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New Techniques for Random Probing Security

Application to Raccoon Signature Scheme

Sonia Belaïd, Matthieu Rivain and Mélissa Rossi

https://eprint.iacr.org/2025/278

European Research Council
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PHISIC
Gardanne May 21, 2025

1) The random probing model

2) Composition in the random probing model

3) Random-probing Raccoon

Masking

$$\begin{tikzcd}
 & & & & \text{Sensitive variable } x \arrow[dlll] \arrow[dl] \arrow[drrr] & & & \\
x = & x_1 & + & x_2 & + & \cdots & + & x_n
\end{tikzcd}$$

A Multiplication gadget

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

```
$r \leftarrow \$$
$z_1 \leftarrow x_1 k_1 + r$
$r' \leftarrow x_1 k_2 - r$
$r'' \leftarrow r' + x_2 k_1$
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```

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x = & x_1 + & x_2 + & \cdots & + & x_n
\end{tikzcd}$$

Attacker view?

A Multiplication gadget

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

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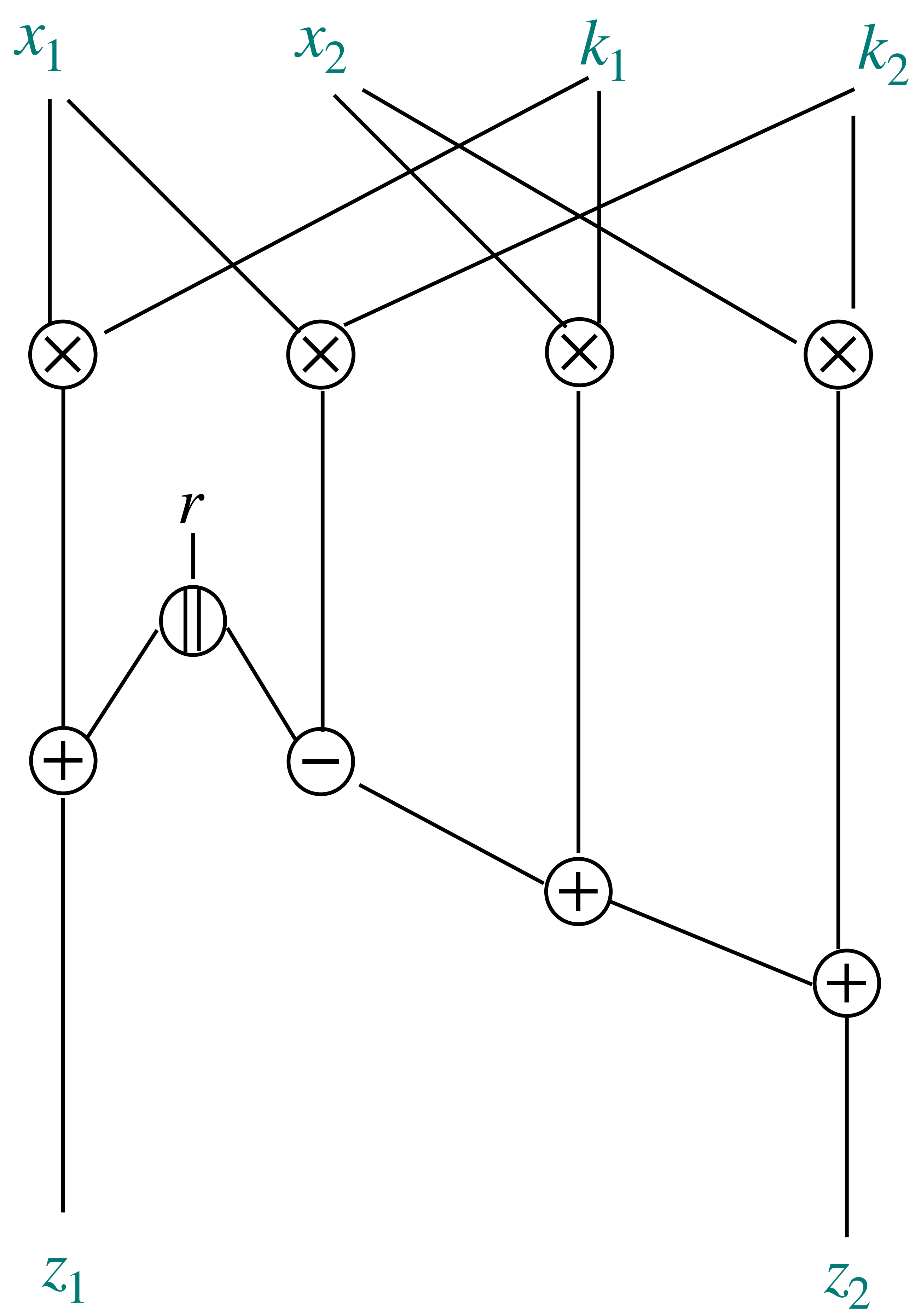
\end{aligned}$$

Leakage Models

Attacker view



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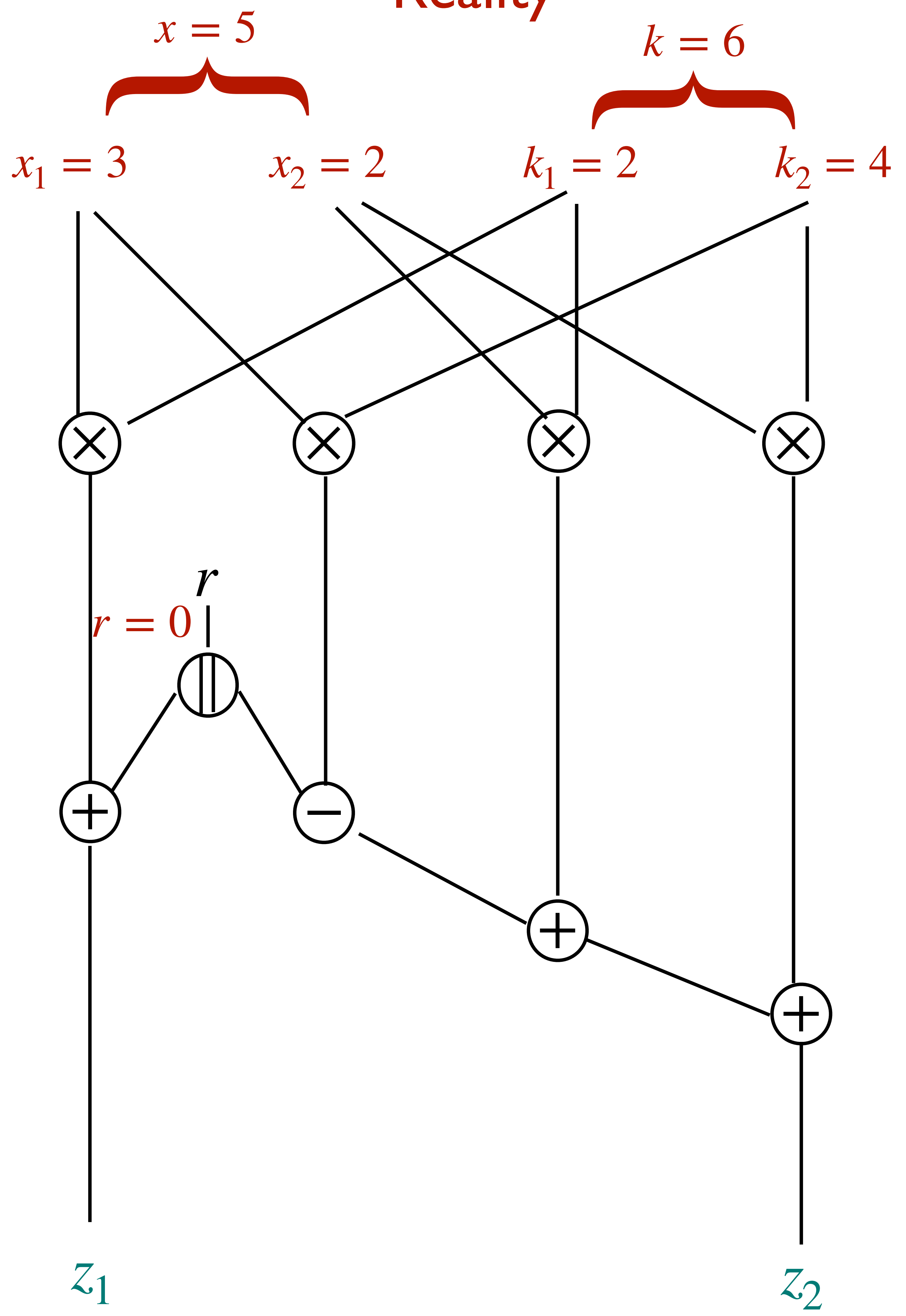
Reality



Leakage Models

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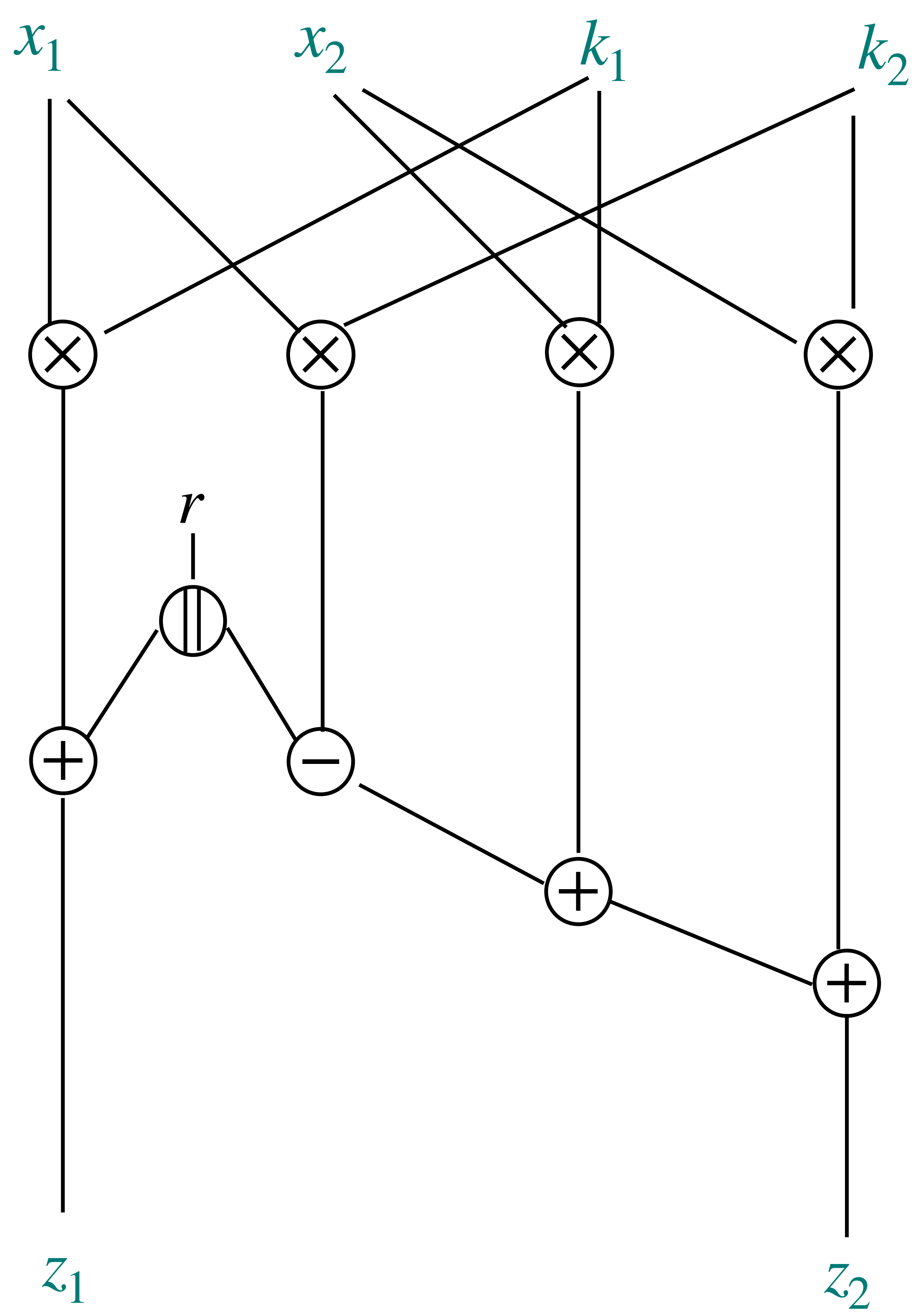
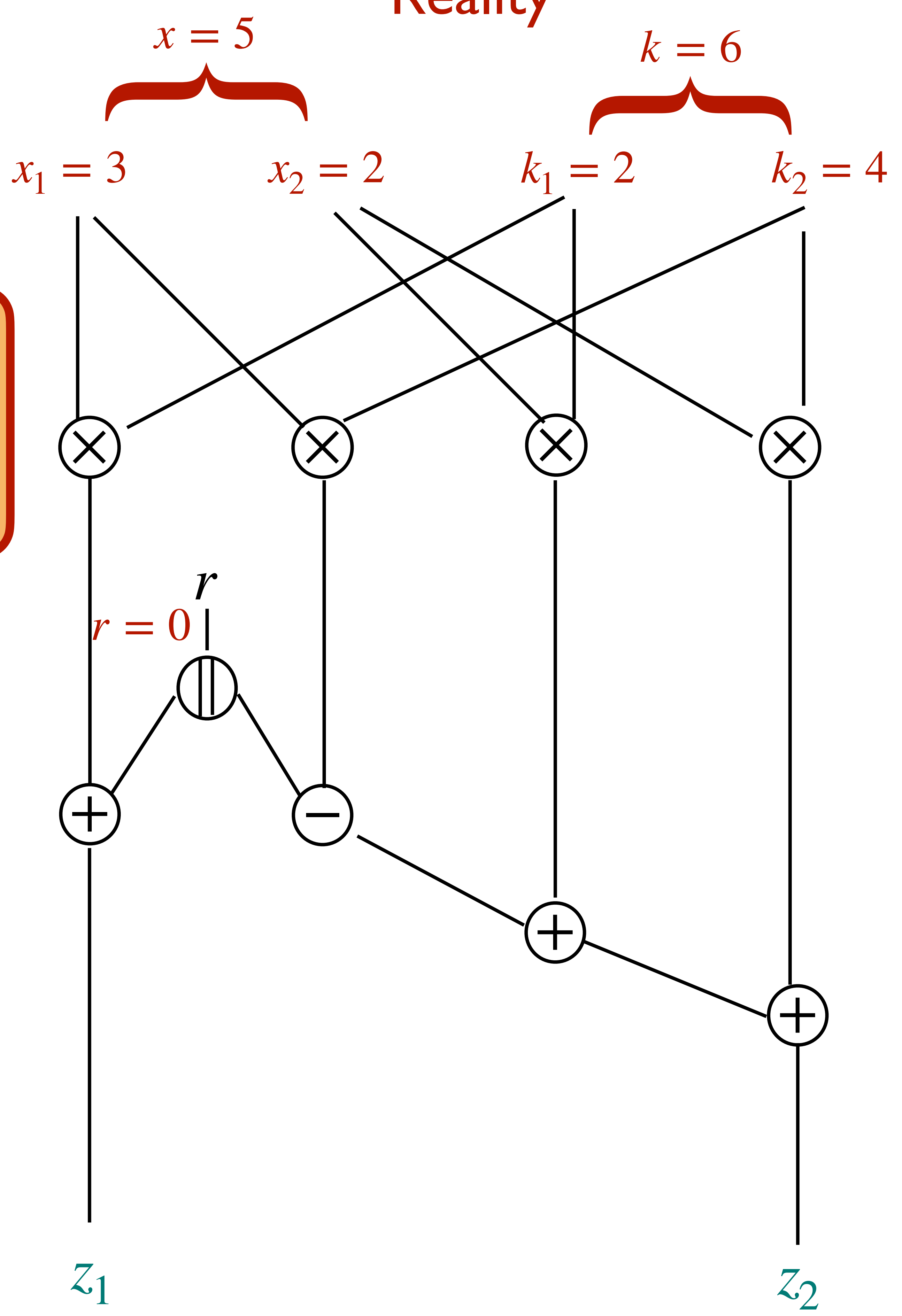


Attacker model

Attacker ← circuit + leakage

The attacker must not recover any information about $x = \sum x_i$ or $k = \sum k_i$.

