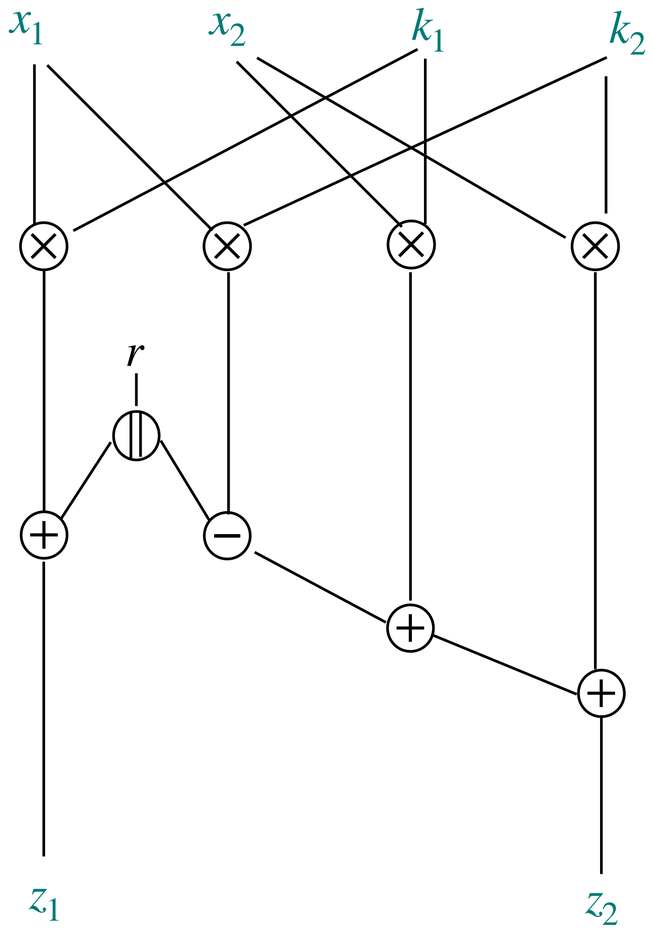

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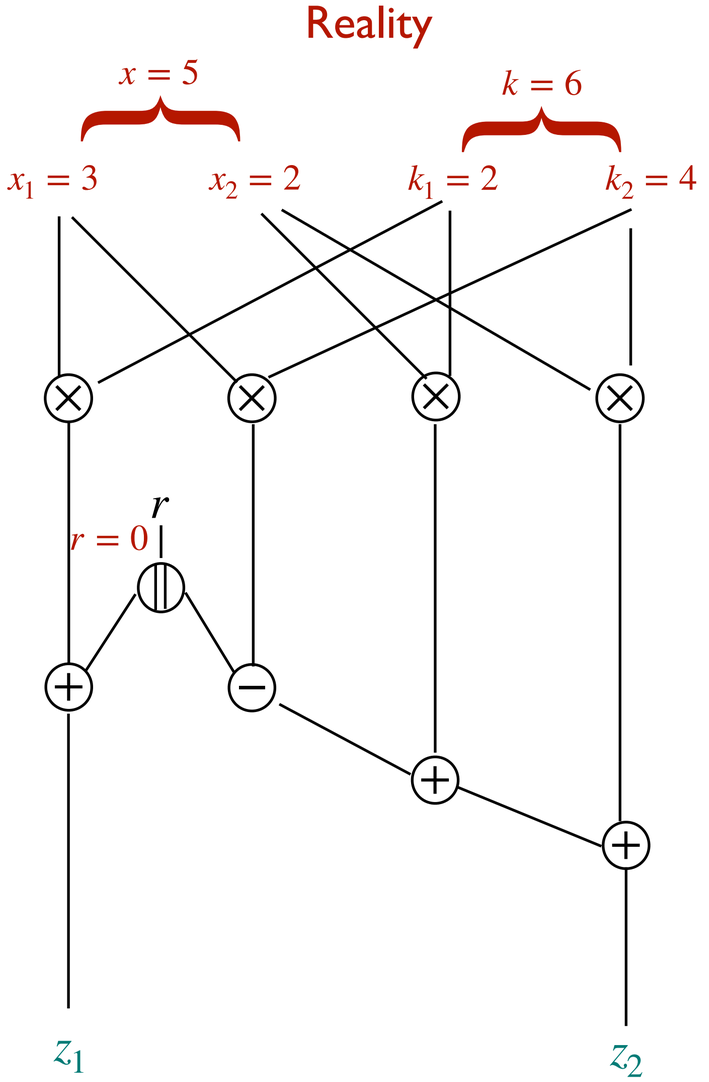
Security Proof

The simulator provides *out* that is **simulated** without the secrets: $\mathscr{L} \overset{id}{\approx}_{\epsilon}$ out.



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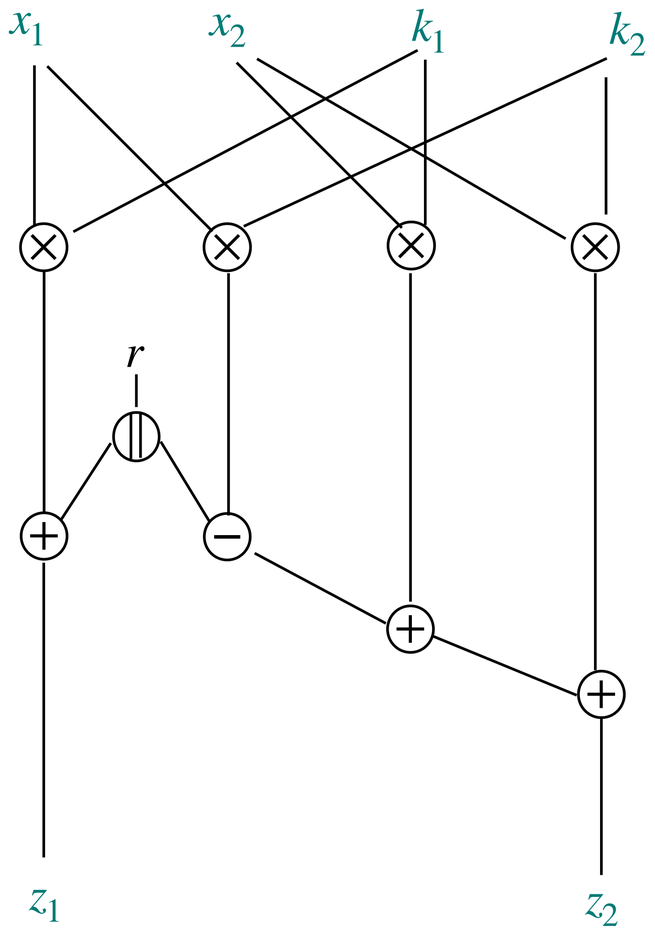

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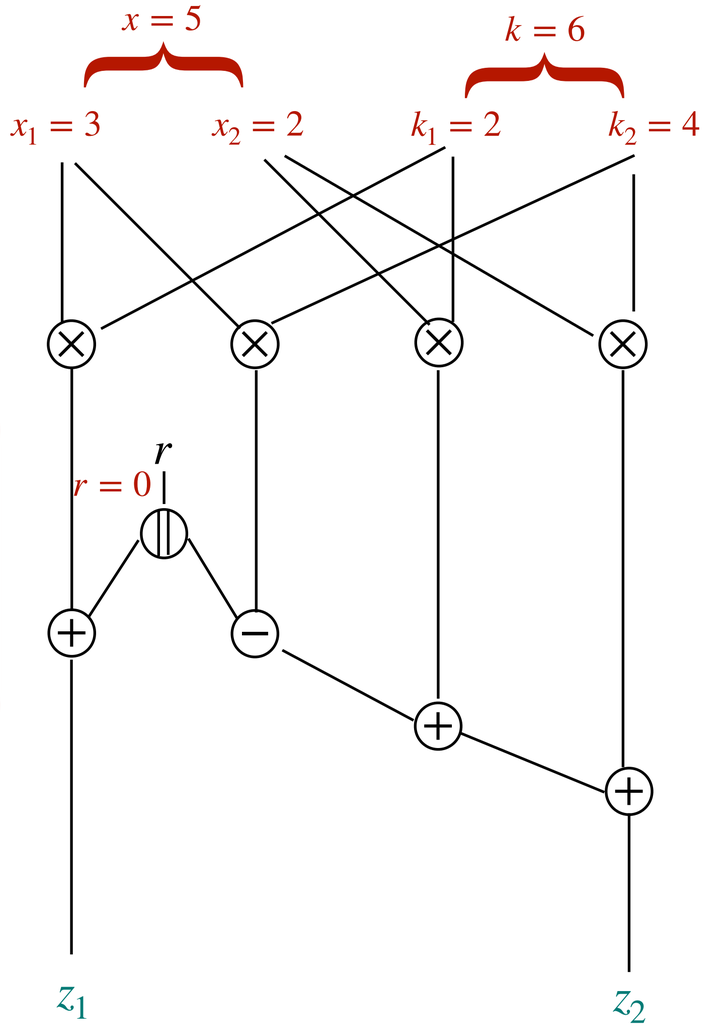
Reality

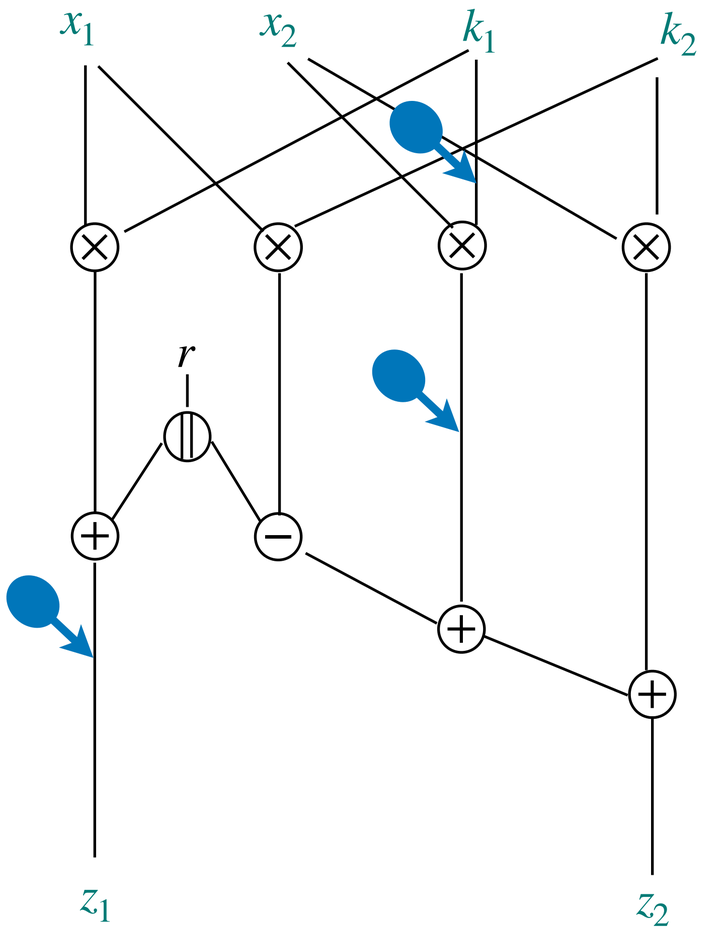


$\mathscr{W} = \varnothing$ with proba $(1-p)^{19}$

[DDF14] A. Duc, S. Dziembowski, S. Faust. *Unifying leakage models: From probing attacks to noisy leakage*. EUROCRYPT 2014

Random probing model

Attacker view



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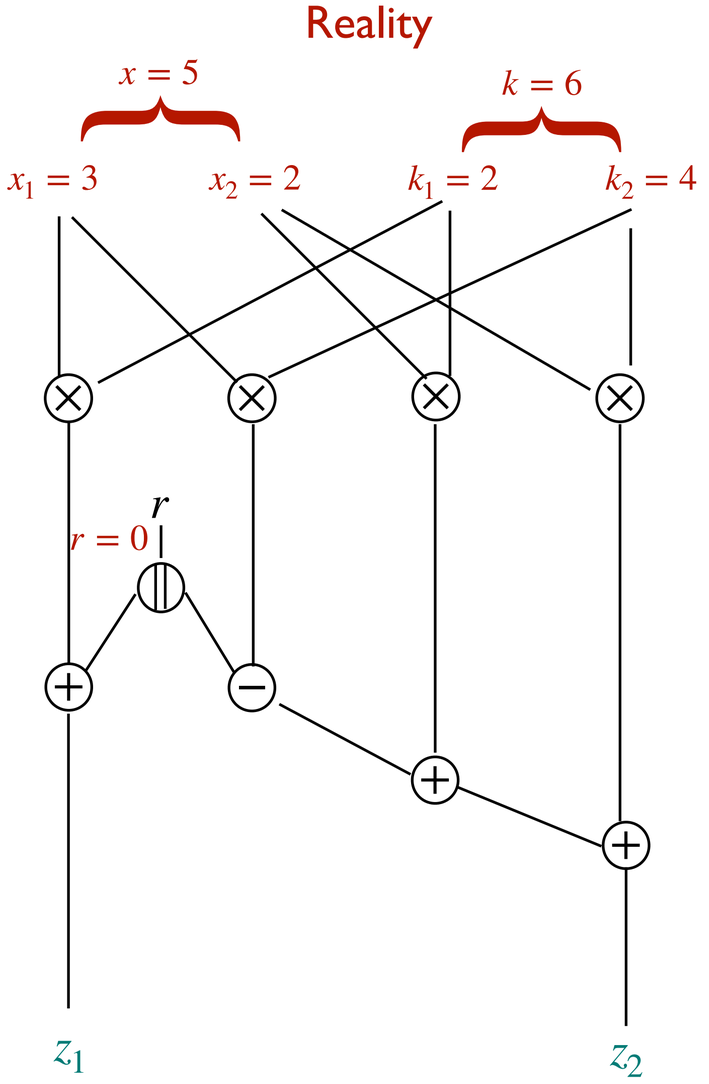

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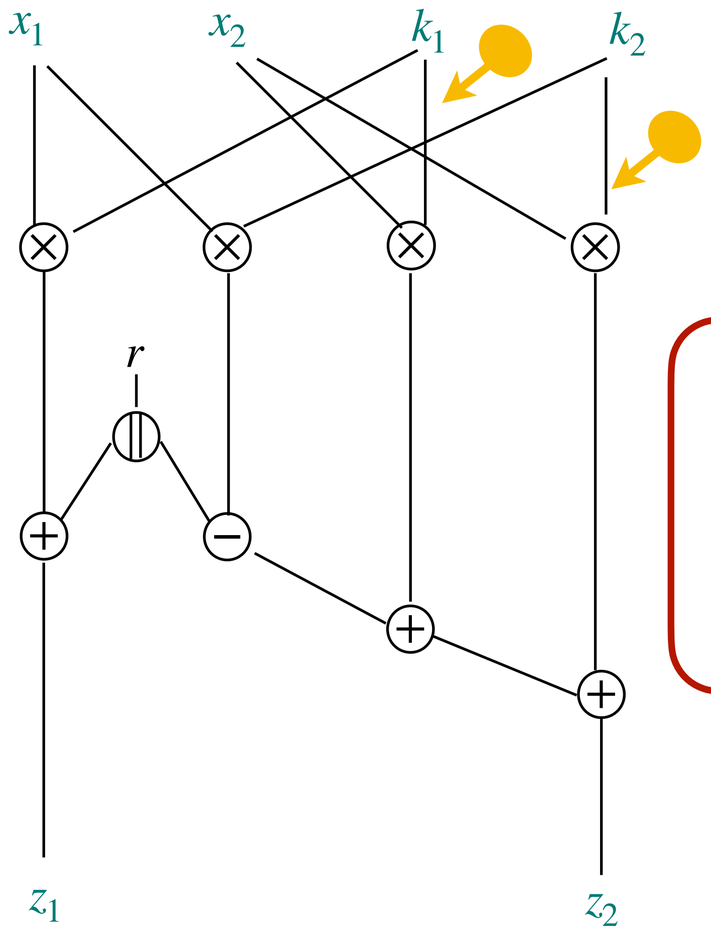

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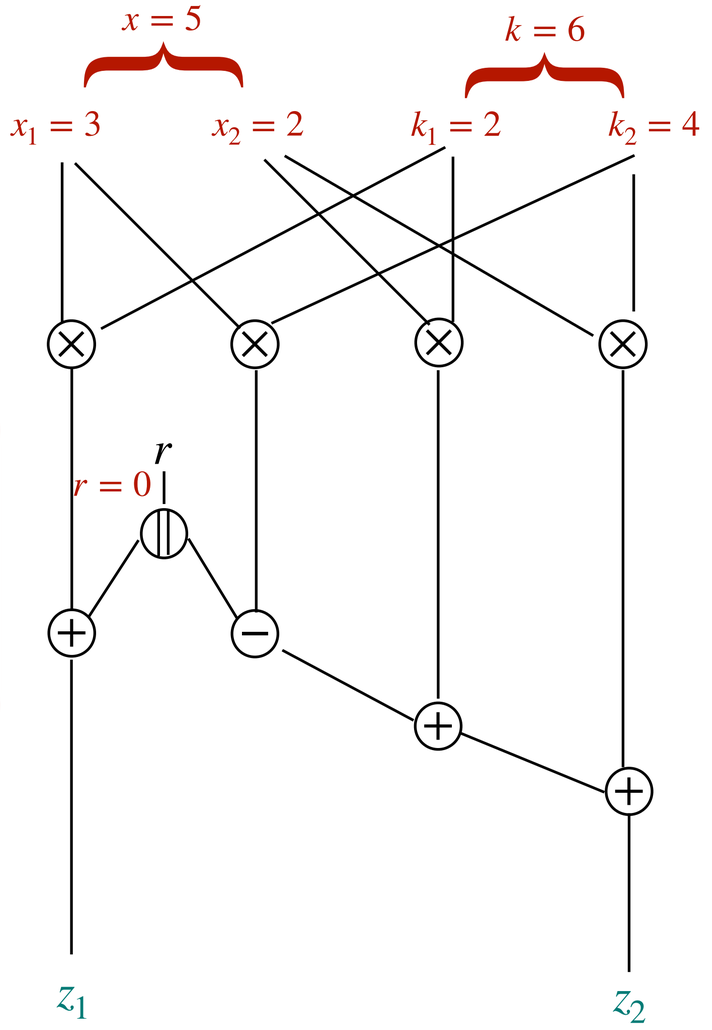

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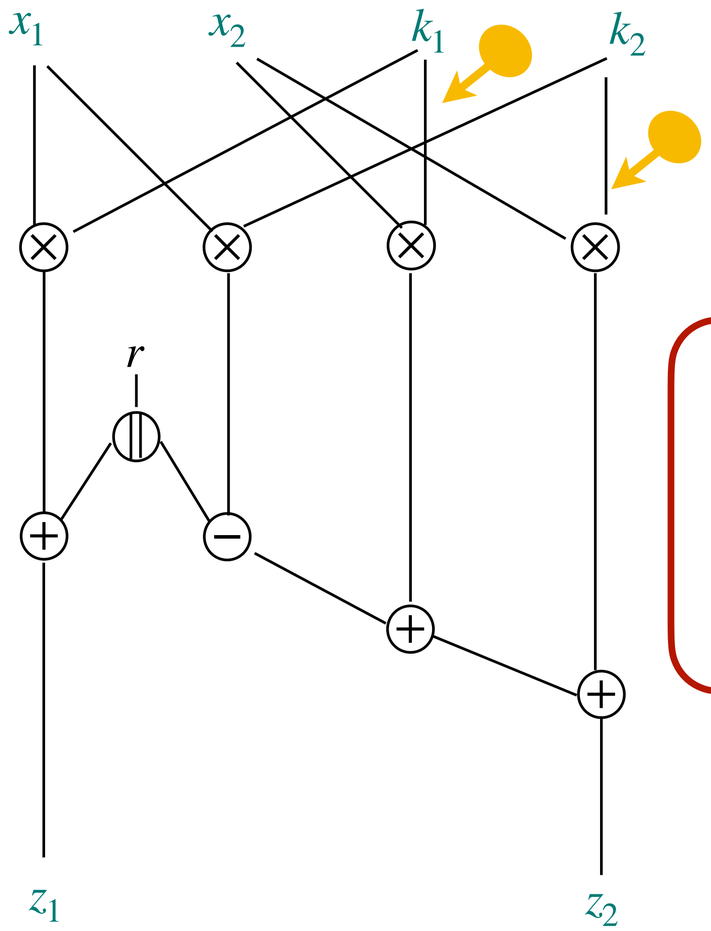

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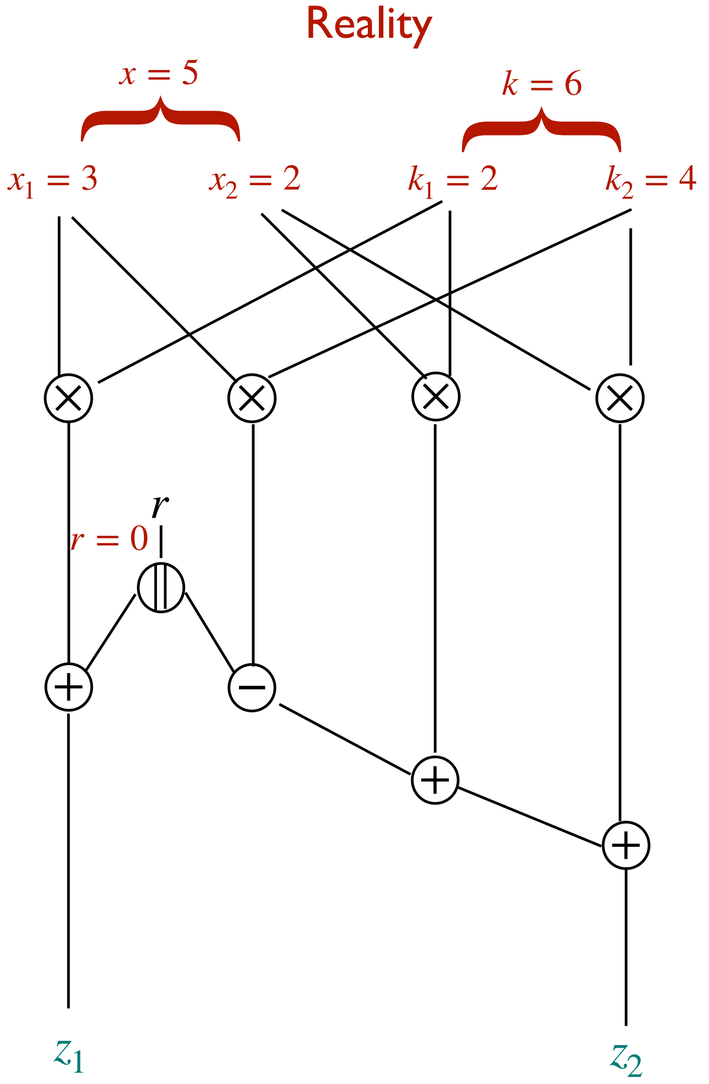