Reality



Leakage Models

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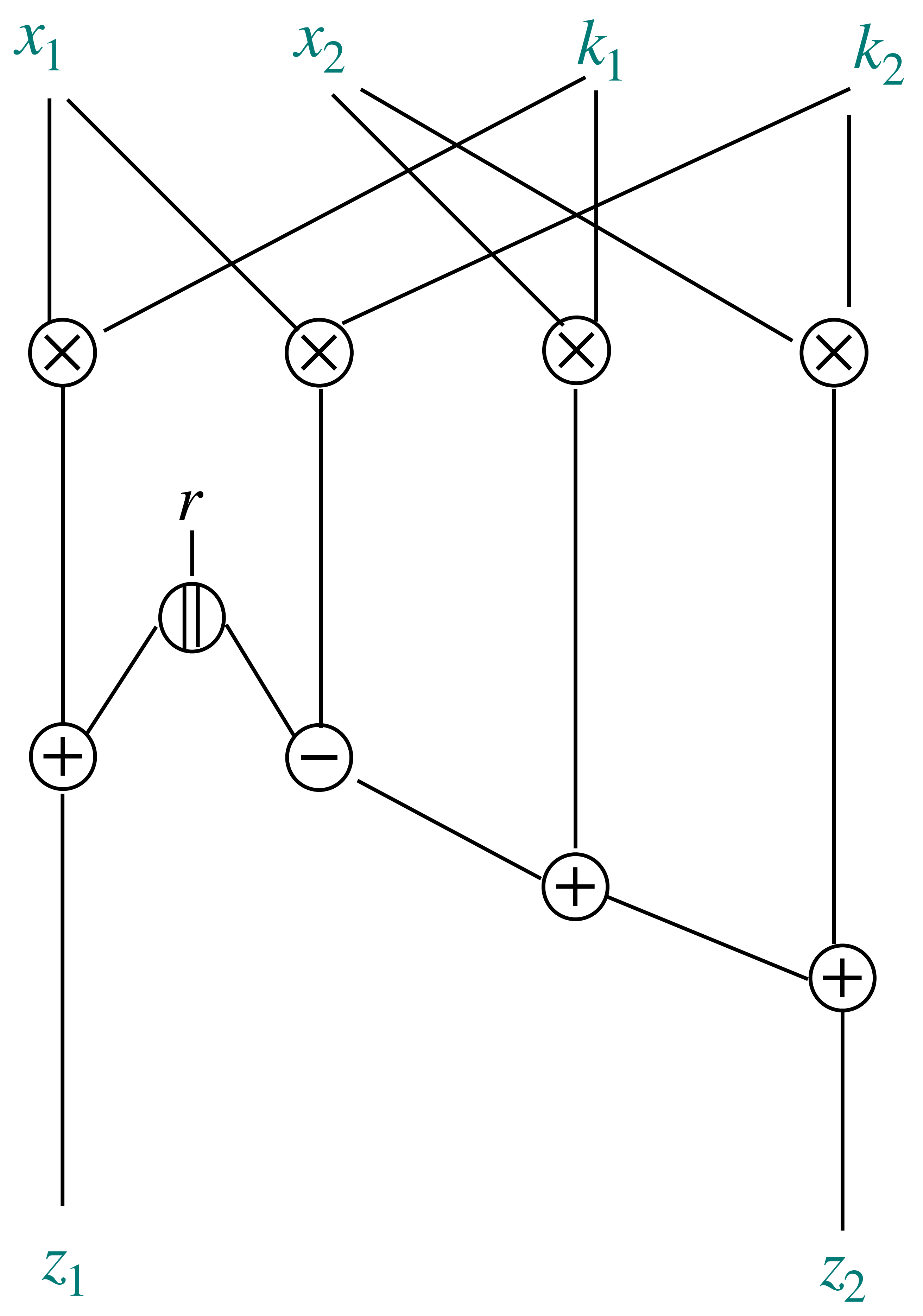

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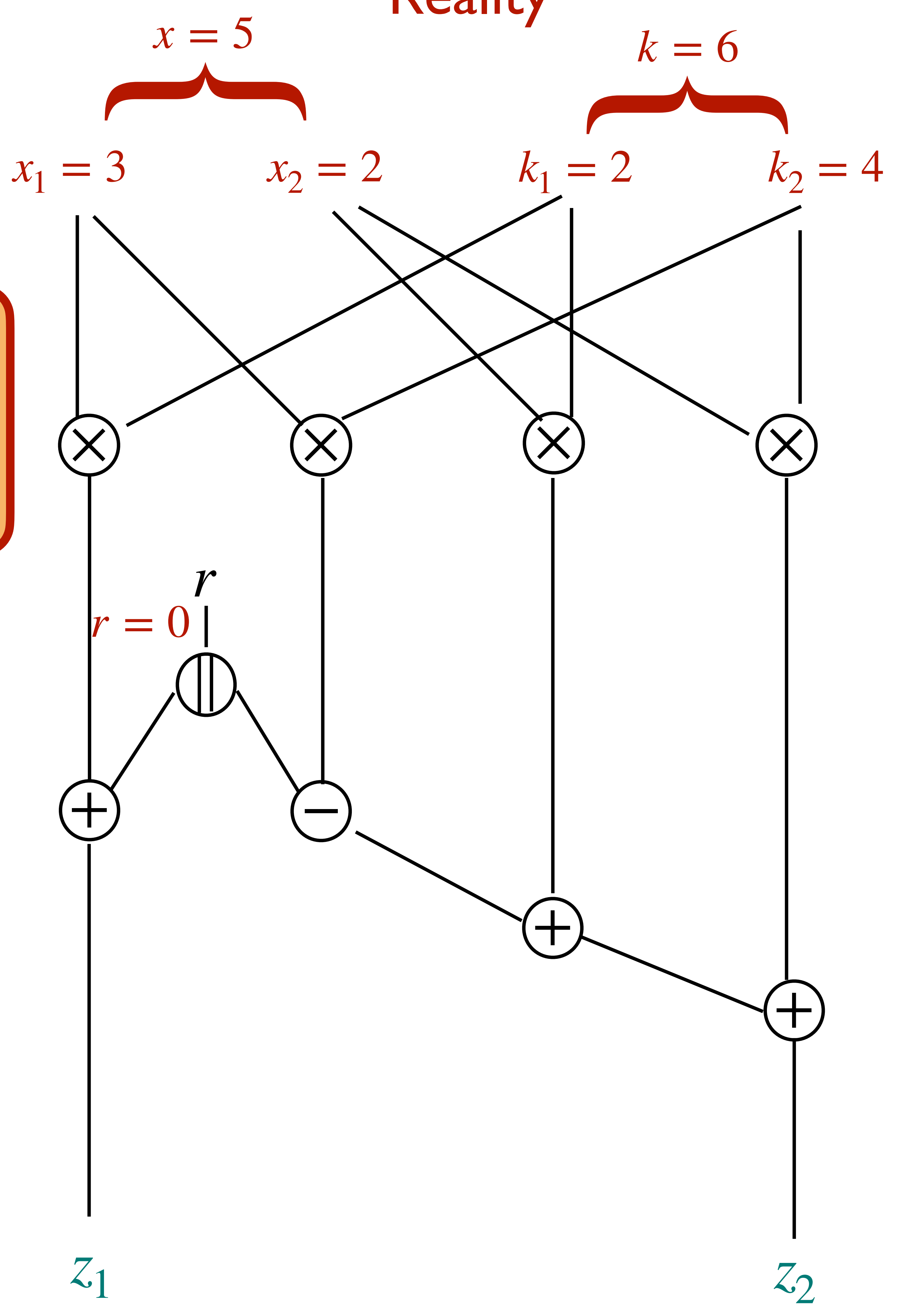

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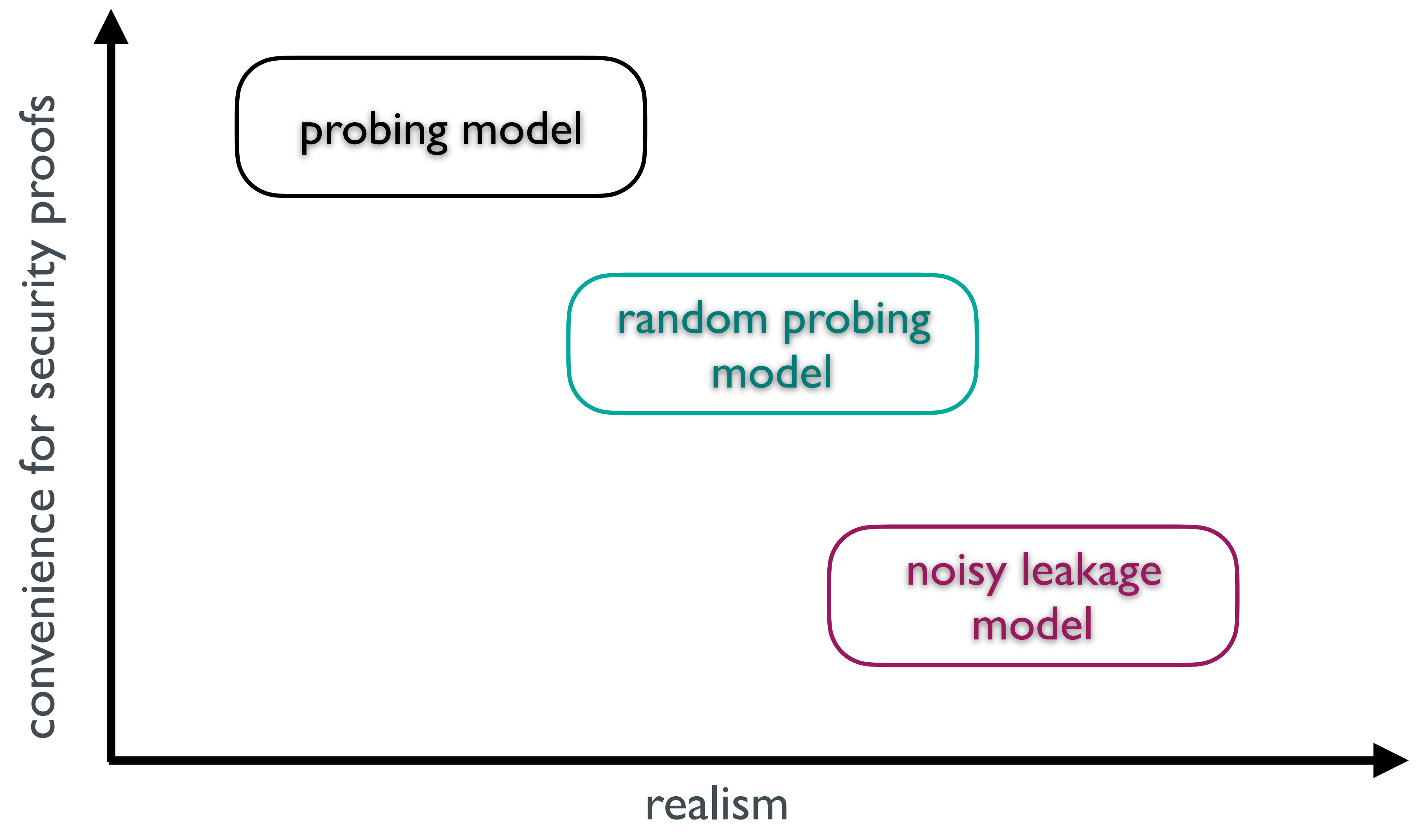
3 flavours



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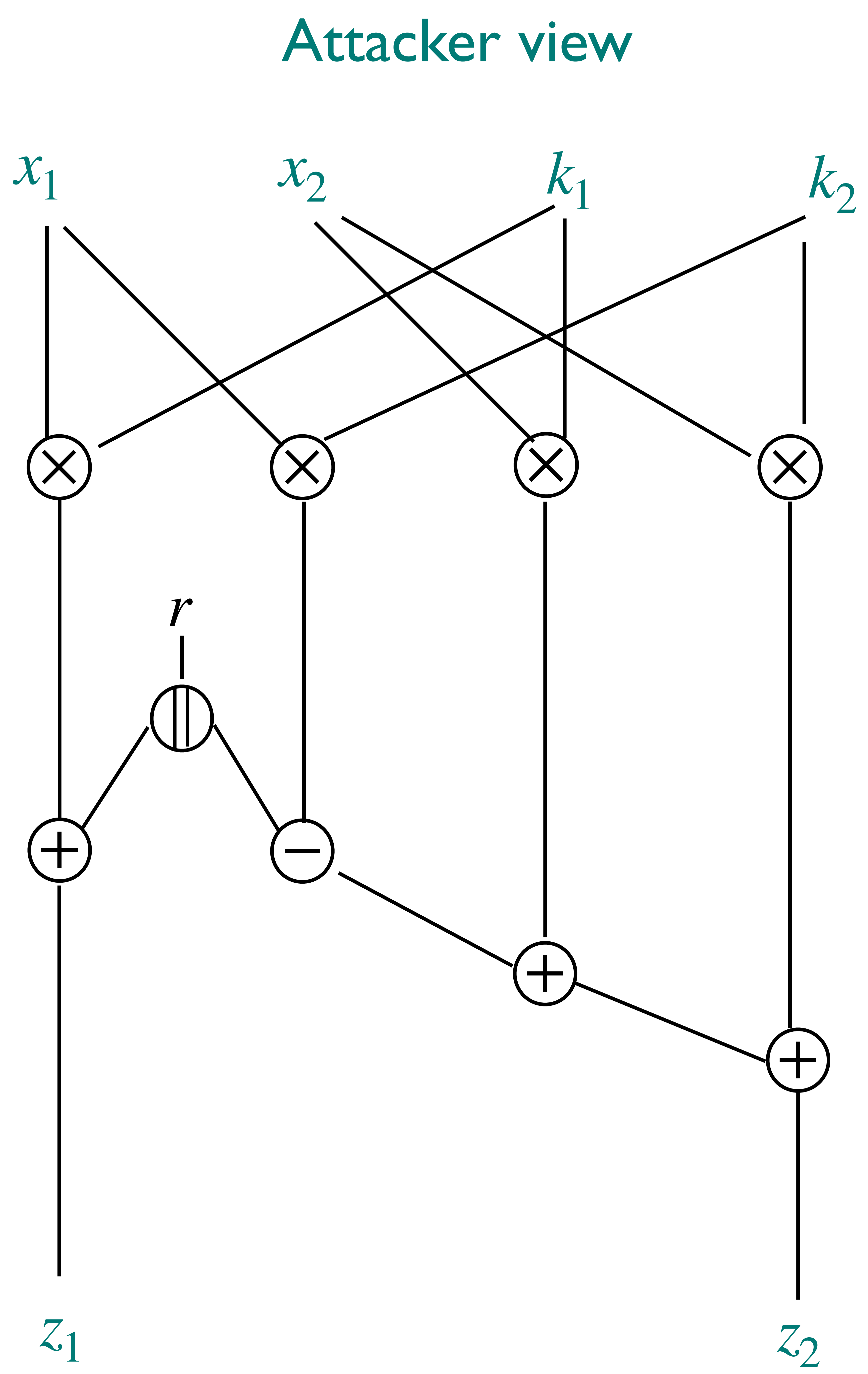

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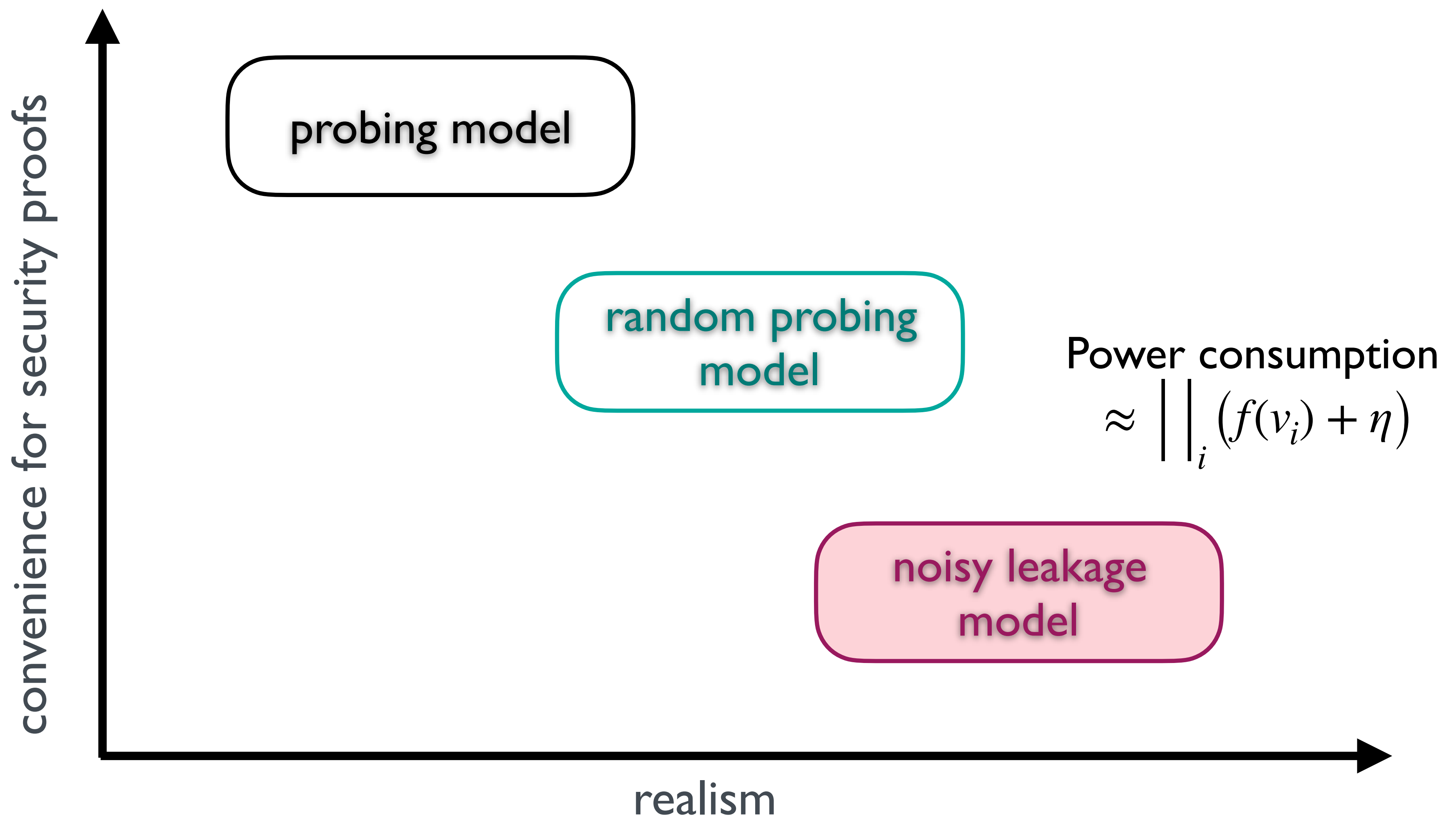