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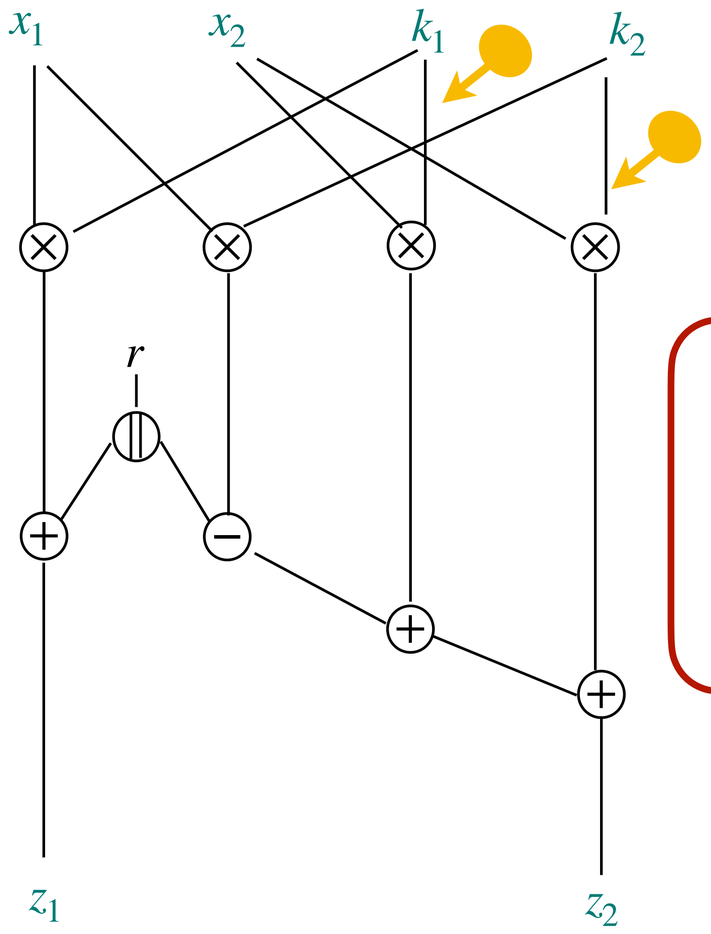

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$\epsilon = 2^{-128} \implies p \geq$ some bound

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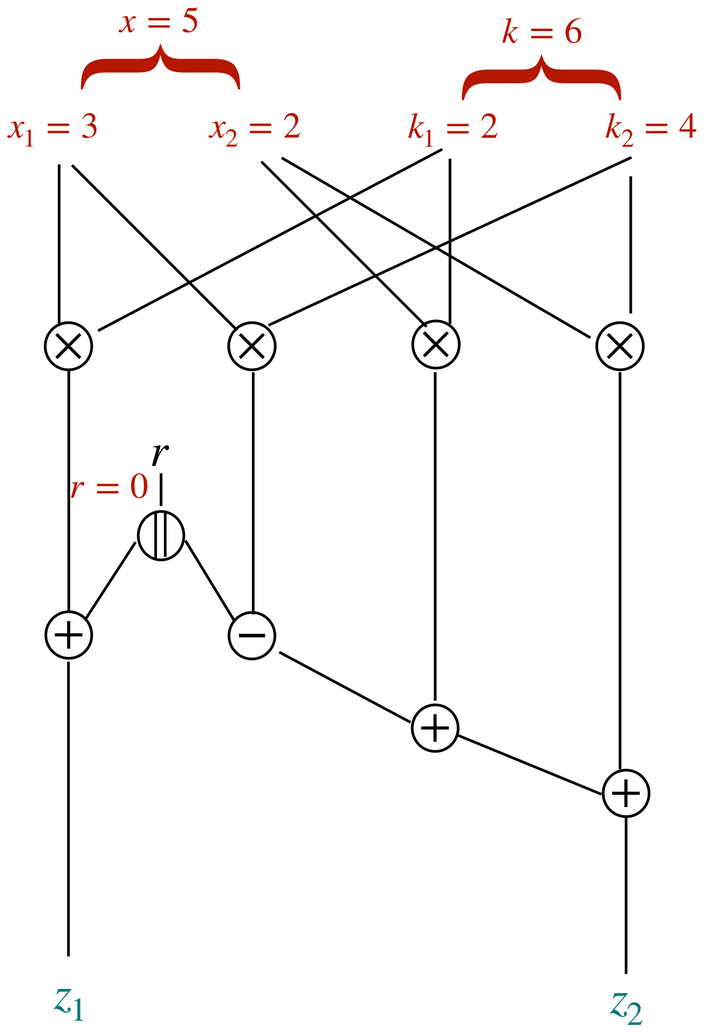

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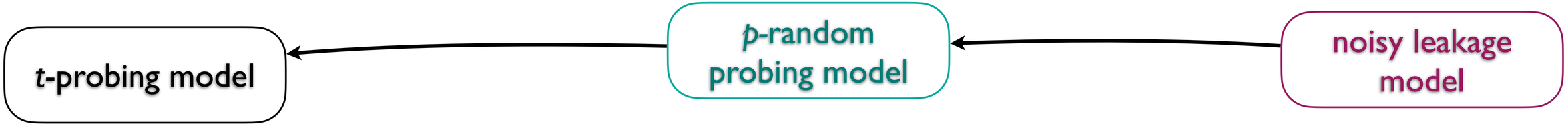

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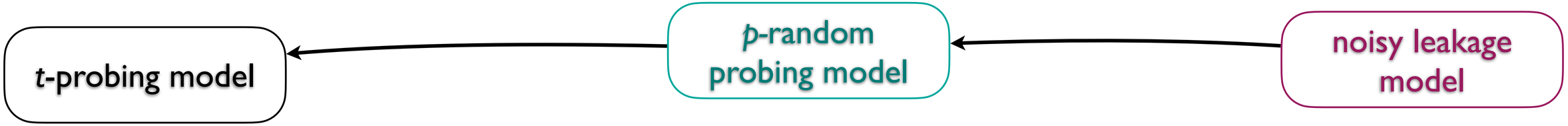

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p-random probing model

- ☑ The success of the simulation depends on the probability p.
  - ➡ semi-direct link with the physical leakage of a chip.
  - ➡ Masked implementations are provably secure up to a certain leakage probability p. For concrete chips, p can lie between 2^{-15} to 2^{-7} ([BCMRRST25])
- ☐ Relatively high entrance price for understanding the proofs.
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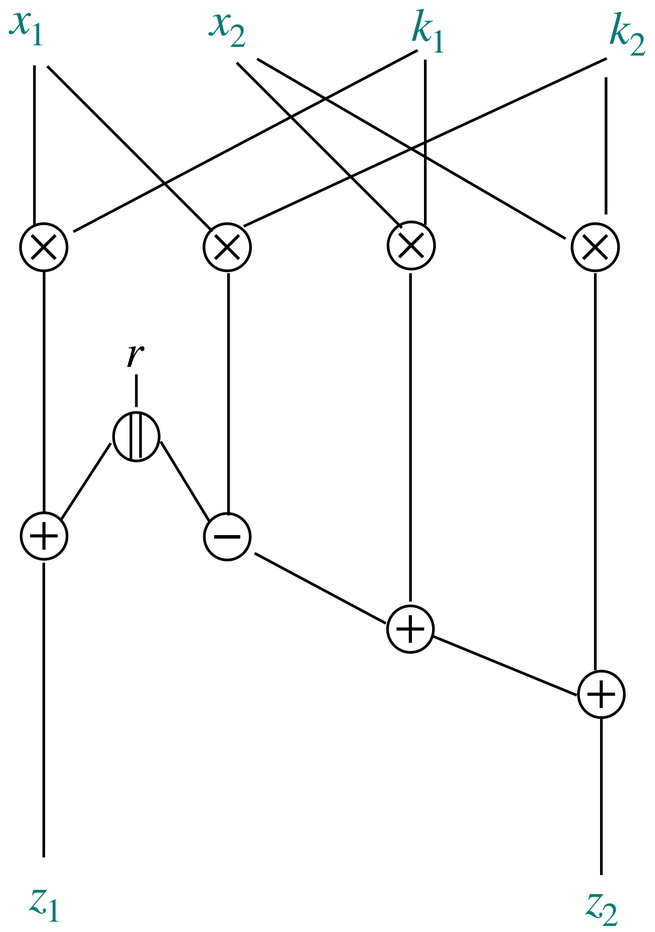
Random Probing Composability

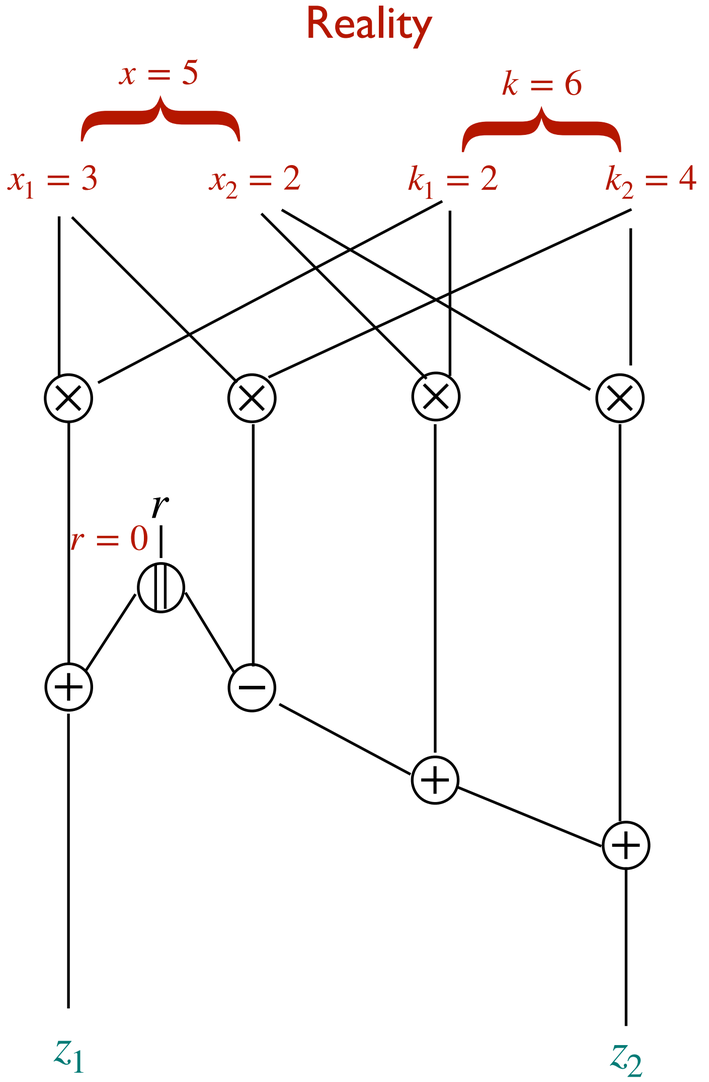
Attacker view



(p, ϵ, t)-threshold RPC

$\mathbb{P}$(« The simulator needs more than t shares of each $[\![x]\!]$ and $[\![k]\!]$ to simulate $\mathscr{L}$ + t output shares ») $\leq \epsilon$

Reality



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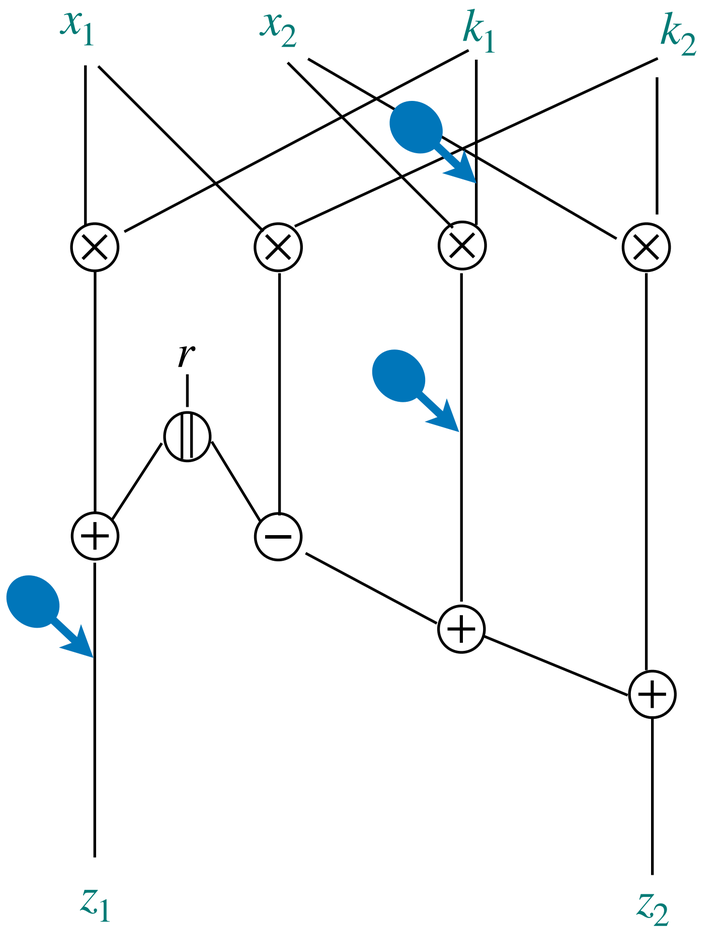