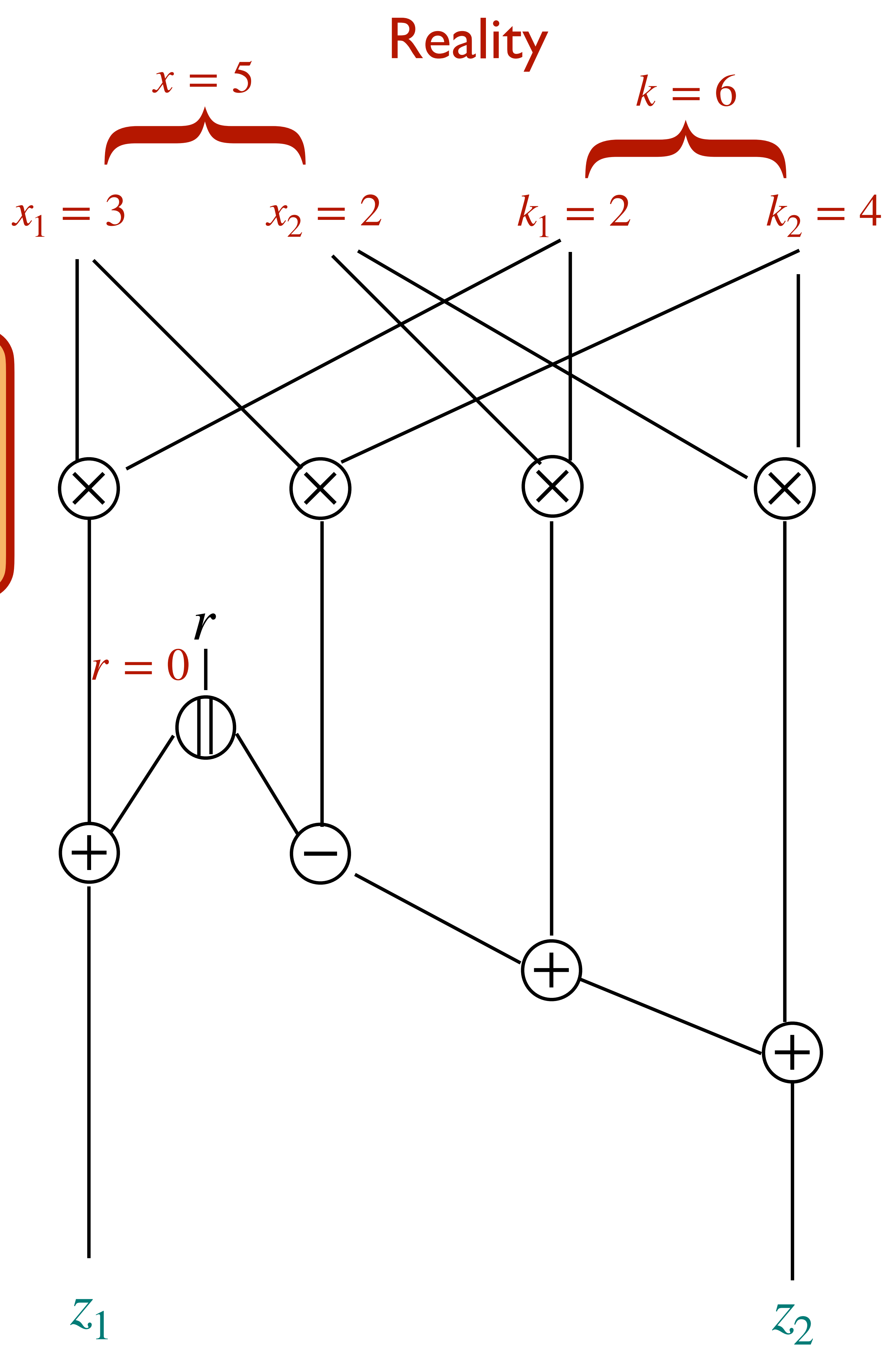

convenience for security proofs
realism
probing model
random probing model
noisy leakage model
Power consumption
$\approx \Big|\Big|_i \big(f(v_i) + \eta\big)$



Leakage Models

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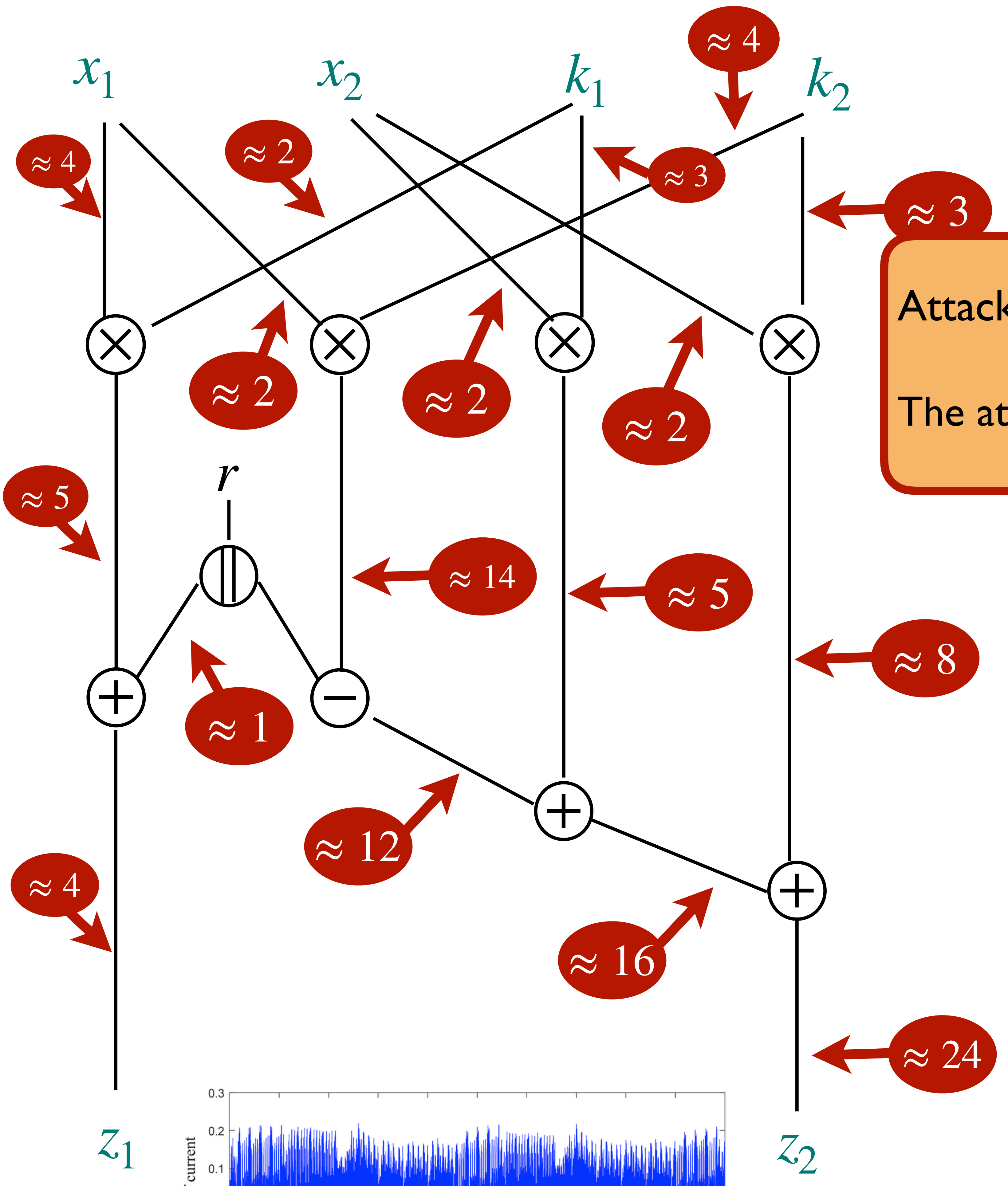

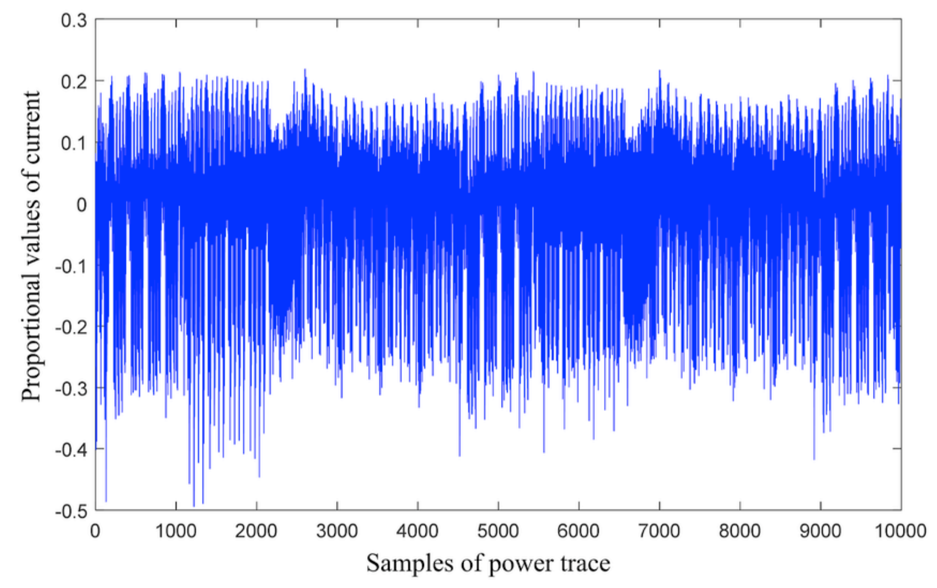

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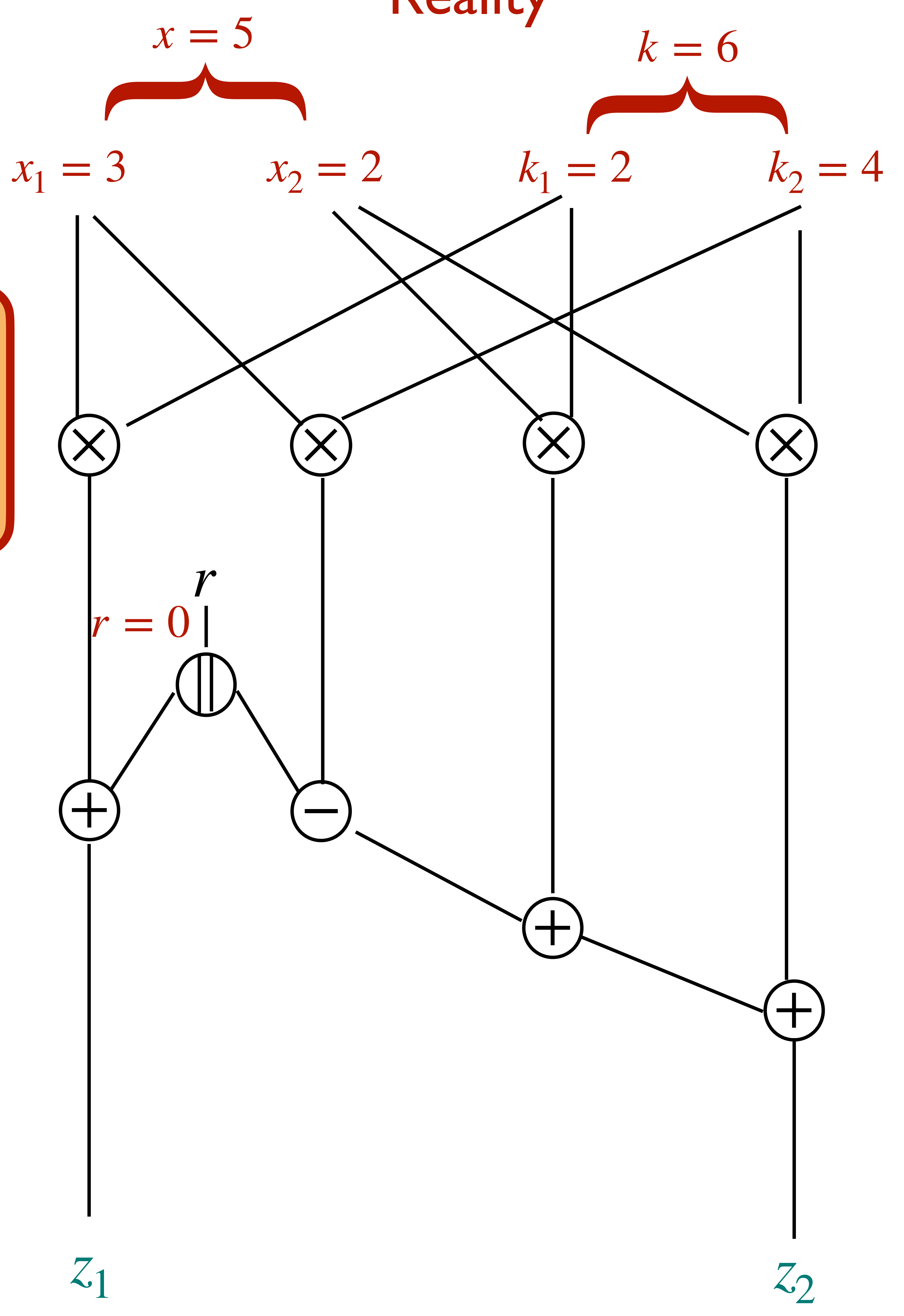

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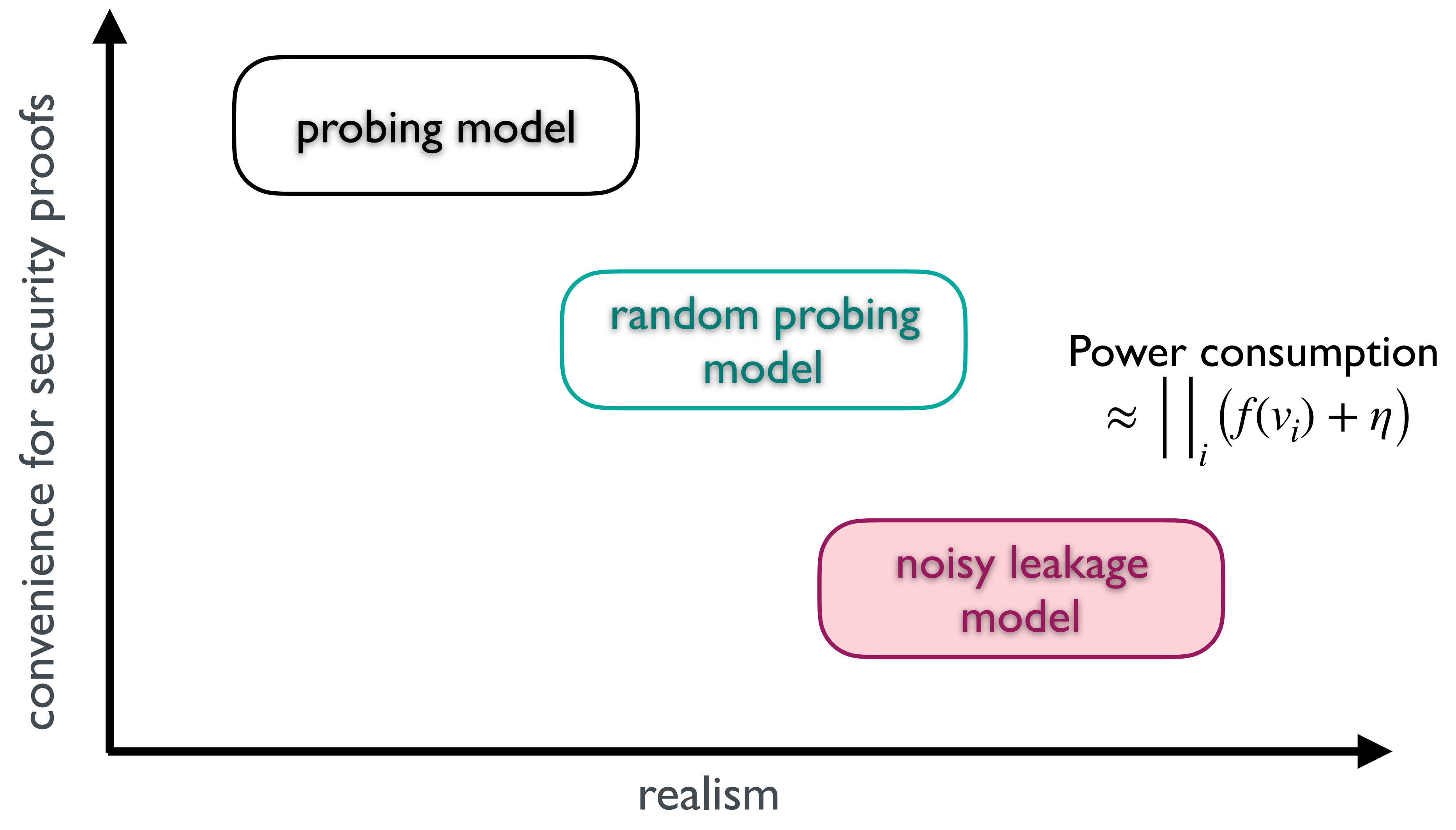

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Leakage Models

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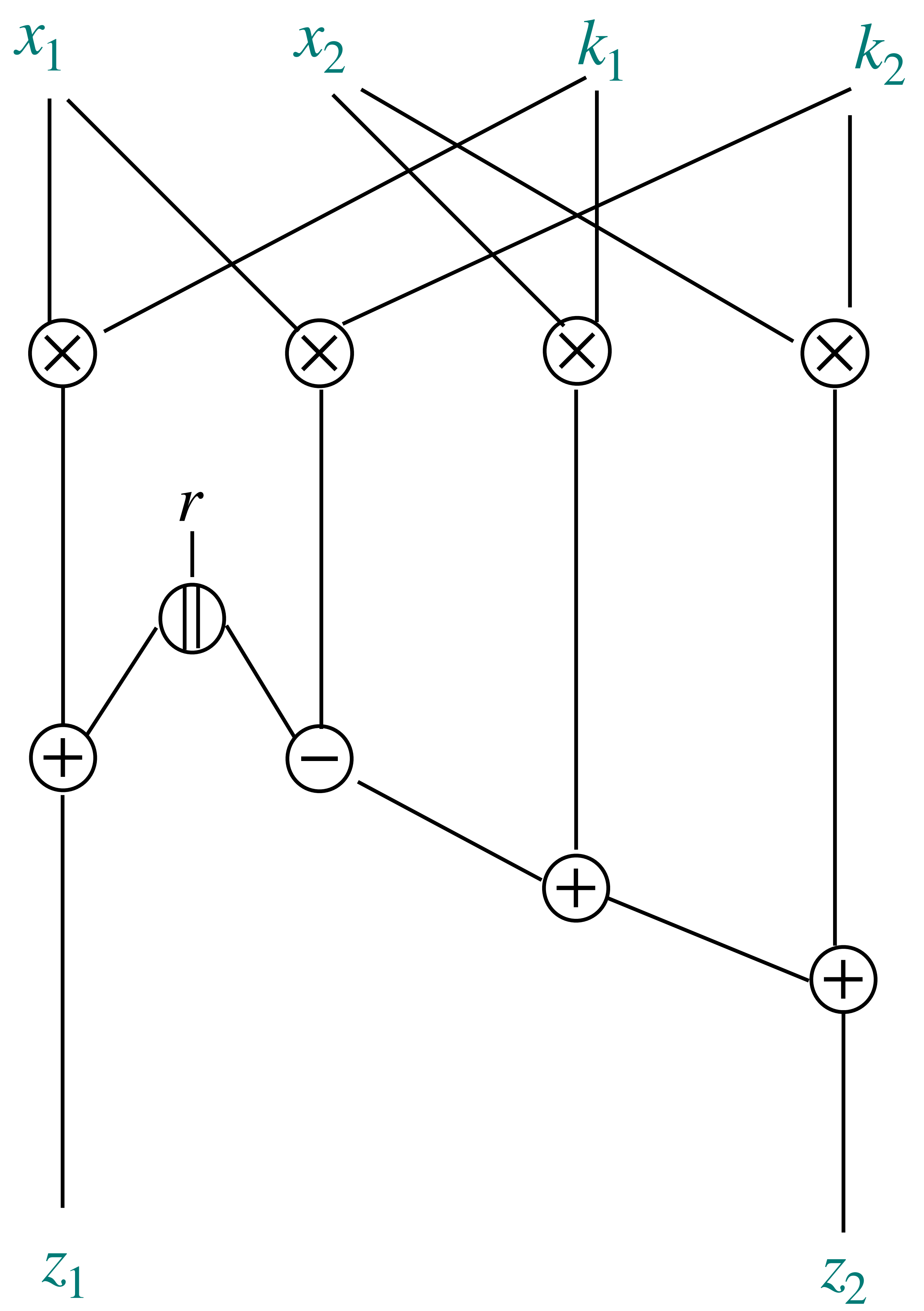

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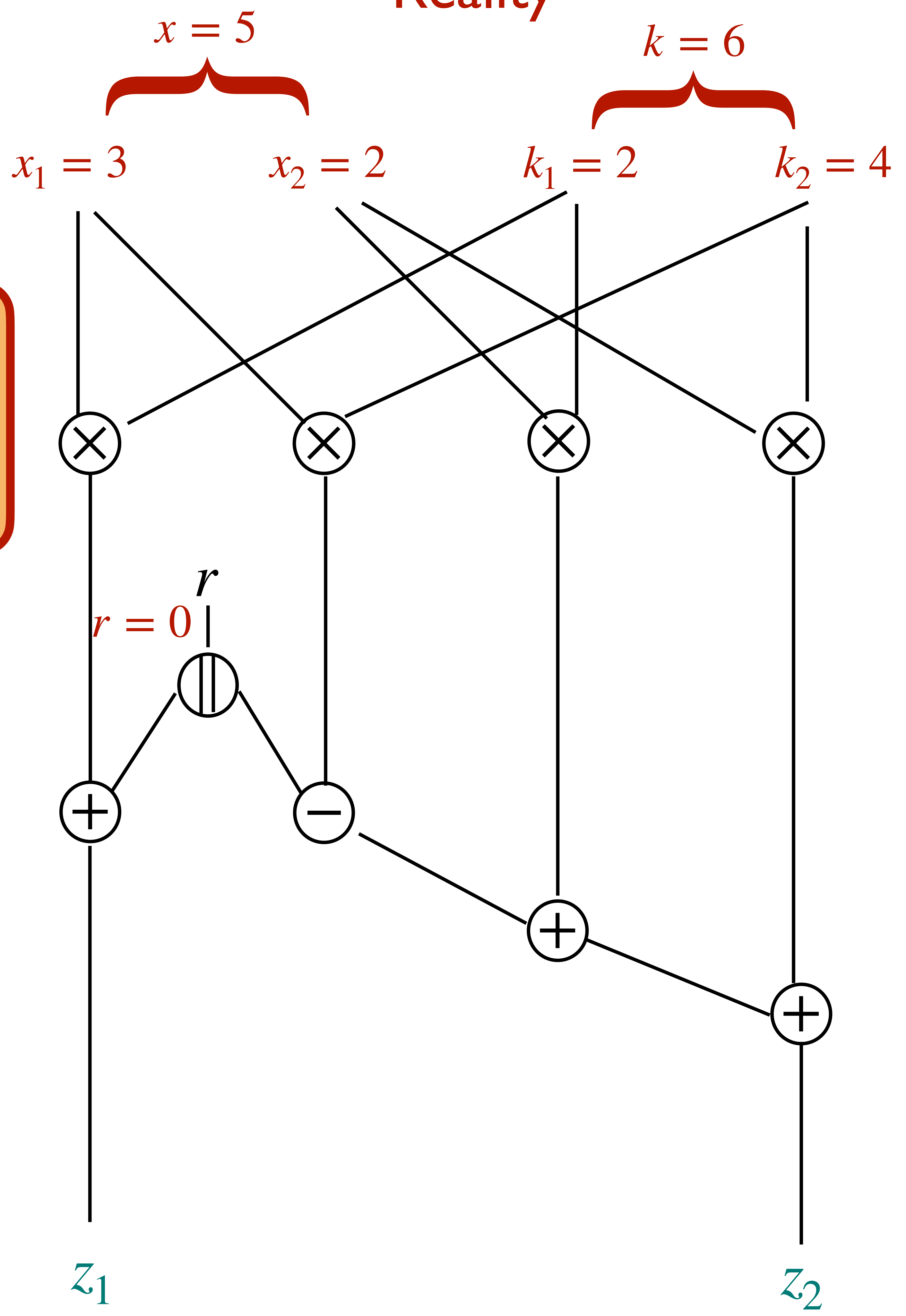

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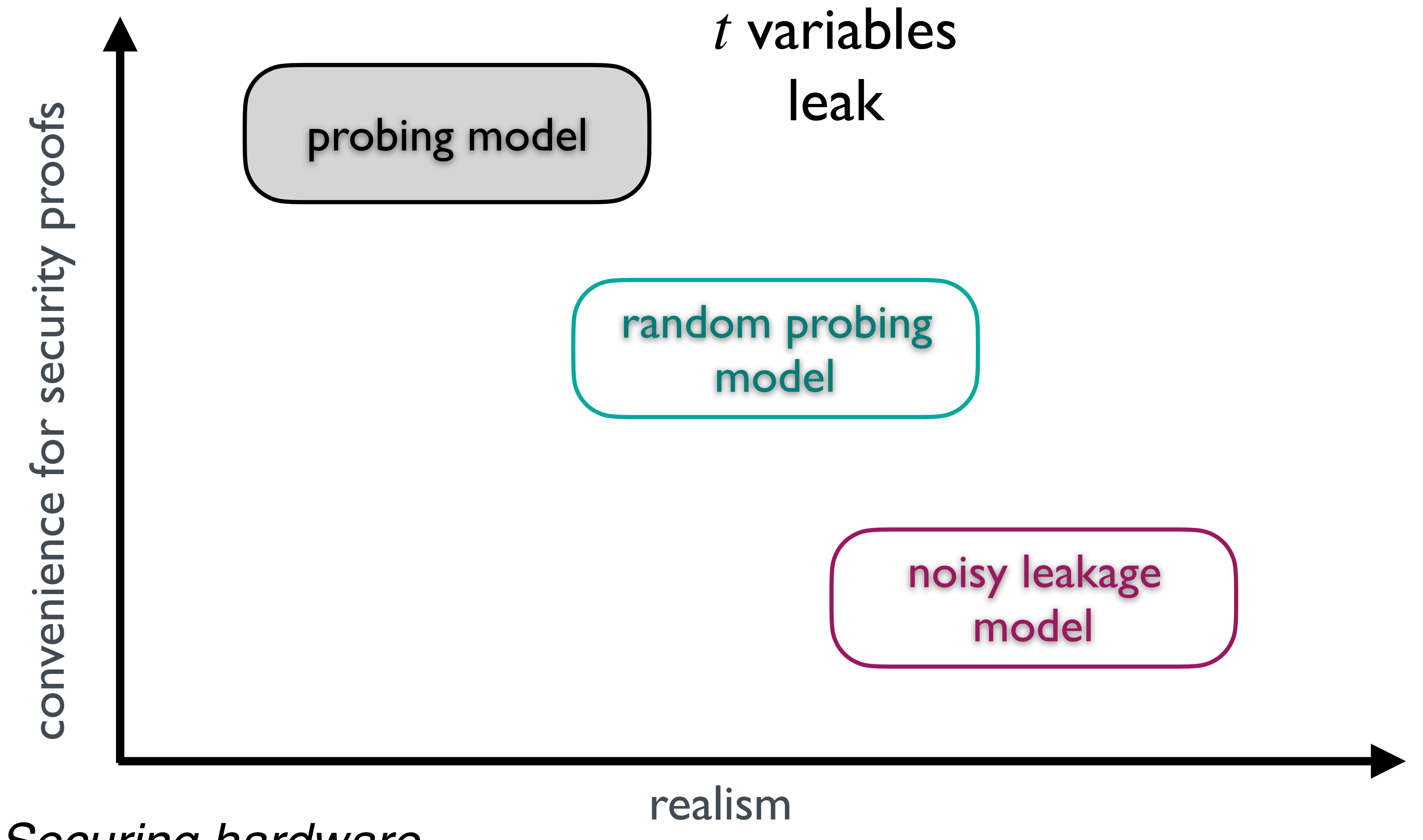
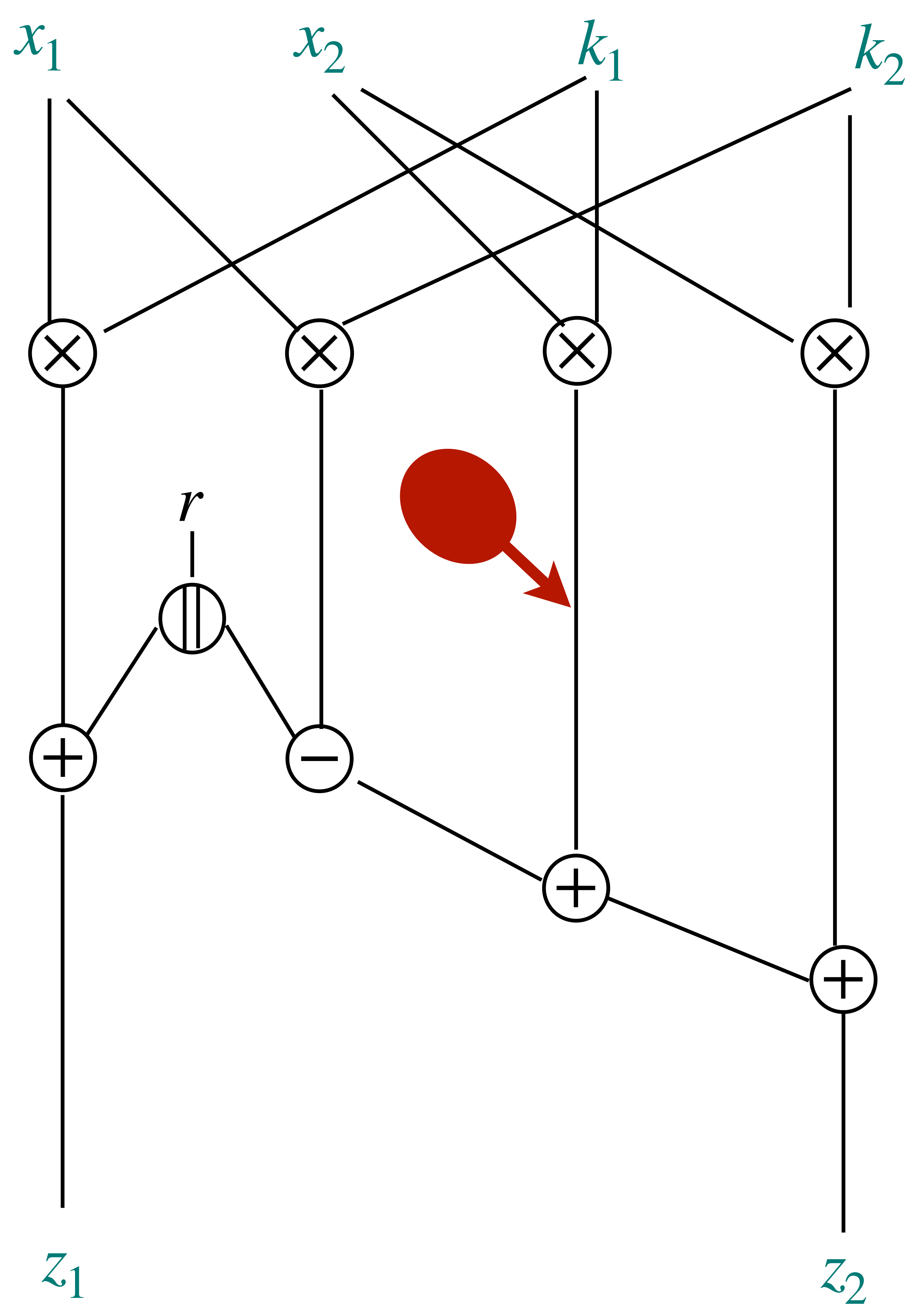