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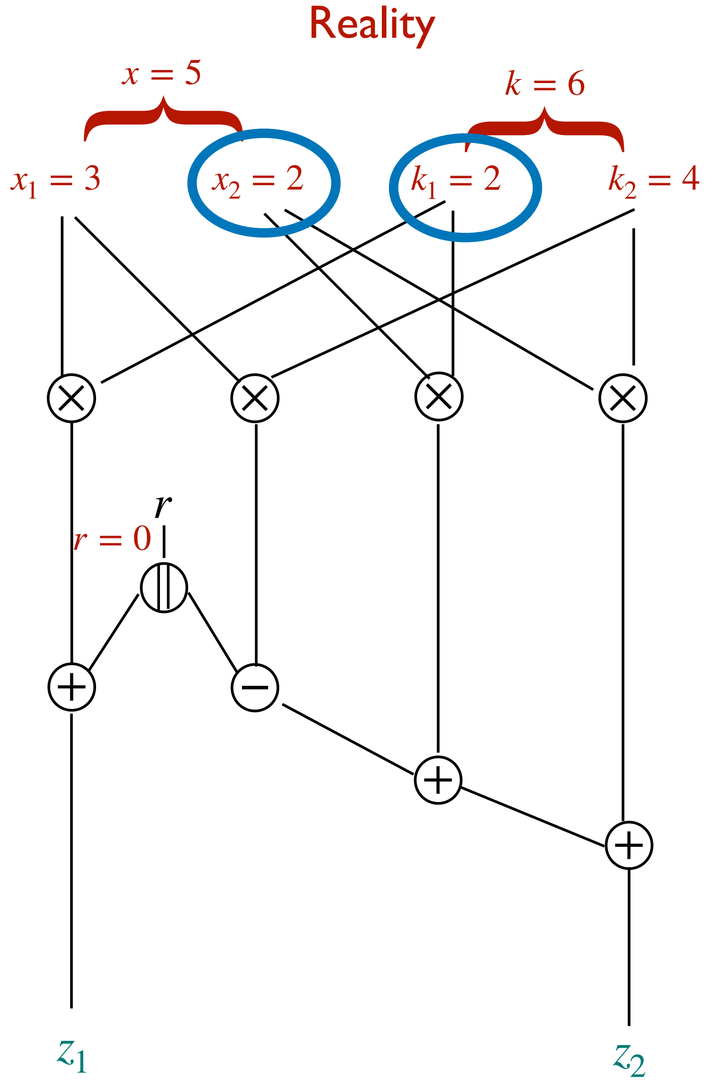

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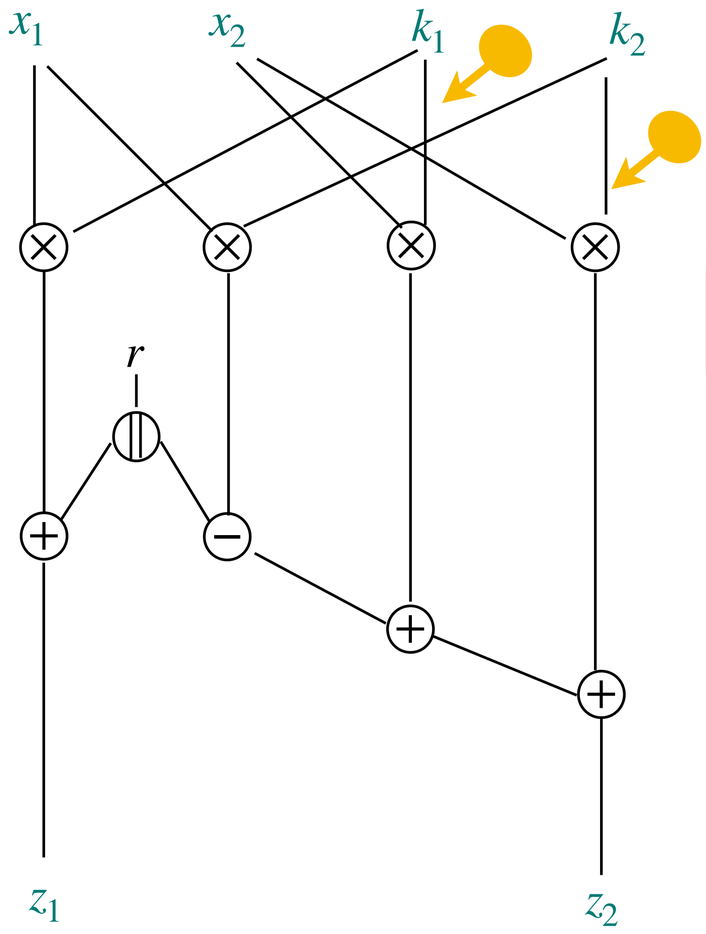

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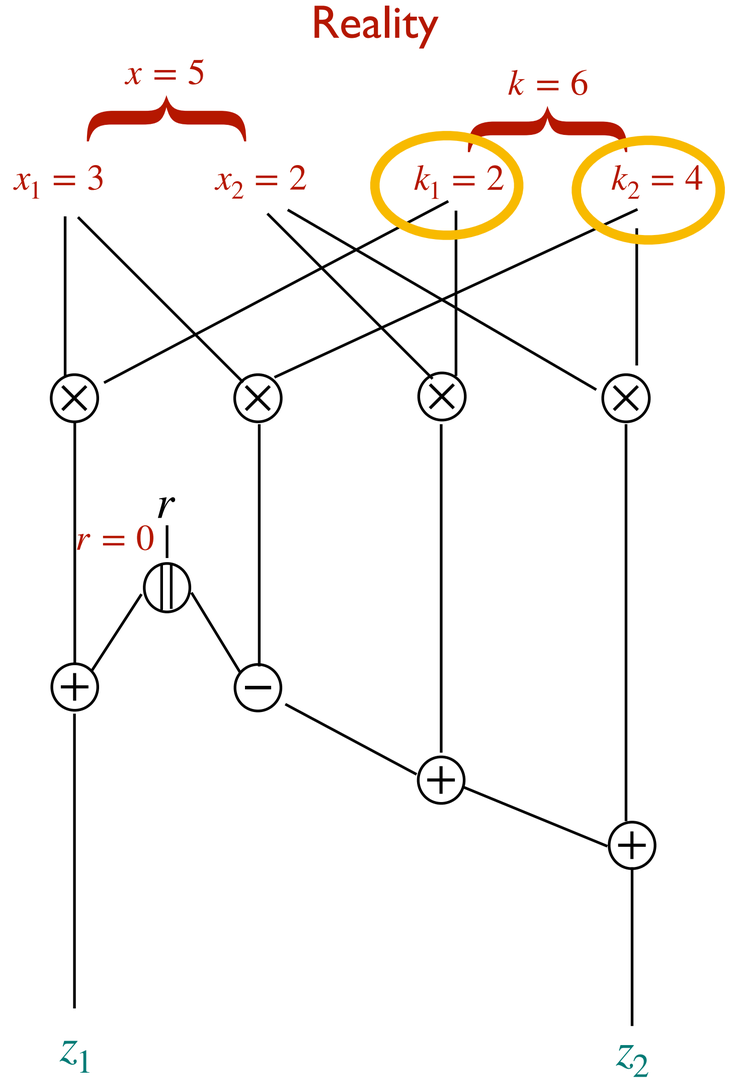

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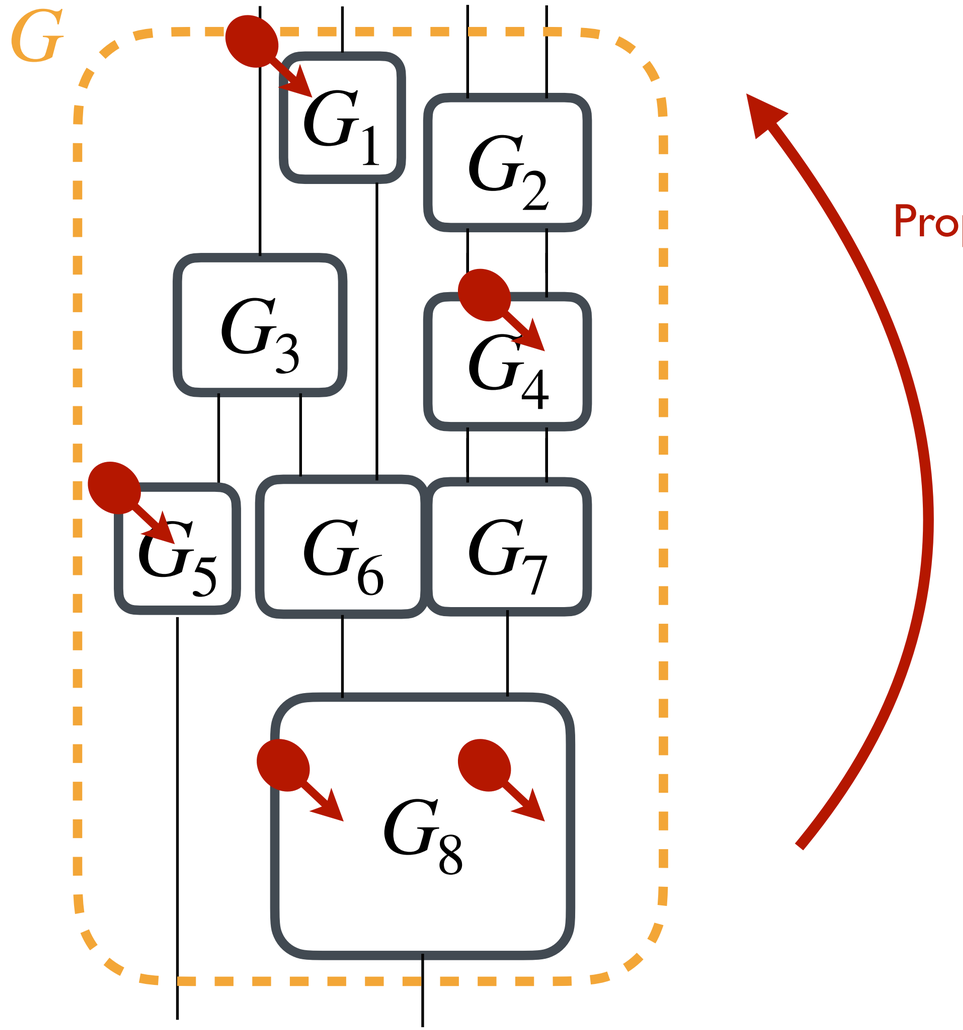
Composition with threshold RPC



Threshold RPC:

Propagation of the leakage and the outputs to the inputs

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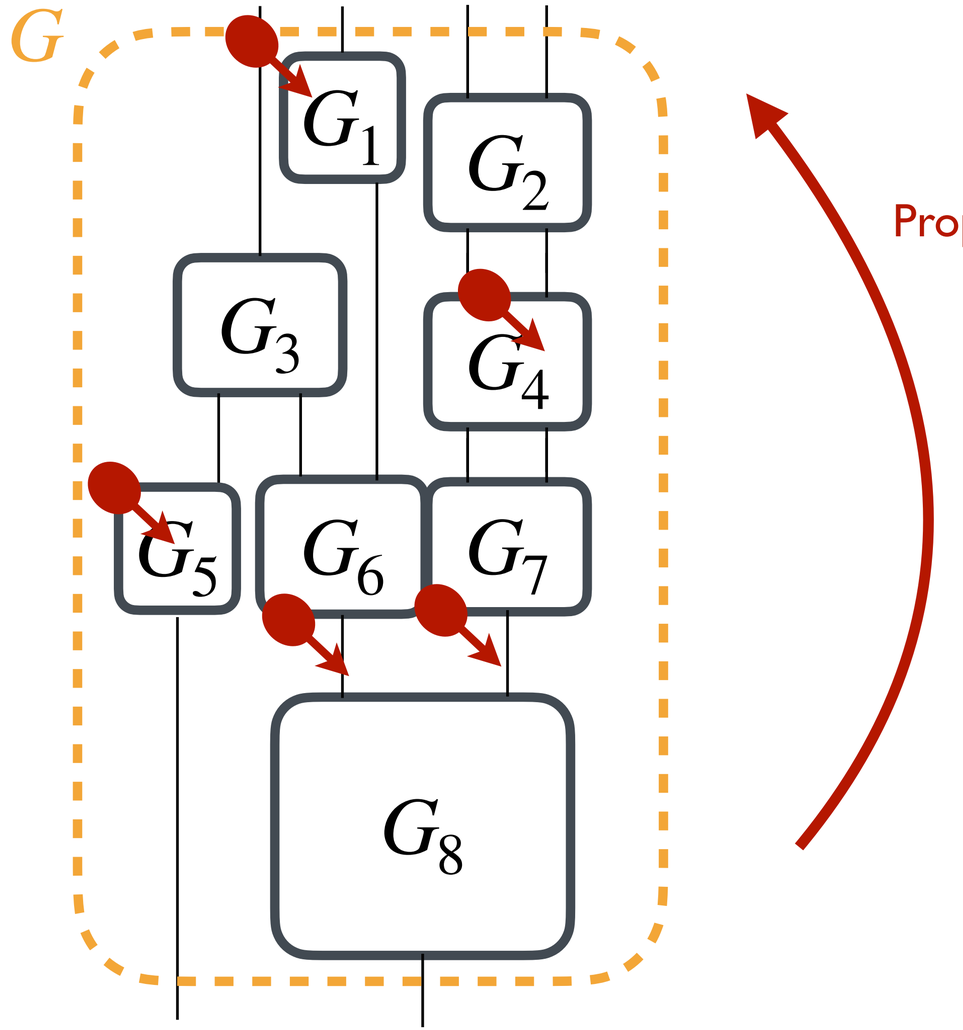

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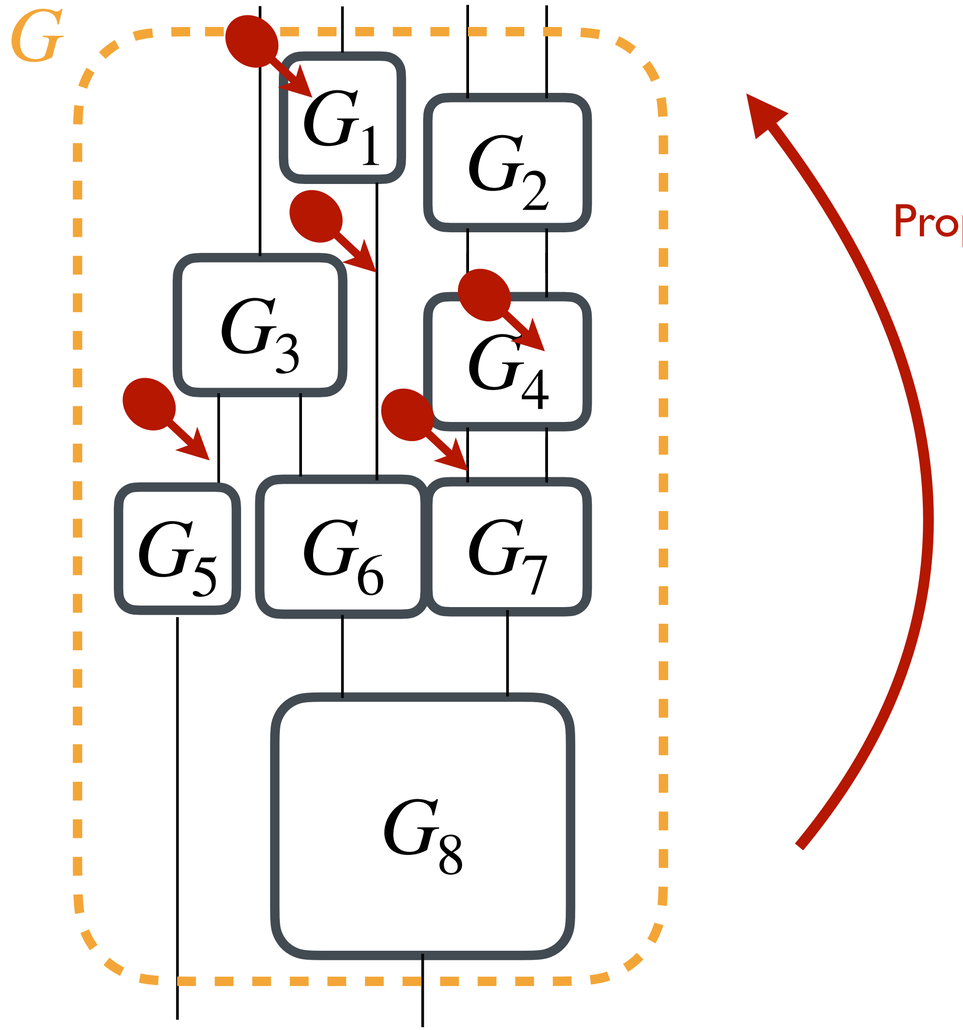

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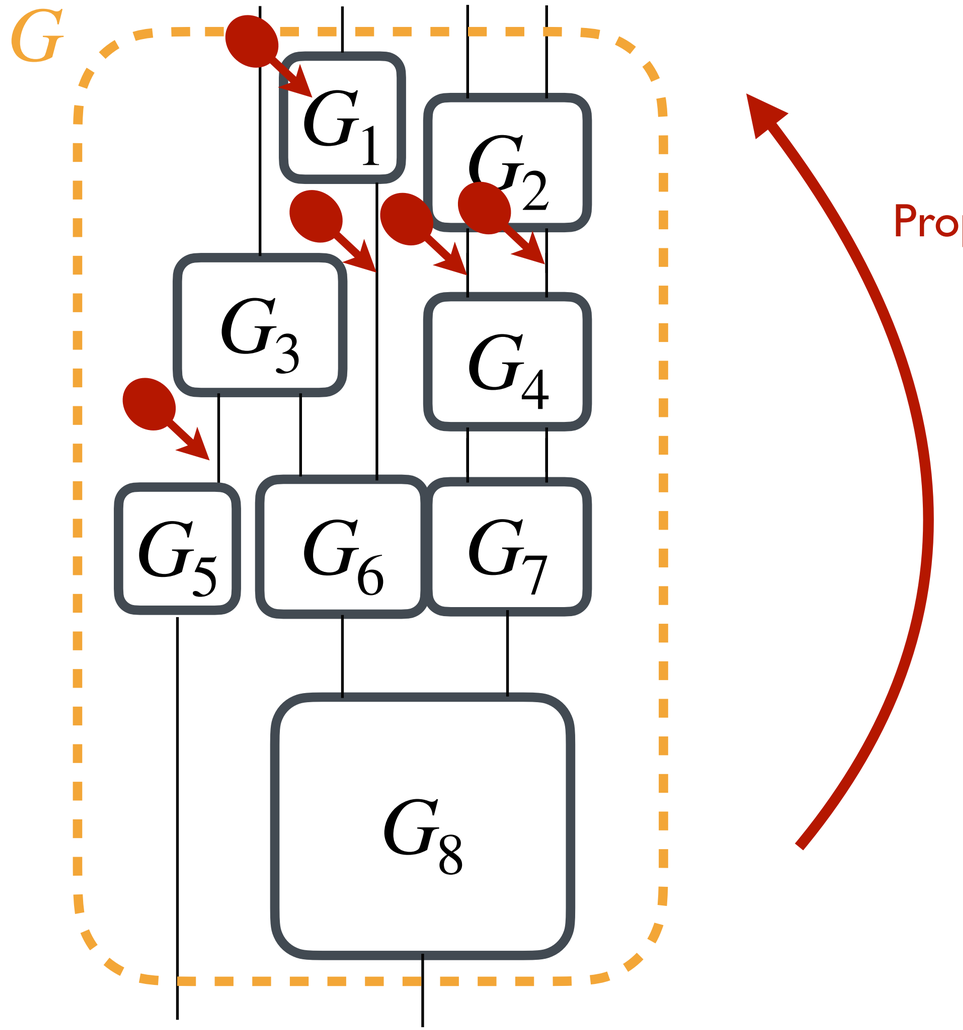

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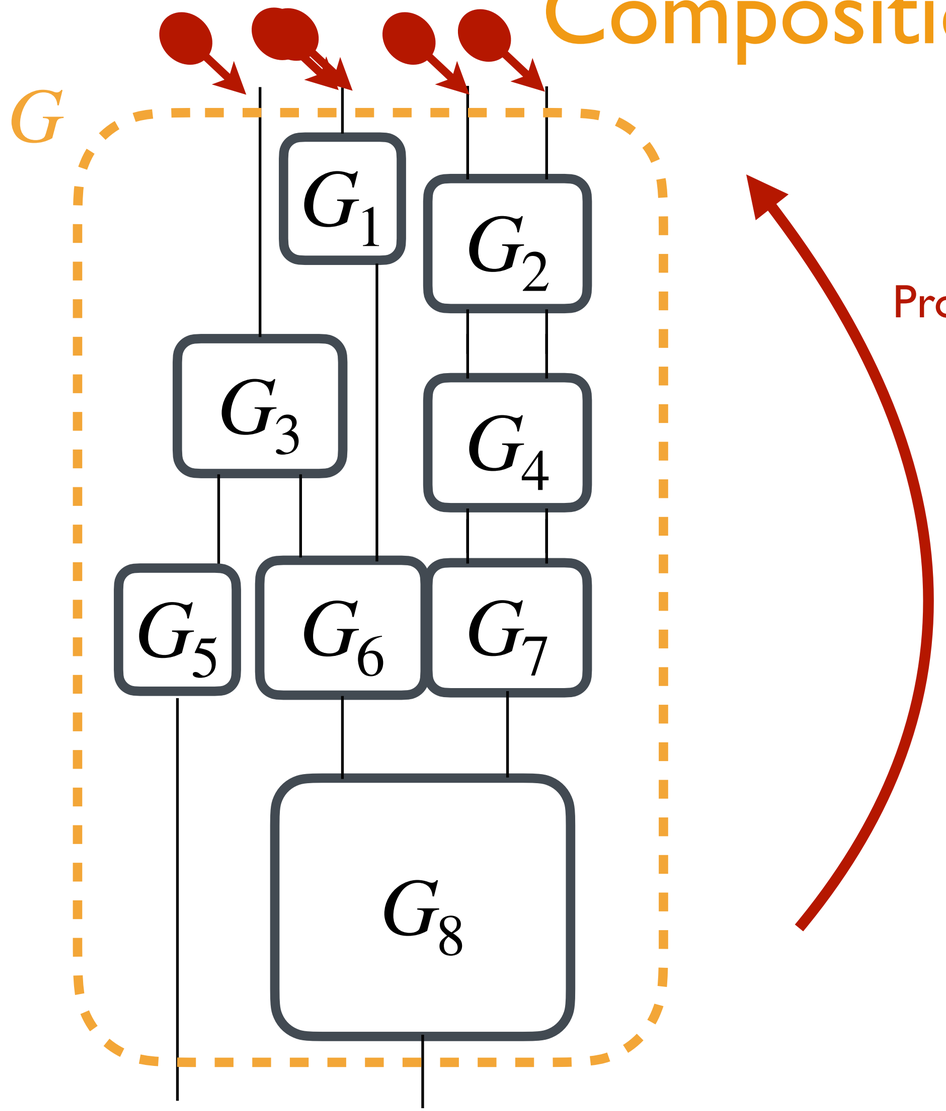