[ISW03] Y. Ishai, A. Sahai, and D. Wagner. *Private circuits: Securing hardware against probing attacks*. CRYPTO 2003

Leakage Models

Attacker view



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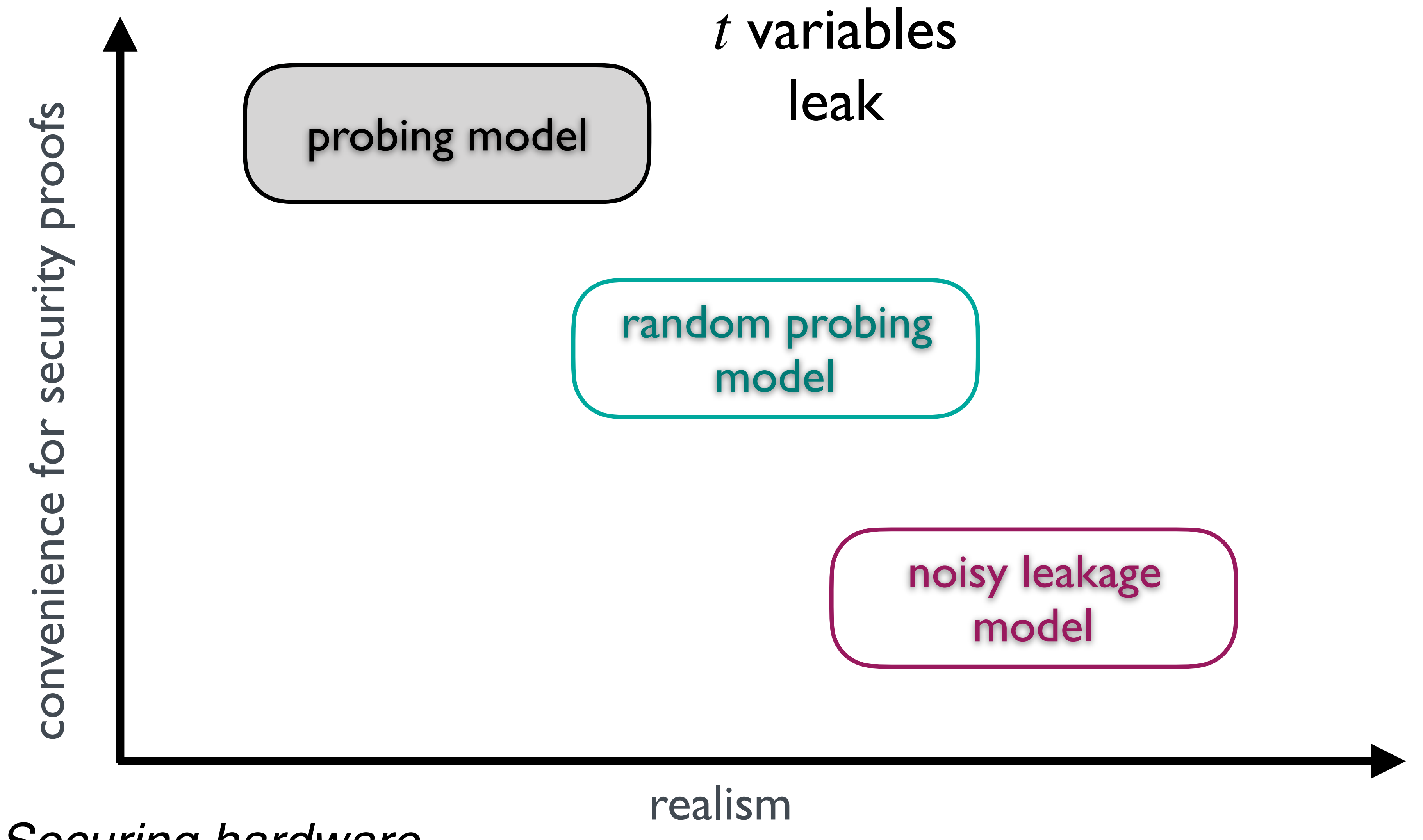

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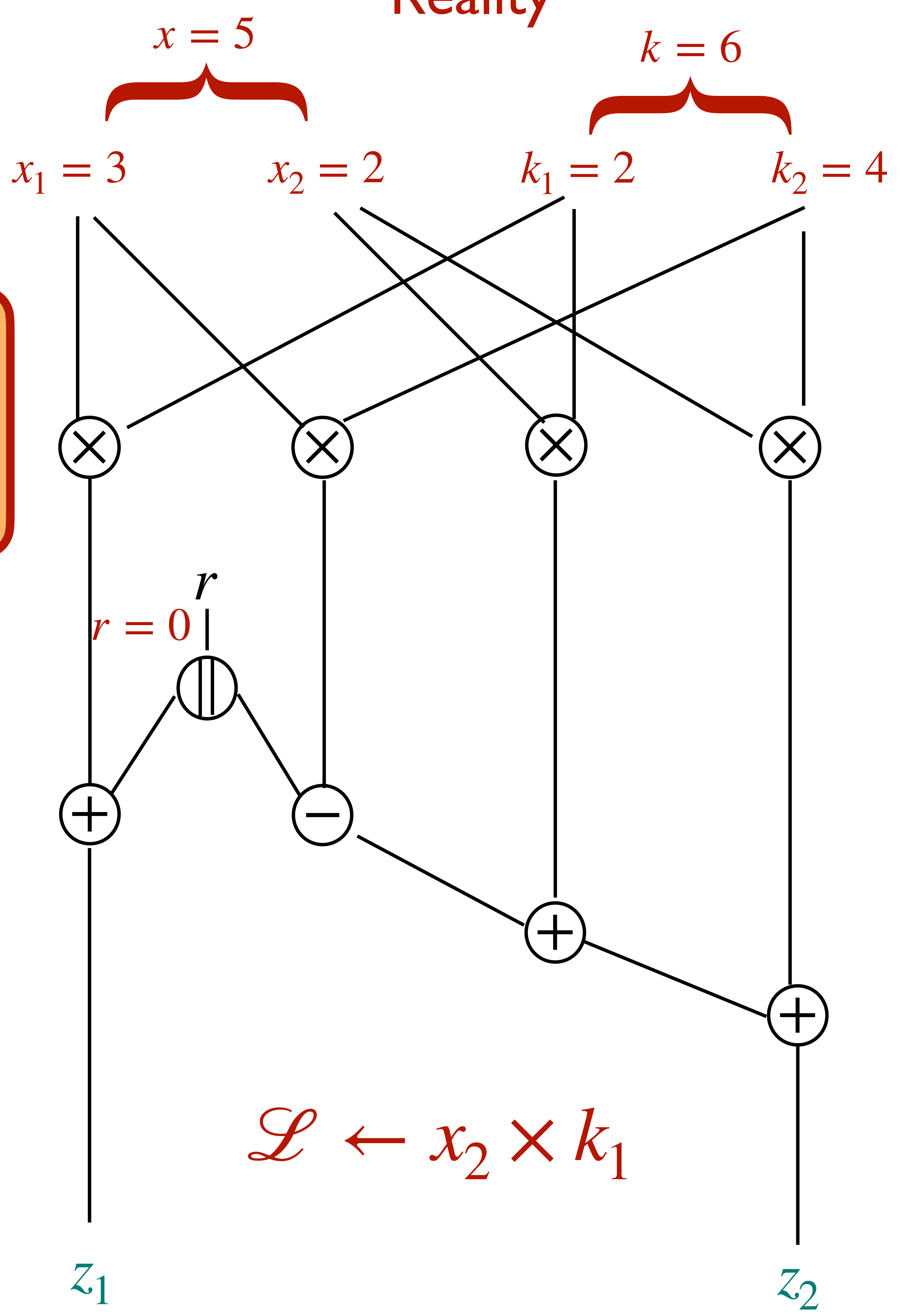

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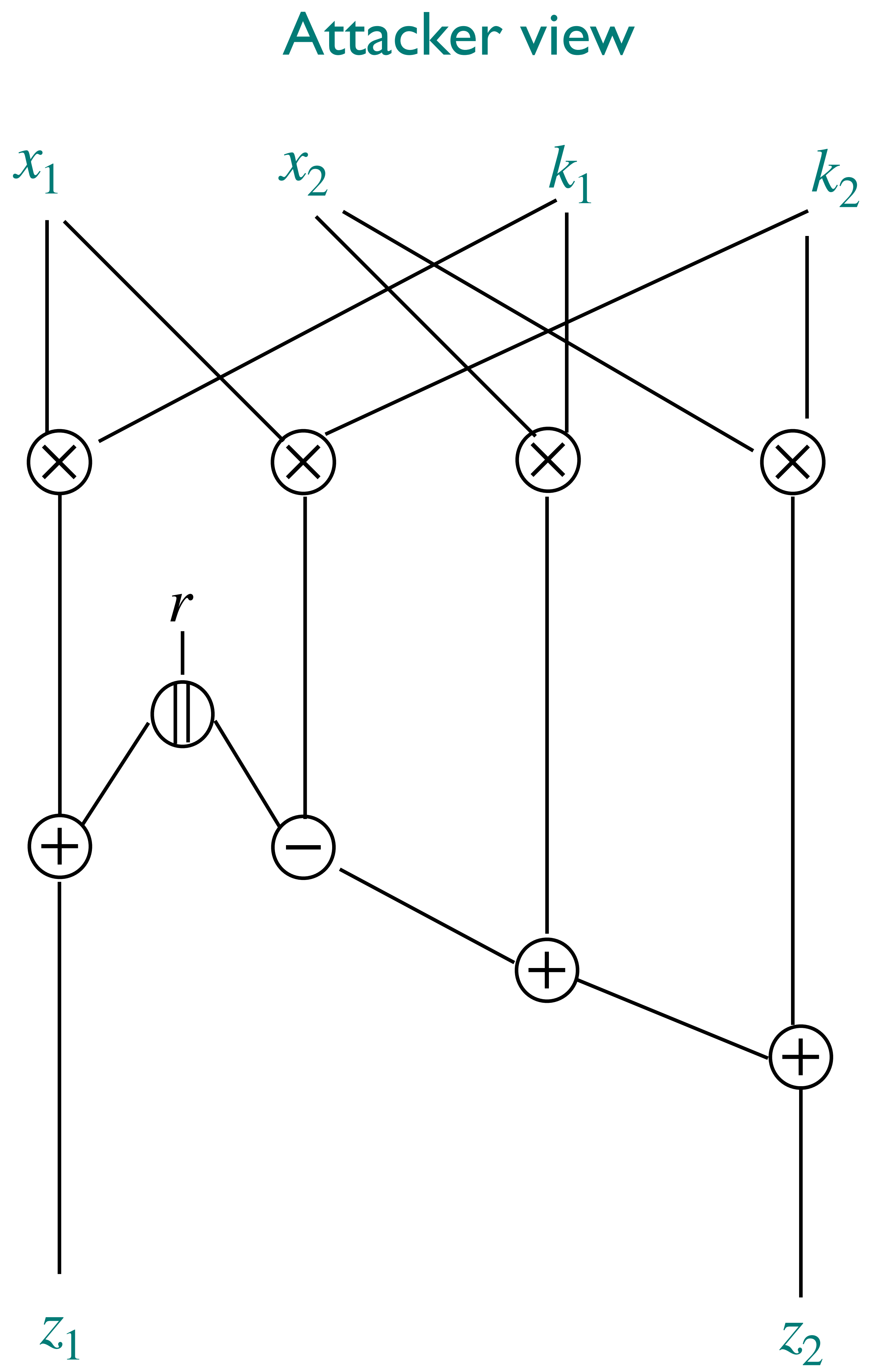
Random probing model



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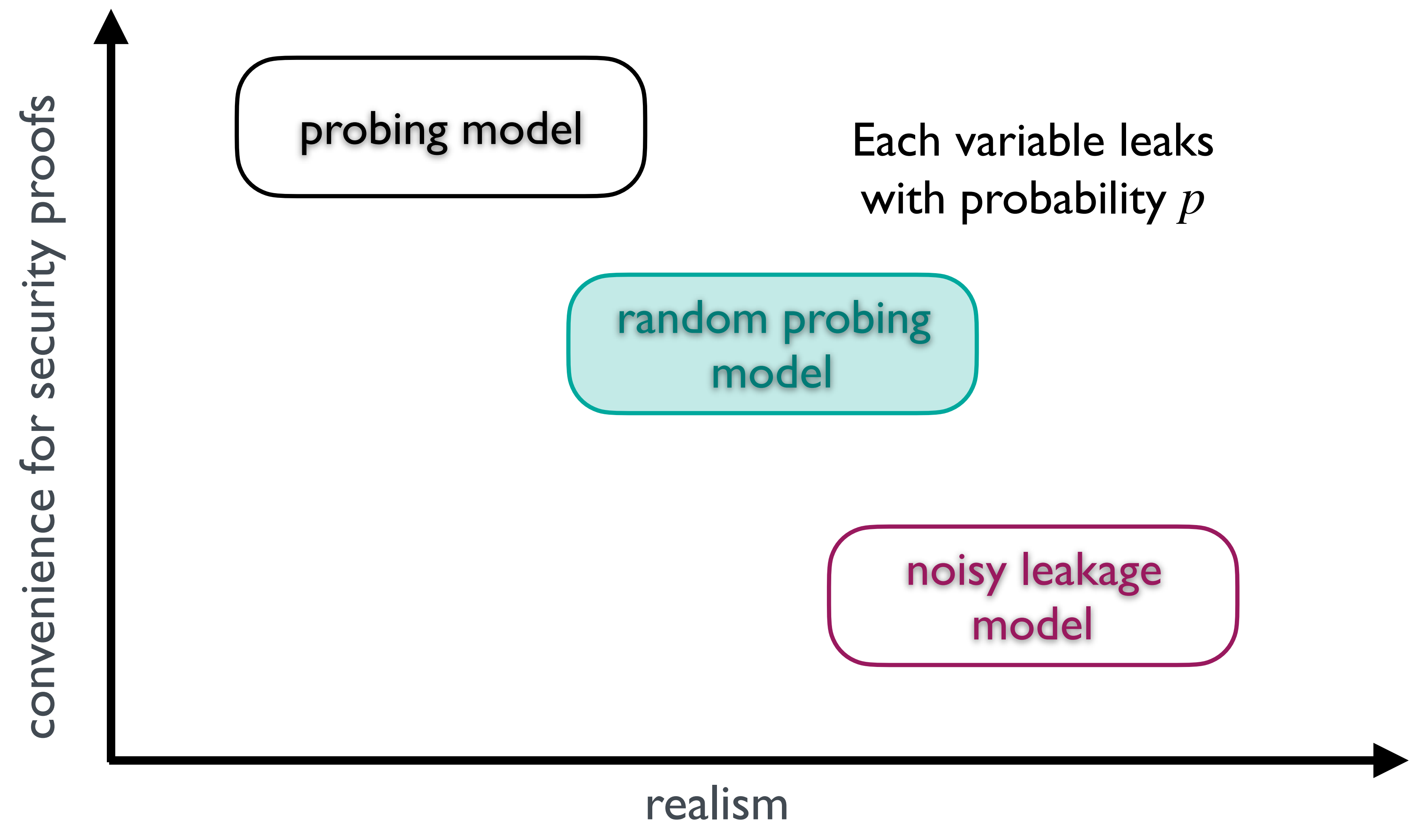
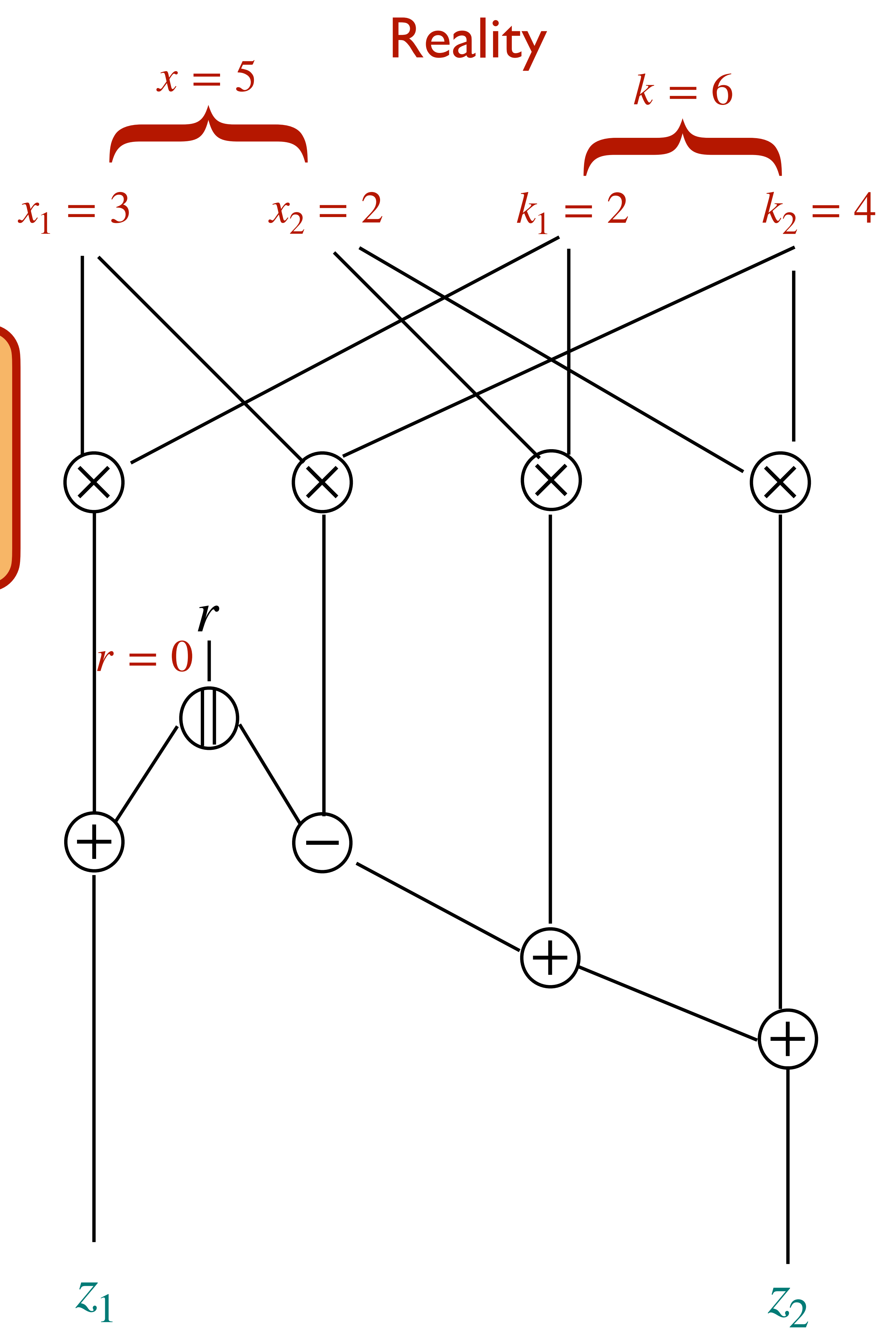


Each variable leaks with probability p



Random probing model

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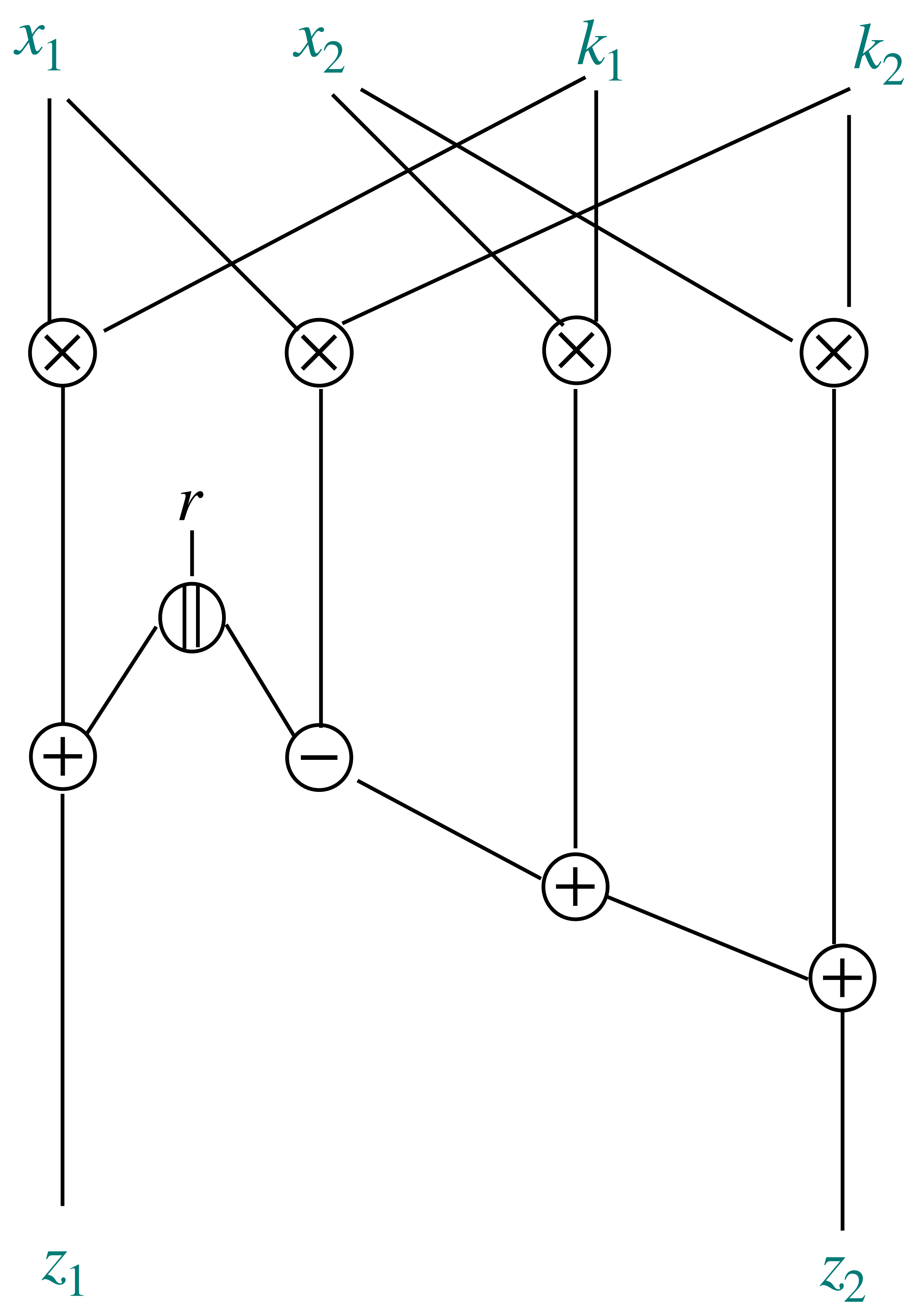

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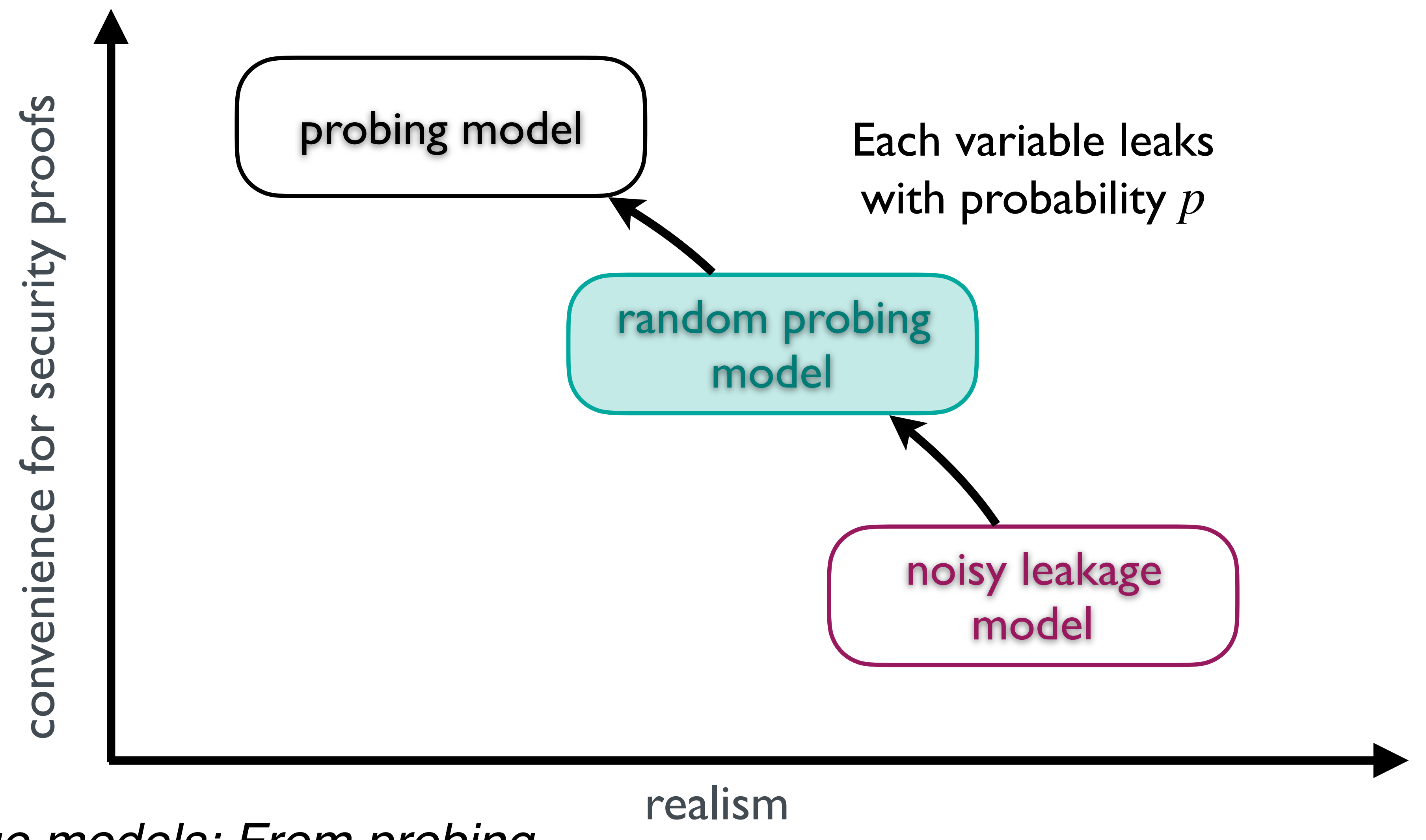

probing model
random probing model
noisy leakage model
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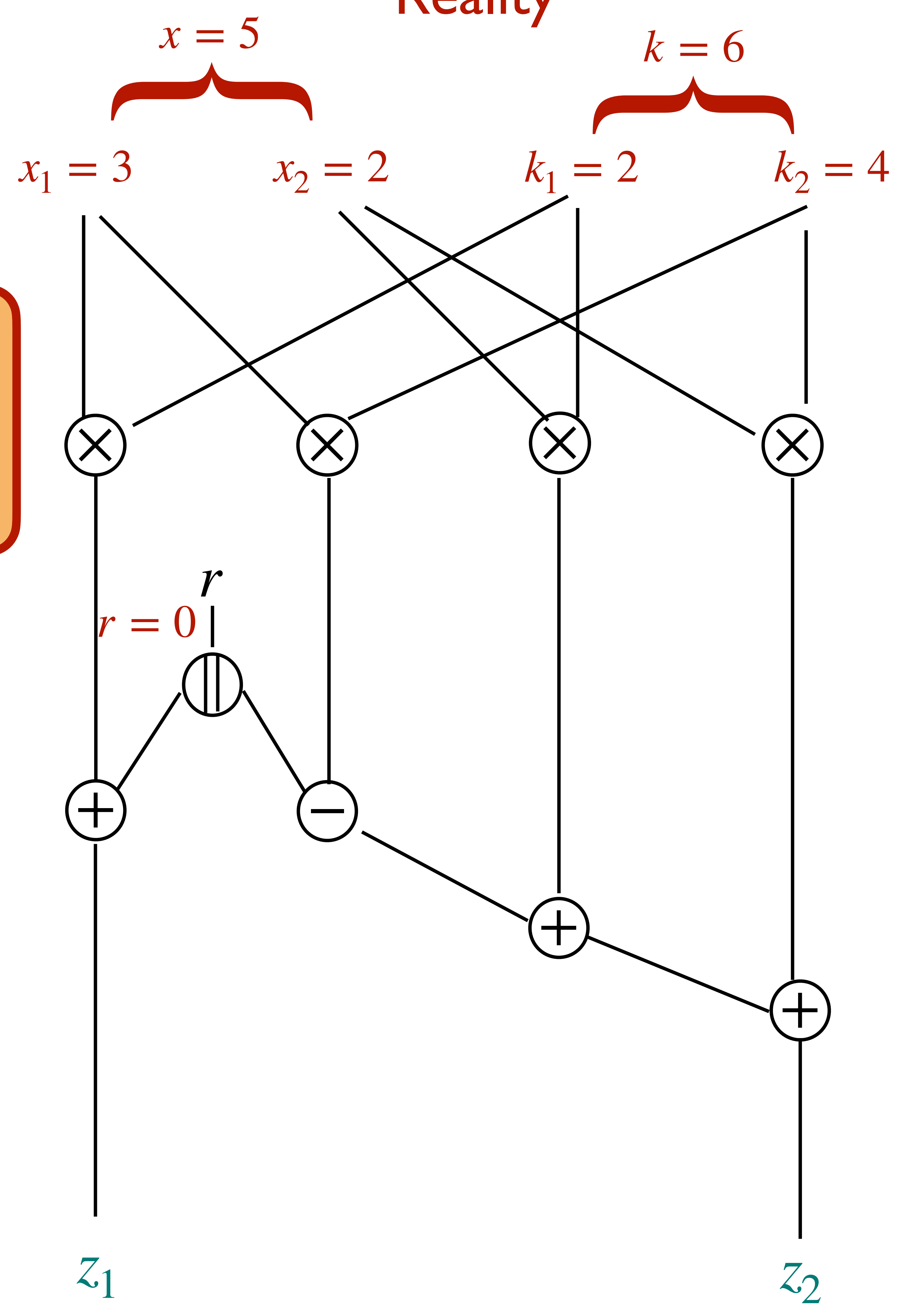
convenience for security proofs
realism