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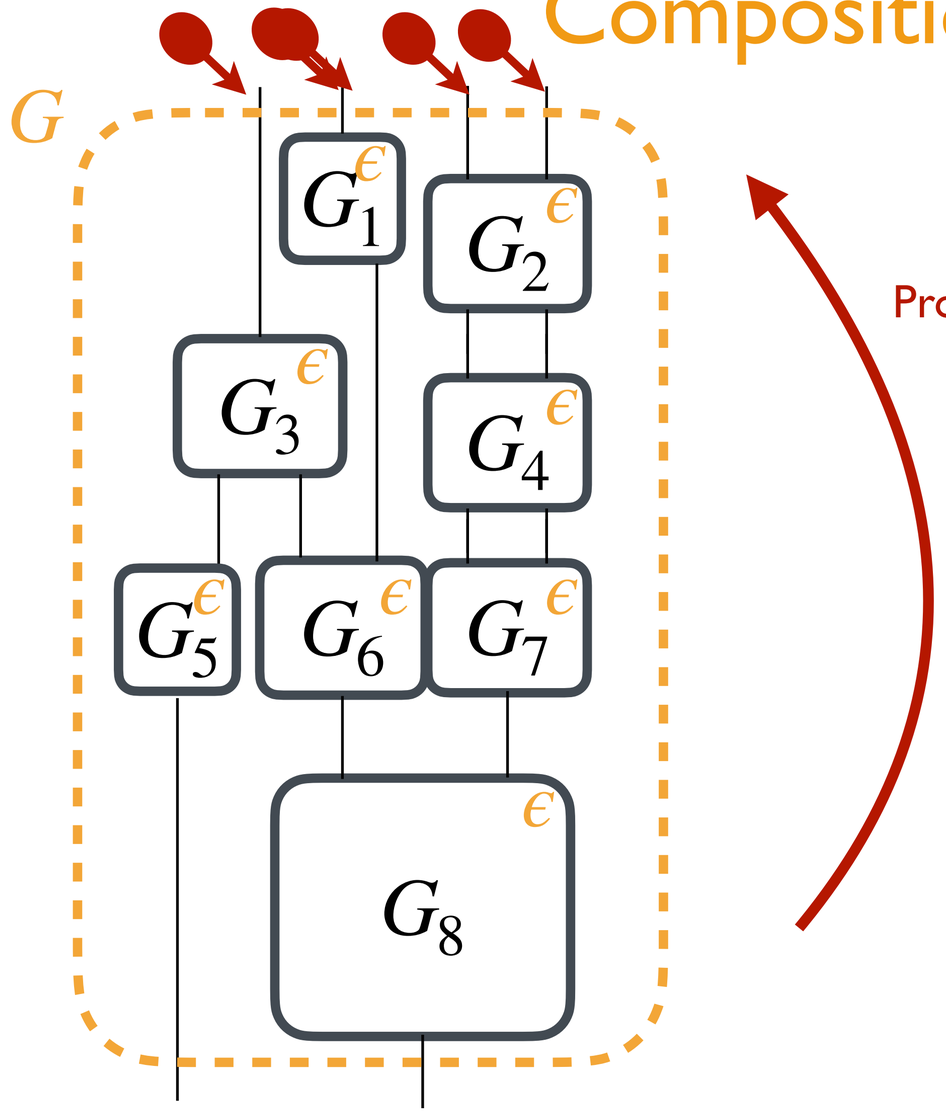

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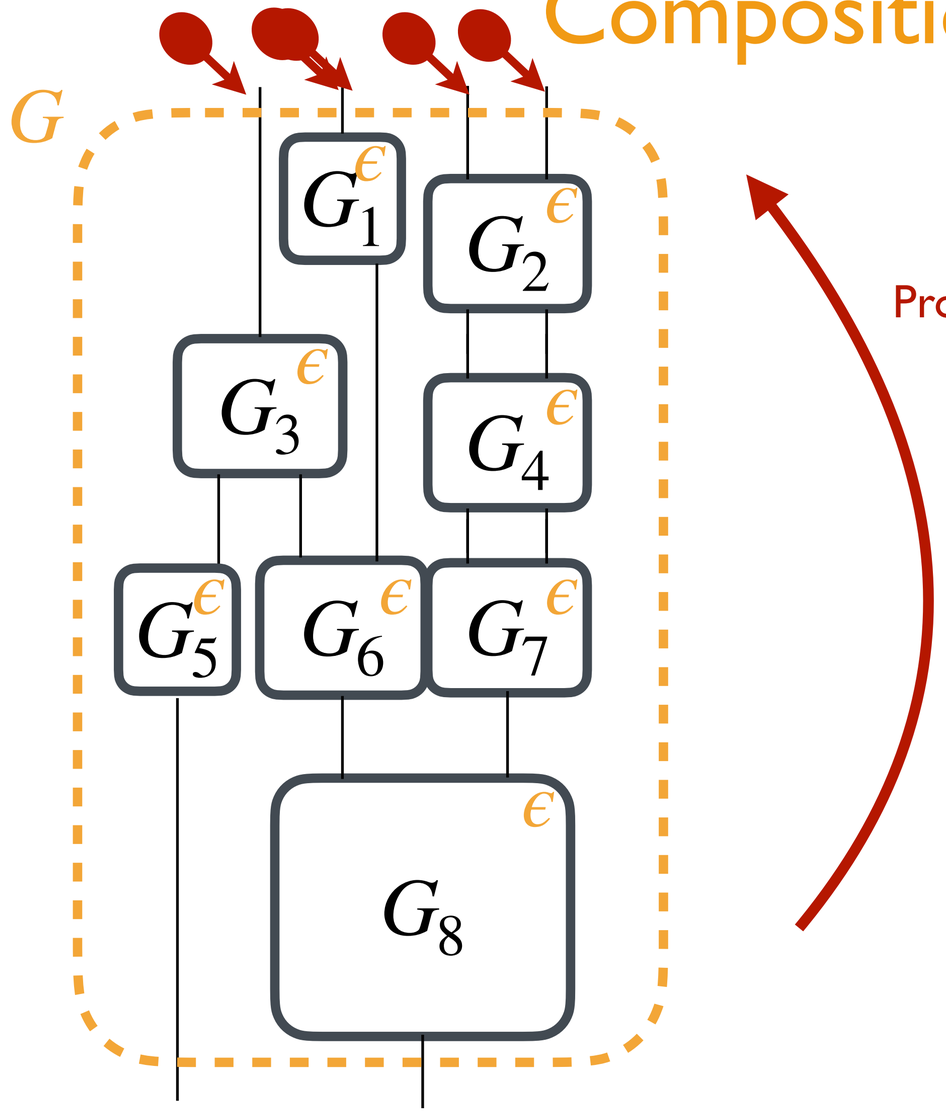

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All G_i are (t, p, ϵ)-threshold RPC $\Longrightarrow$ G is (t, p, ϵ') -threshold RPC with

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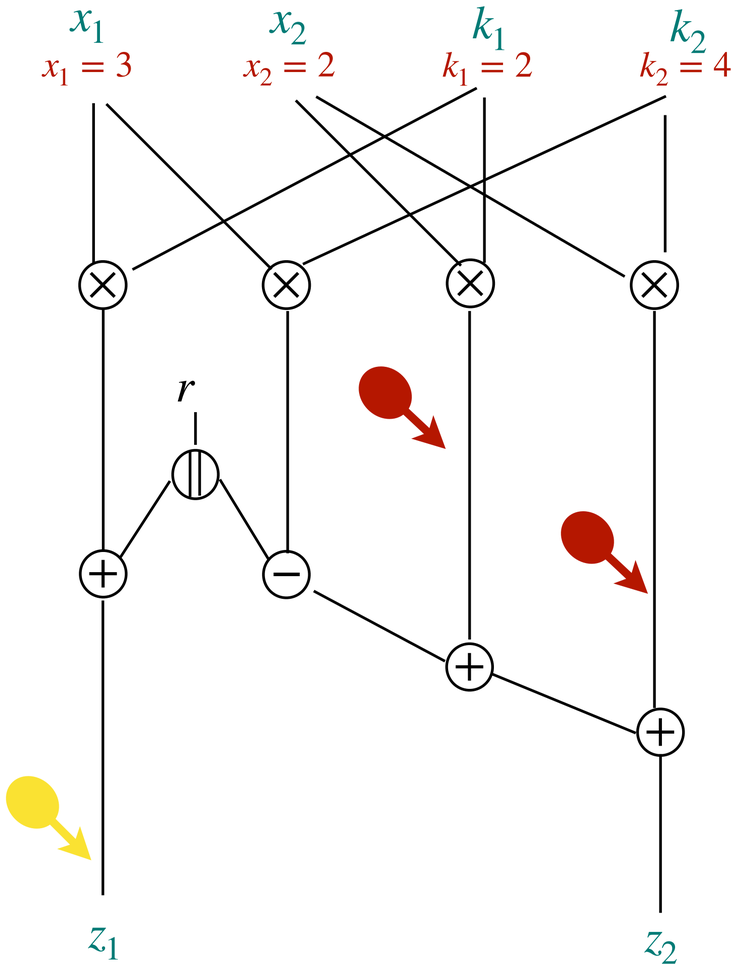

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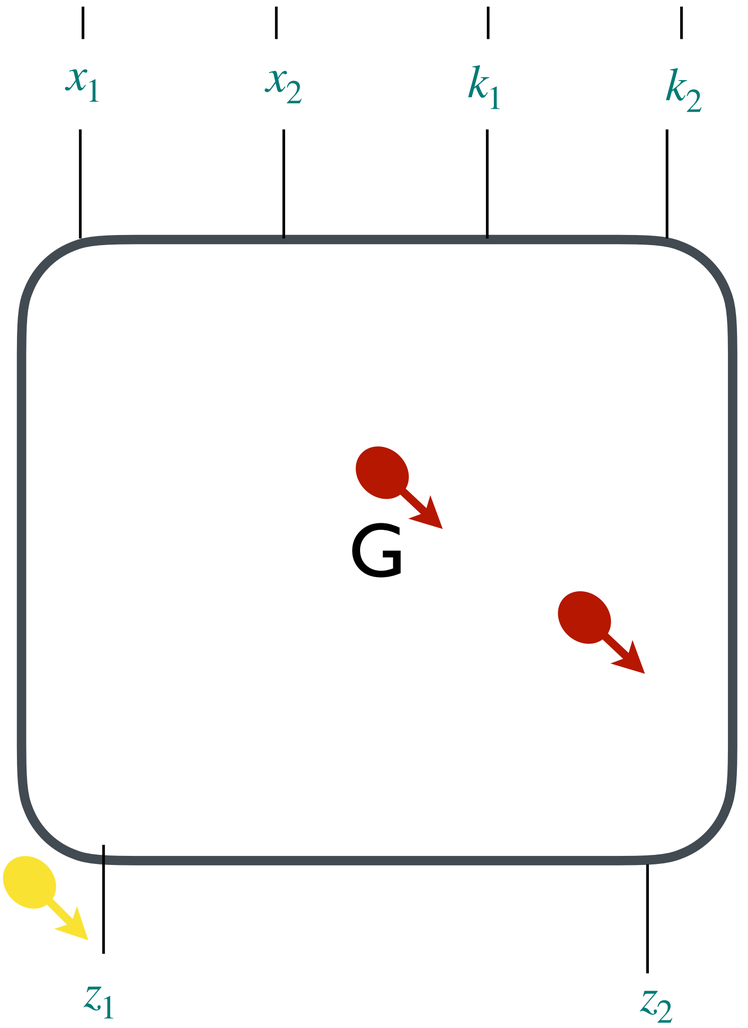