Reality



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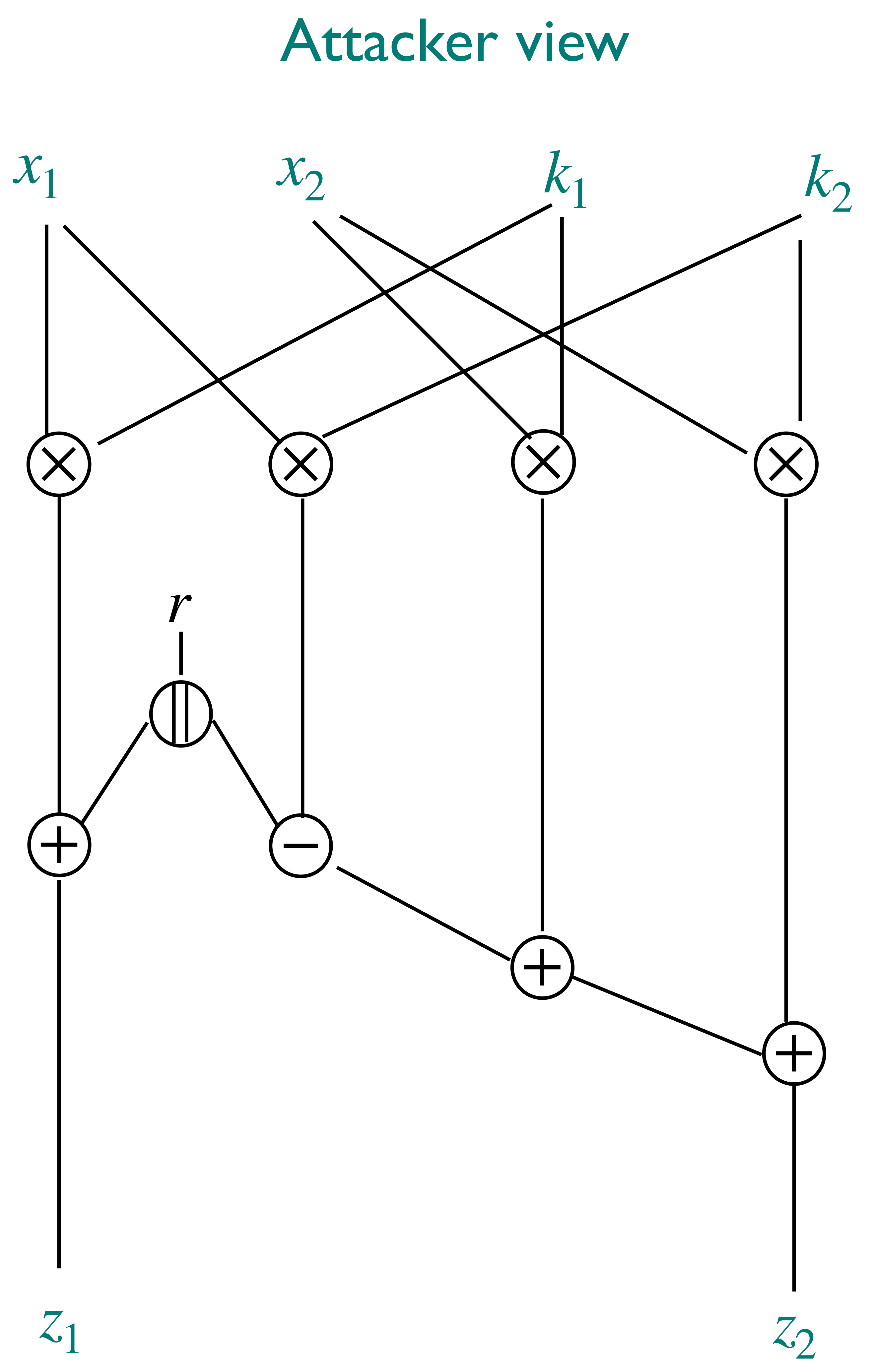
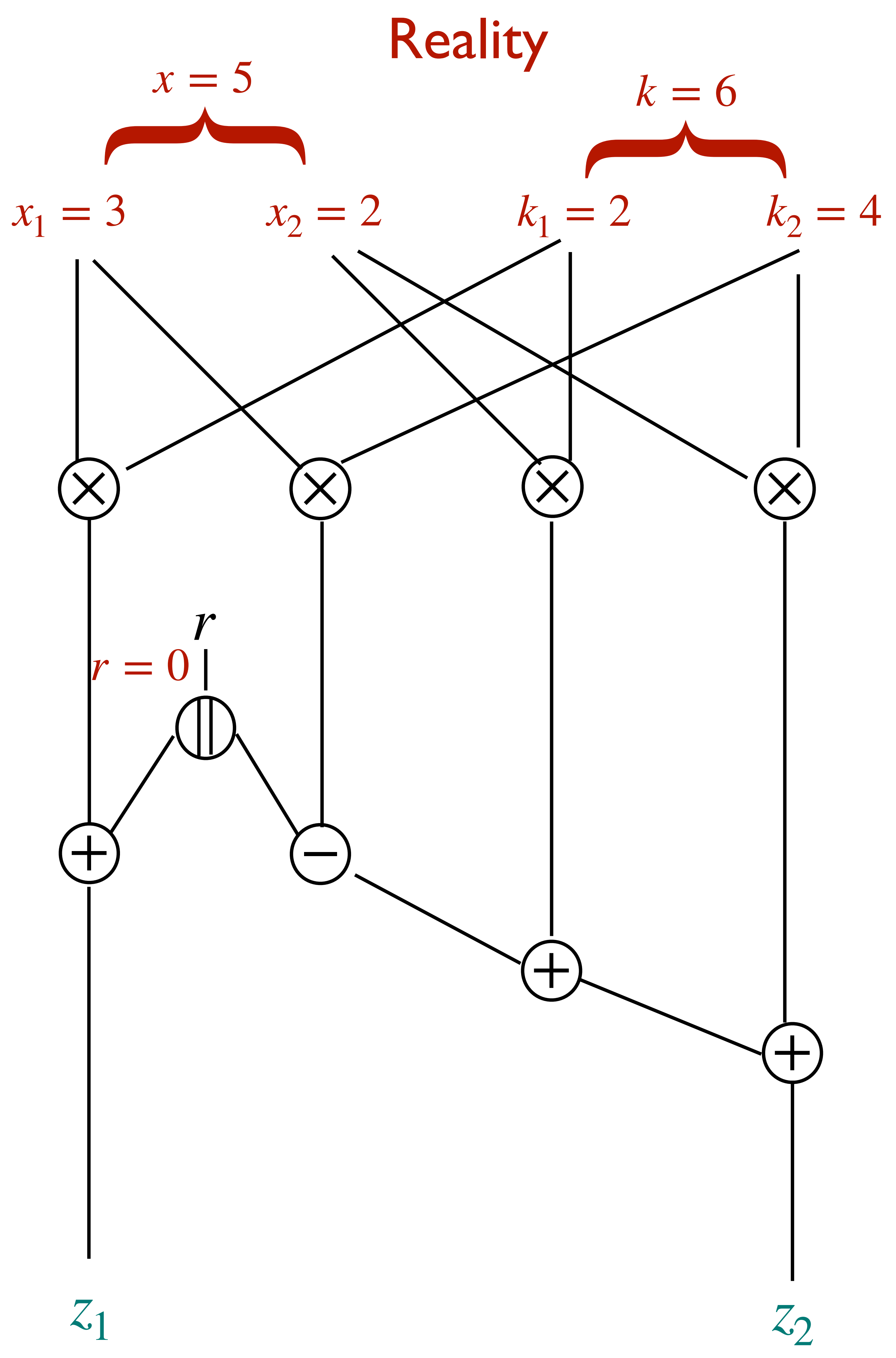


Attacker model

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



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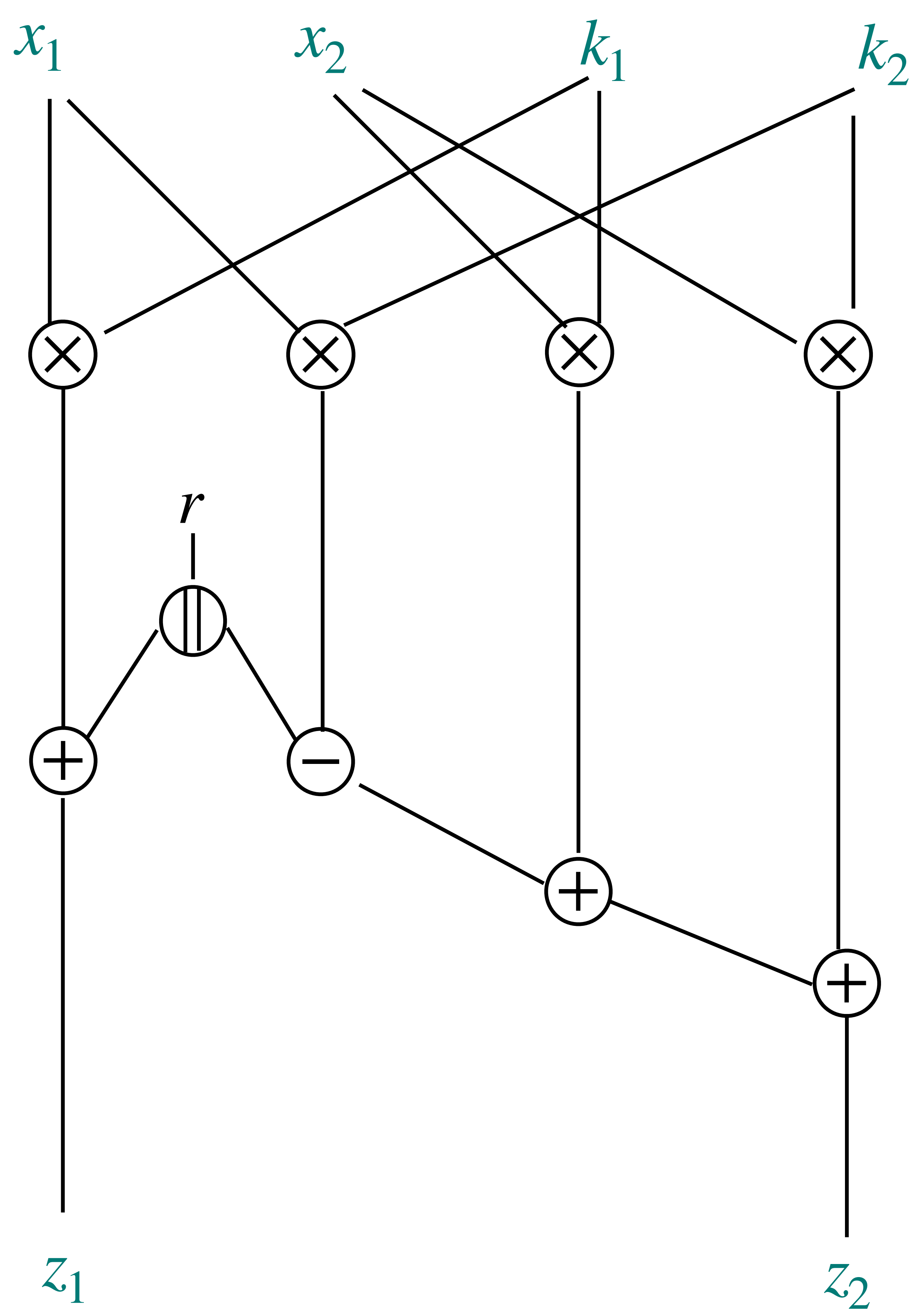

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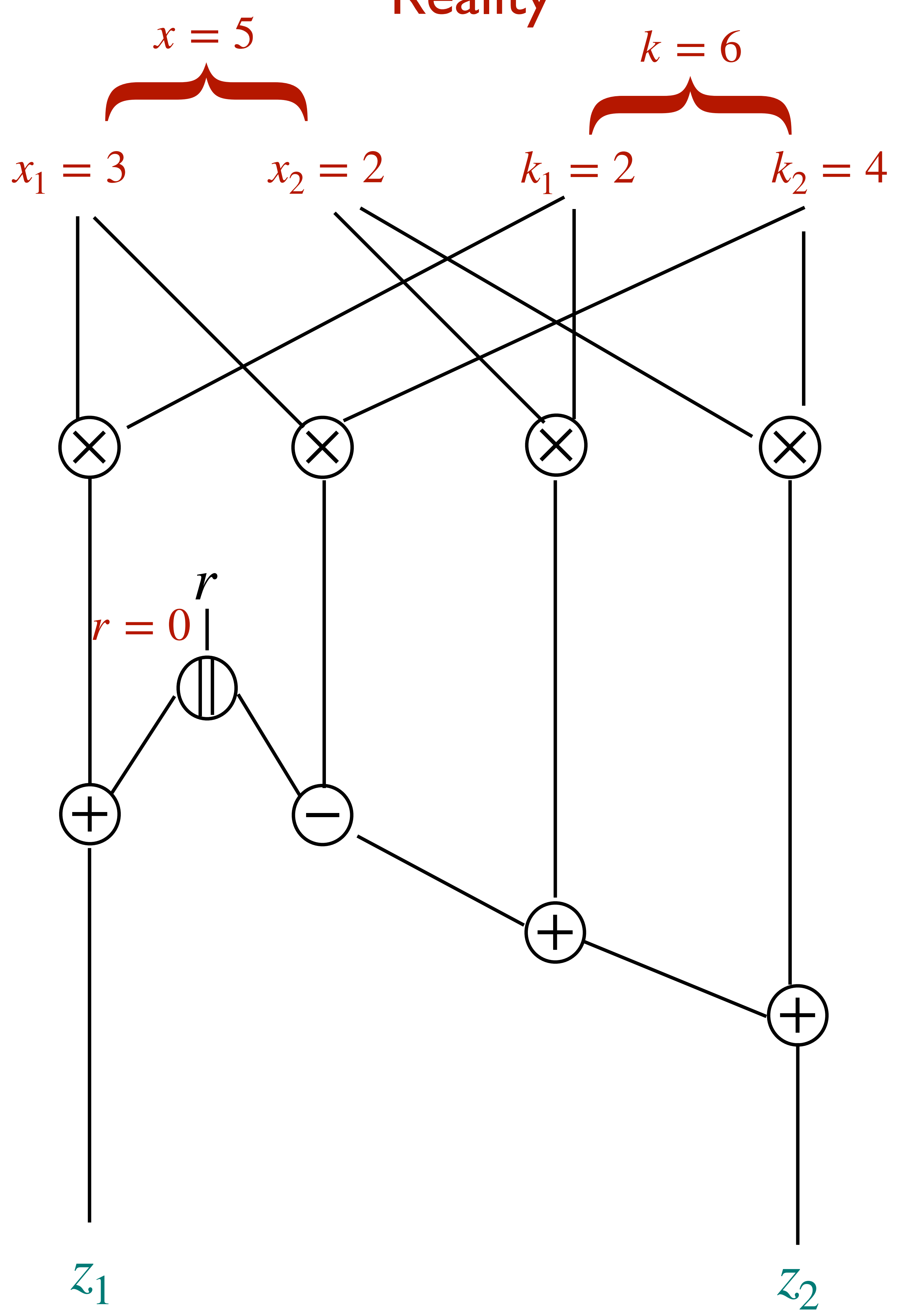
(p, ϵ)-random-probing security

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.