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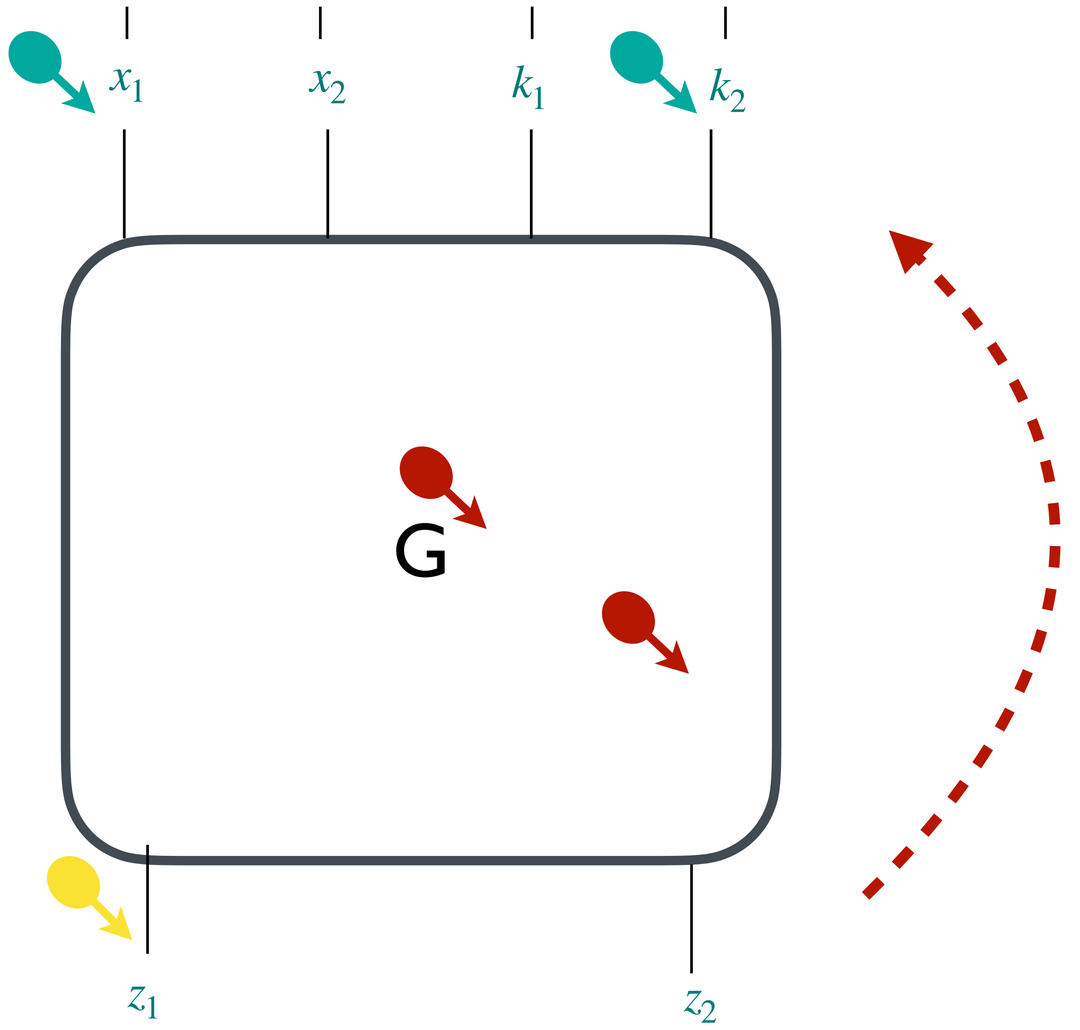

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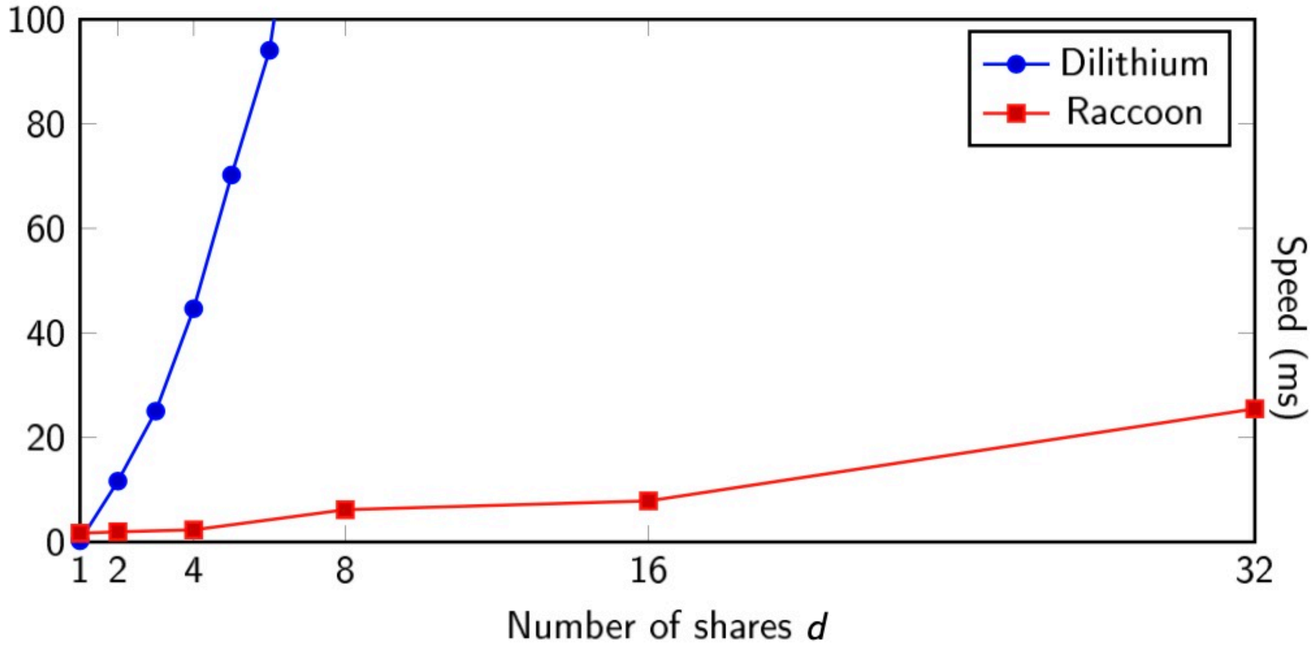
3) Random-probing Raccoon

Raccoon Signature Scheme



Raccoon 128-16

q	5498245831720 97
n	512
k	5
l	4
d	16
T	2

➡ Quasi-linear in the masking order
➡ Proof in the $(d-1)$-probing model
➡ Same assumptions as Dilithium/ML-DSA

Signatures $4\times$ larger

[dPKPR24] R. del Pino, S. Katsumata, T. Prest and M. Rossi
Raccoon: A Masking-Friendly Signature Proven in the Probing Model. CRYPTO 2024

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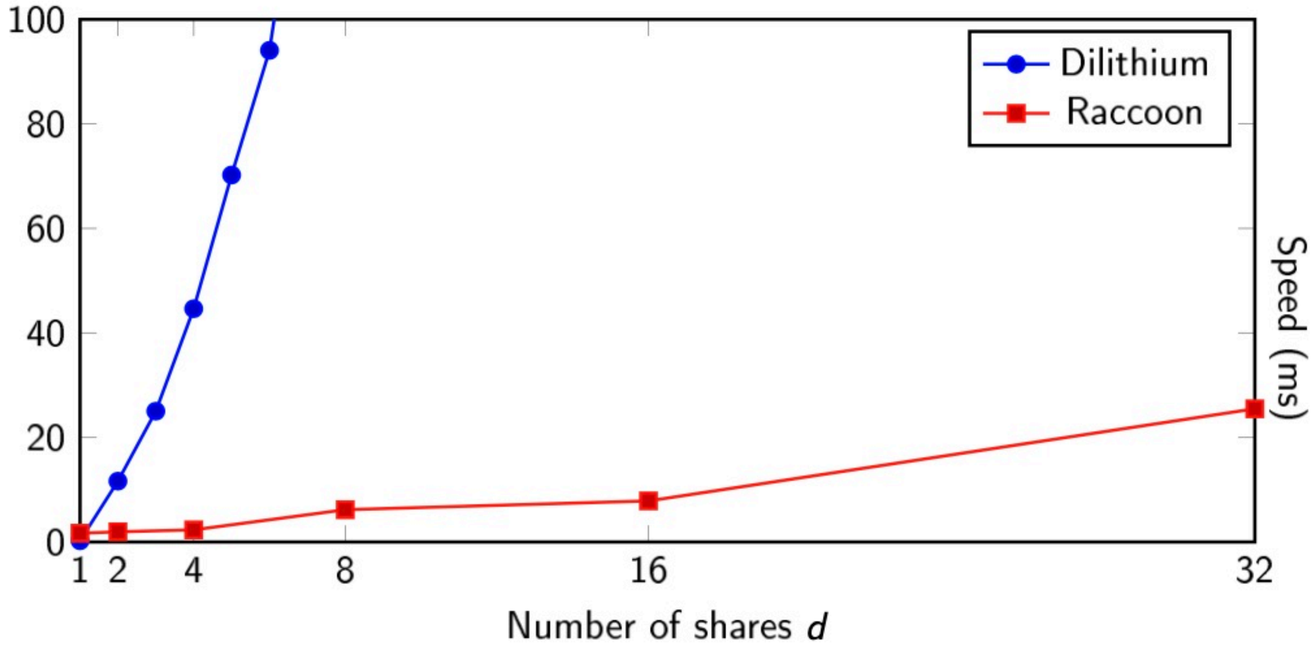

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Not selected for NIST additional post-quantum signatures (RIP)

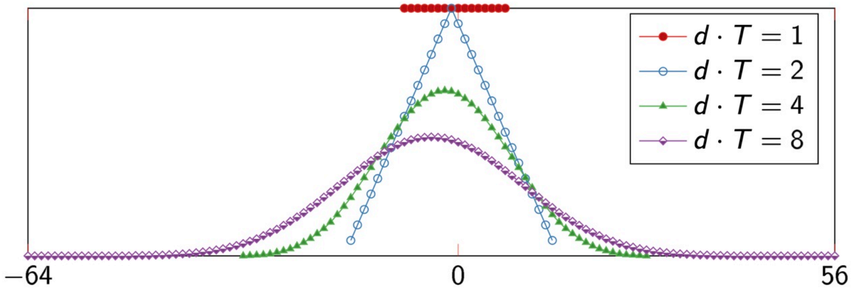
Random Probing Raccoon

KeyGen

1. Generate a large matrix $\mathbf{A} \in \mathscr{R}_q^{k \times \ell}$
2. $[\![s]\!] = (0,\ldots,0)$
3. Add noise to $[\![s]\!]$
4. Compute $[\![t]\!] = \mathbf{A} \cdot [\![s]\!]$
5. Add noise to $[\![t]\!]$
6. Decode $[\![t]\!]$ to t
7. The verification key is $(\mathbf{A}, t)$
8. The signing key is $[\![s]\!]$

« Add noise to »

Add $d \cdot T$ small uniform randoms



Distribution of the random that is added

Signature

1. $[\![r]\!] = \mathrm{Refresh}(0,\ldots,0)$
2. Add noise to $[\![r]\!]$
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4. Add noise to $[\![w]\!]$
5. Decode $[\![w]\!]$ to w
6. Compute the challenge $c = \mathrm{H}(w, \mathrm{msg}, \mathrm{vk})$
7. Compute the response $[\![z]\!] = [\![s]\!] \cdot c + [\![r]\!]$
8. Decode $[\![z]\!]$ to z
   No Rejection Sampling
9. The signature is sig = (c, z)

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A New Notion

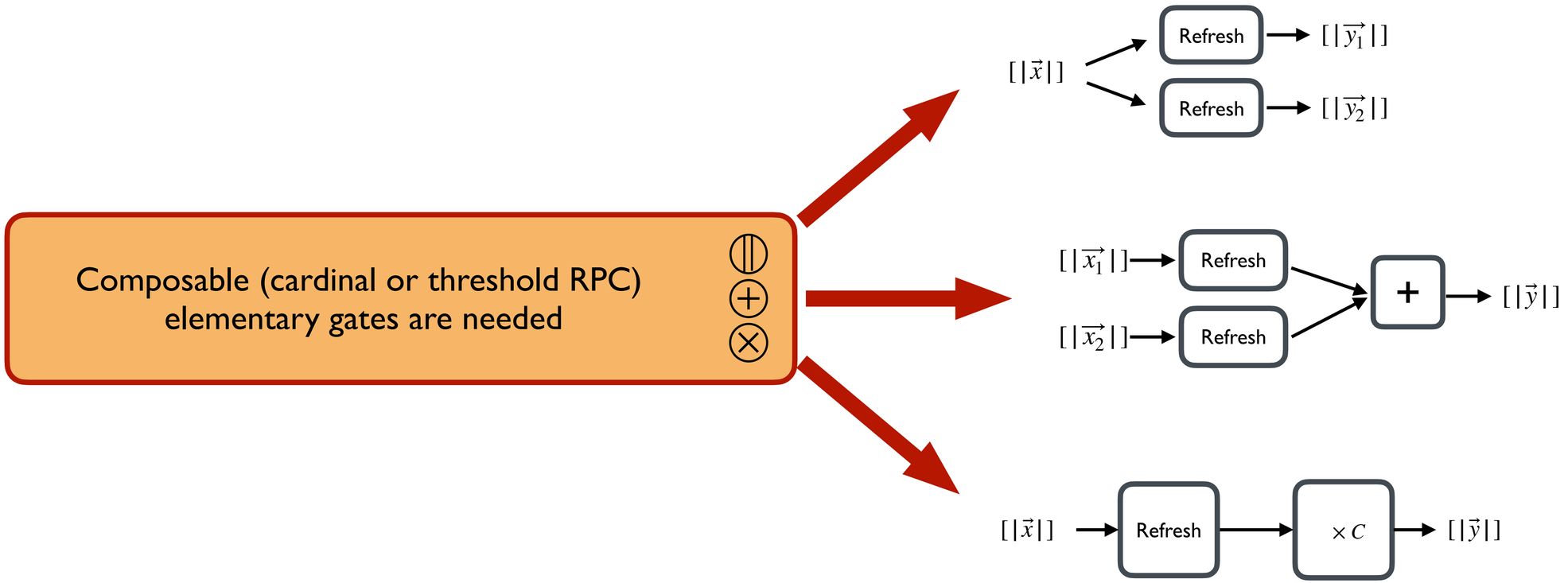
Random Probing Security with Auxiliary Inputs and public Outputs (RPS-AI-O)

« Add noise to »

Add $d \cdot T$ small uniform randoms

New gadgets

Composable (cardinal or threshold RPC) elementary gates are needed



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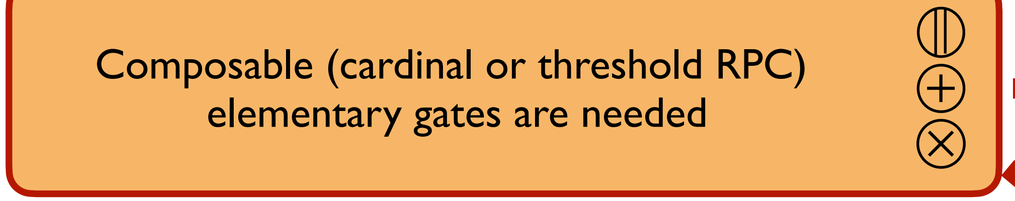

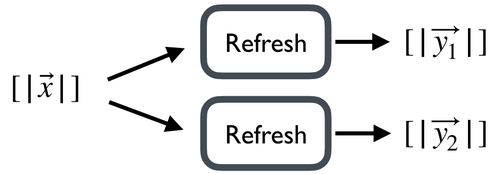

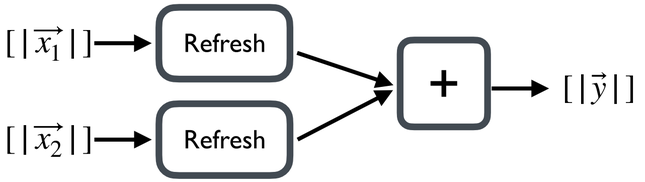

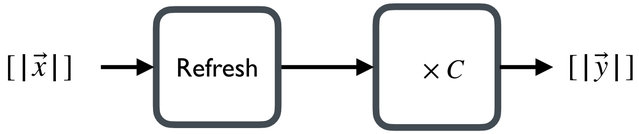

To be composable, they need to include some refreshes

Refresh ?

New gadgets

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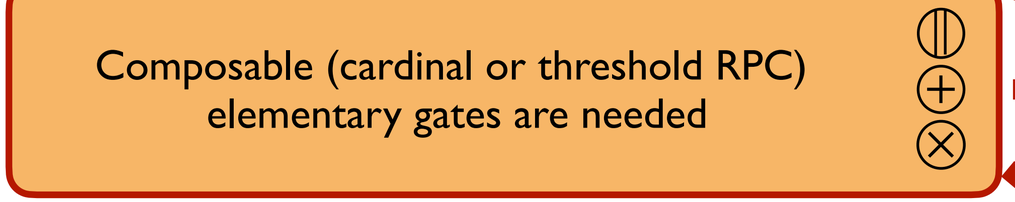
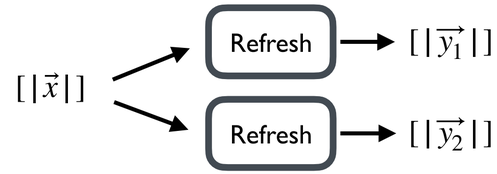
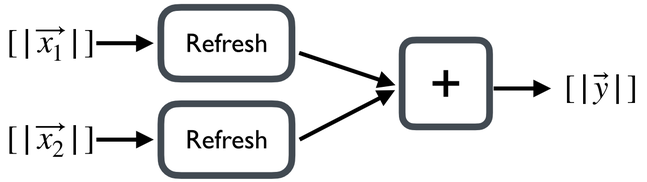
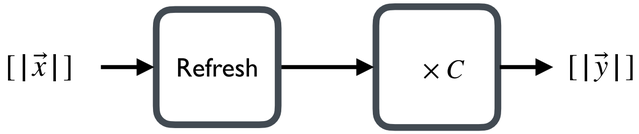






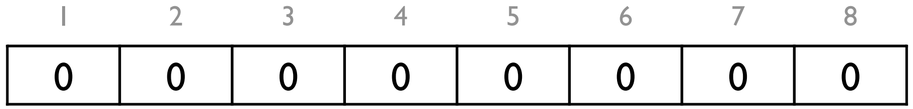


To be composable, they need to include some refreshes

Refresh ?

New Random Probing Composable Refresh

$[|z|] =$



New Random Probing Composable Refresh

$[|z|] =$

1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0

1st iteration

$r_1 \leftarrow \$, (i_1, j_1) \leftarrow \$ \qquad [(i_1, j_1) = (3,7)]$

$[|z|] =$

1	2	3	4	5	6	7	8
0	0	r_1	0	0	0	$-r_1$	0

New Random Probing Composable Refresh

$[|z|] =$

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$[|z|] =$

1	2	3	4	5	6	7	8
0	0	r_1	0	0	0	$-r_1$	0

2nd iteration

$r_2 \leftarrow \$, (i_2, j_2) \leftarrow \$ \qquad [(i_2, j_2) = (1,8)]$

$[|z|] =$

1	2	3	4	5	6	7	8
r_2	0	r_1	0	0	0	$-r_1$	$-r_2$

New Random Probing Composable Refresh

$[|z|] =$

1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0

1st iteration

$r_1 \leftarrow \$, (i_1, j_1) \leftarrow \$ \qquad [(i_1, j_1) = (3,7)]$

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2nd iteration

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$[|z|] =$

1	2	3	4	5	6	7	8
r_2	0	r_1	0	0	0	$-r_1$	$-r_2$

3rd iteration

$r_3 \leftarrow \$, (i_3, j_3) \leftarrow \$ \qquad [(i_3, j_3) = (2,3)]$

$[|z|] =$

1	2	3	4	5	6	7	8
r_2	r_3	$r_1 - r_3$	0	0	0	$-r_1$	$-r_2$

New Random Probing Composable Refresh

$[|z|] =$

1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0

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1	2	3	4	5	6	7	8
0	0	r_1	0	0	0	$-r_1$	0

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1	2	3	4	5	6	7	8
r_2	0	r_1	0	0	0	$-r_1$	$-r_2$

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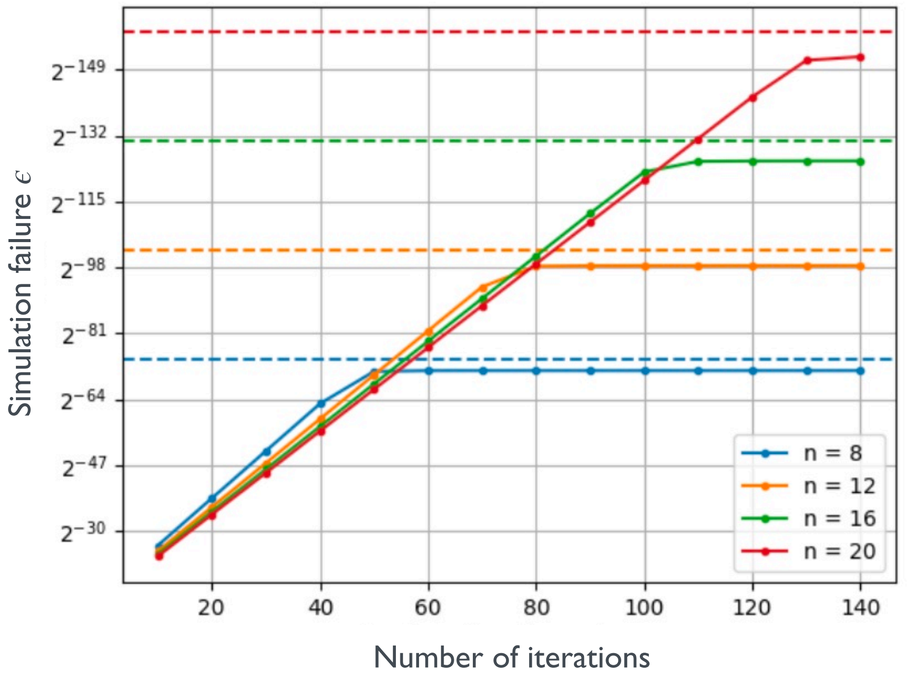
1	2	3	4	5	6	7	8
r_2	r_3	$r_1 - r_3$	0	0	0	$-r_1$	$-r_2$



RPC-AI advantage of RPRefresh from cardinal-RPC

$p = 2^{-16}$

$t = n/2$

Random Probing Secure version of Raccoon

	Key Generation		Signature	
	Original	New Gadgets	Original	New Gadgets
# shares	16	16	16	16
# additions	8.49e7	1.82e9	1.02e8	3.44e9
# linear mult.	8.39e7	8.39e7	1.01e8	1.01e8
# randoms	3.60e5	6.57e8	5.57e5	1.42e9
Security RPS/C	1	2^{-132}	1	2^{-130}

Raccoon 128-16 ($n = 16$ shares)

- EUF-CMA secure even if 15 values of each auxiliary inputs leak
- $p = 2^{-24}$

Random Probing Secure version of Raccoon

	Key Generation			Signature		
	Original		New Gadgets	Original		New Gadgets
# shares	16		16	16		16
# additions	8.49e7	$\times 20$	1.82e9	1.02e8	$\times 30$	3.44e9
# linear mult.	8.39e7	$\times 1$	8.39e7	1.01e8	$\times 1$	1.01e8
# randoms	3.60e5	$\times 2000$	6.57e8	5.57e5	$\times 2500$	1.42e9
Security RPS/C	1		2^{-132}	1		2^{-130}

Raccoon 128-16 ($n = 16$ shares)

- EUF-CMA secure even if 15 values of each auxiliary inputs leak
- $p = 2^{-24}$

Current state of the art

☑ Existing elementary gadgets proved (Cardinal or threshold)-RPC
- ➡ Addition
- ➡ Multiplication
- ➡ Copy
- ➡ Refresh

☑ Composition achievable by combining the enveloppes.

☑ Complexity and penalty factor estimation for Raccoon.

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☑ Composition achievable by combining the enveloppes.

☑ Complexity and penalty factor estimation for Raccoon.

Exciting work still lies ahead !

☐ More advanced gadgets
- ➡ Mask conversions, comparisons (secadd)
- ➡ Sampling with specific distributions
- ➡ Quasilinear refresh

☐ Optimized composition for tighter bounds
- ➡ Comparing existing composition techniques

☐ Formal verification

☐ Efficient implementations

[BCPRT20] 8. Belaïd, S., Coron, J.S., Prouff, E., Rivain, M., Taleb, A.R. *Random probing security: Verification, composition, expansion and new constructions.* CRYPTO 2020

[BFO23] Berti, F., Faust, S., Orlt, M. *Provable secure parallel gadgets*. TCHES 2023

[DFZ19] S. Dziembowski, S. Faust, K. Zebrowski
Simple refreshing in the noisy leakage model. ASIACRYPT 2019

[JMB24] V. Jahandideh, B. Mennink and L. Batina
An Algebraic Approach for Evaluating Random Probing Security With Application to AES. TCHES 2024

Thank you