Reality



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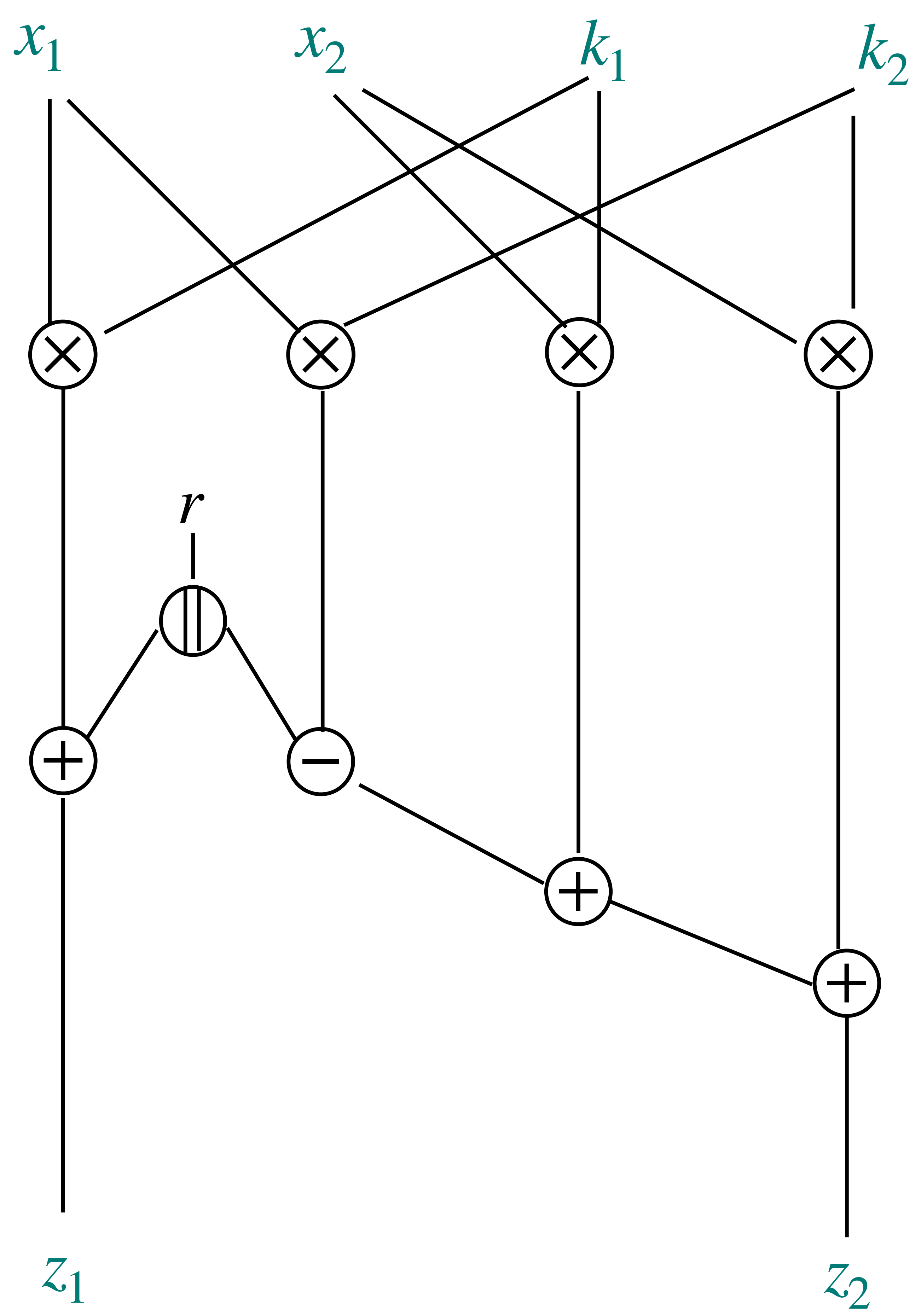

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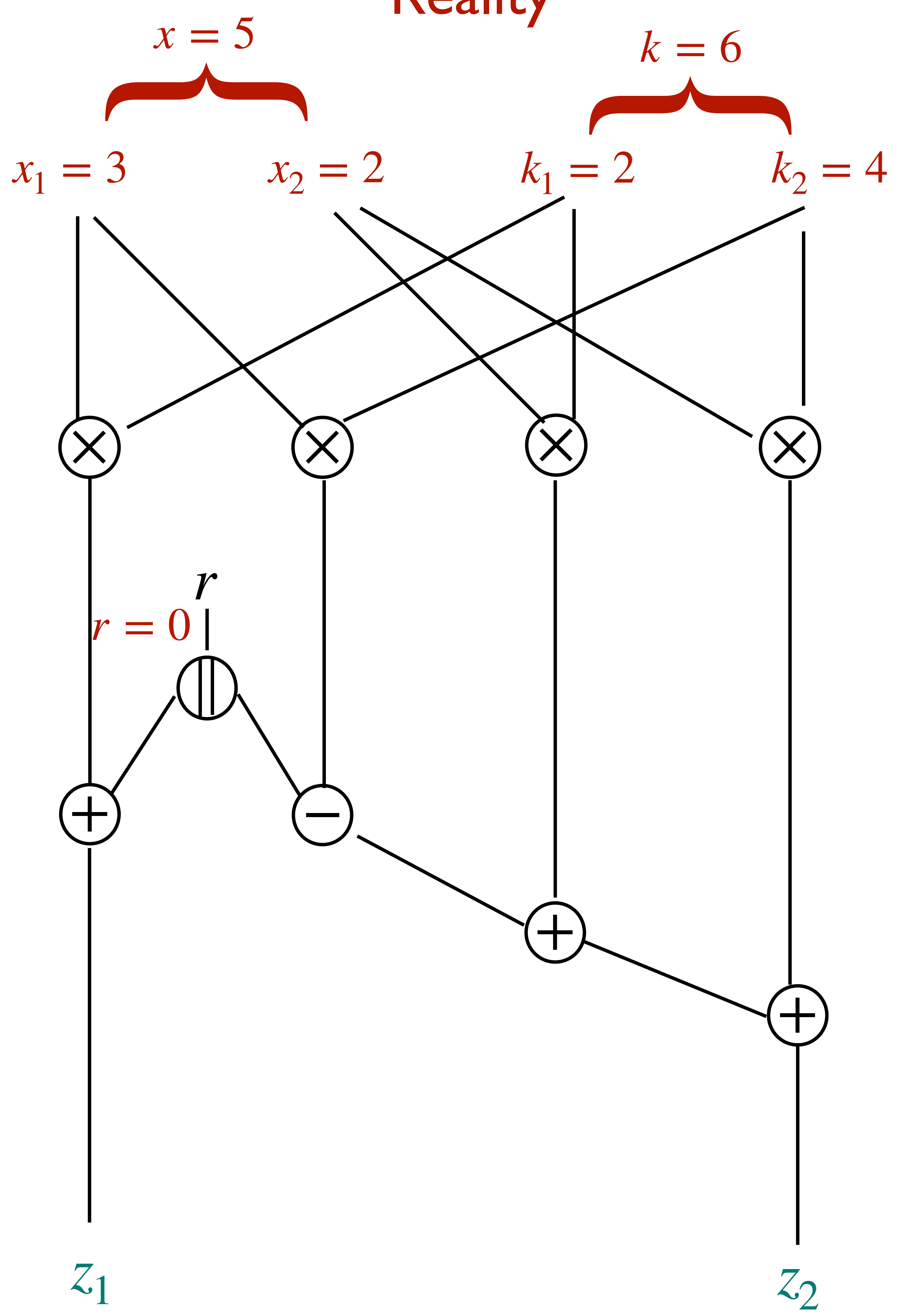
Security Proof

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

Reality



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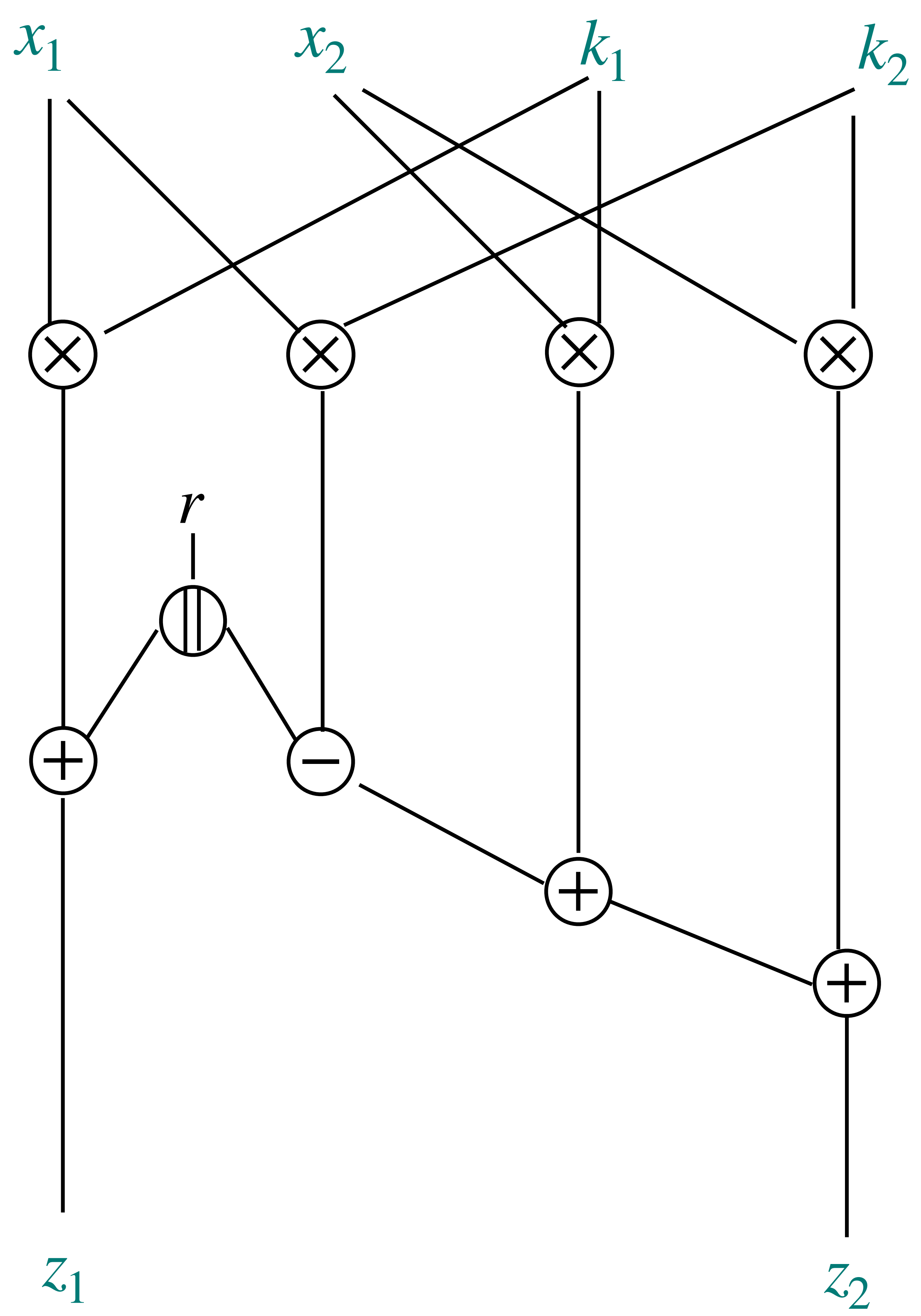

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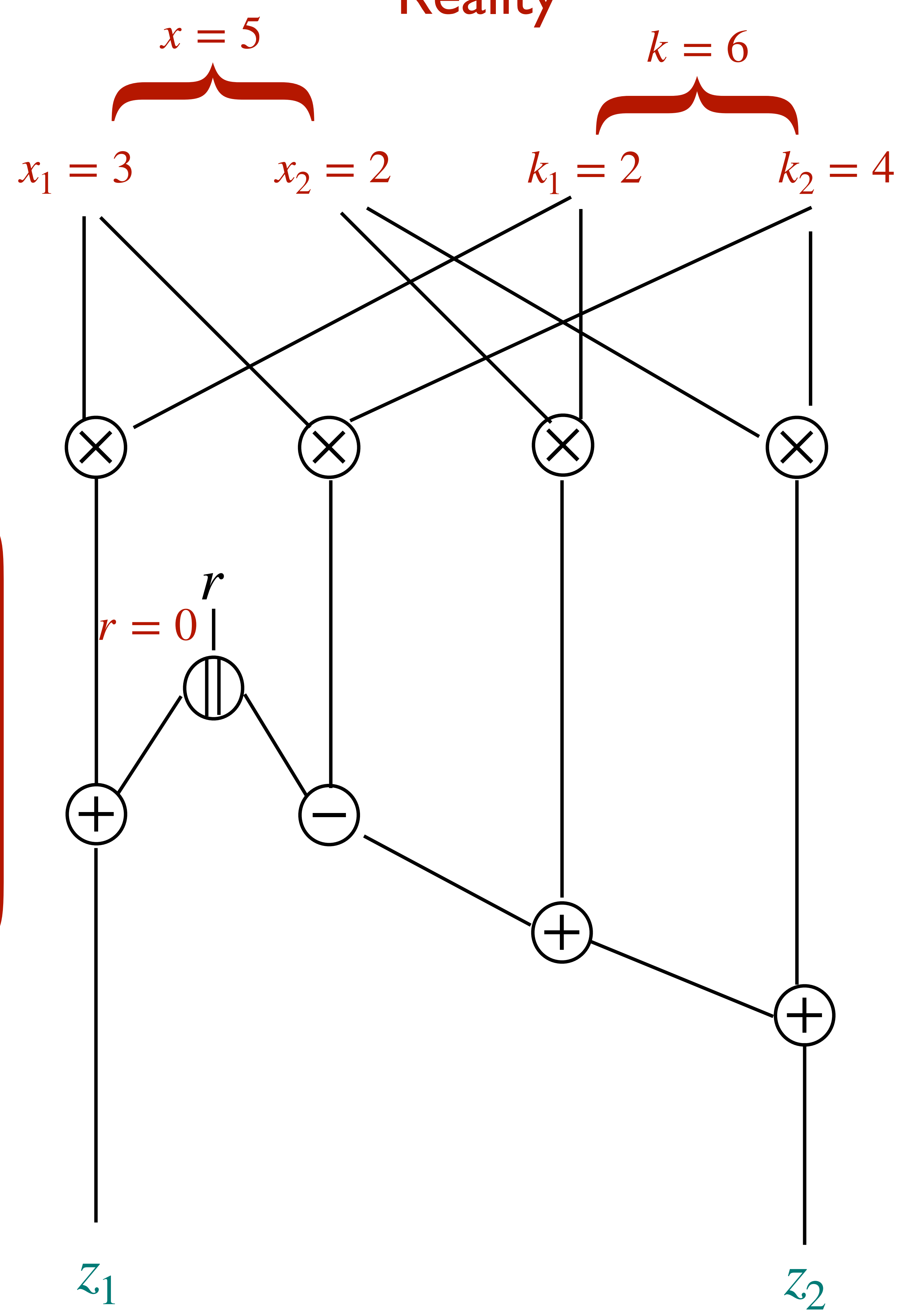
$\overbrace{x_1 = 3 \quad x_2 = 2}^{x = 5}$
$\overbrace{k_1 = 2 \quad k_2 = 4}^{k = 6}$
$r = 0$
r
z_1
z_2

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

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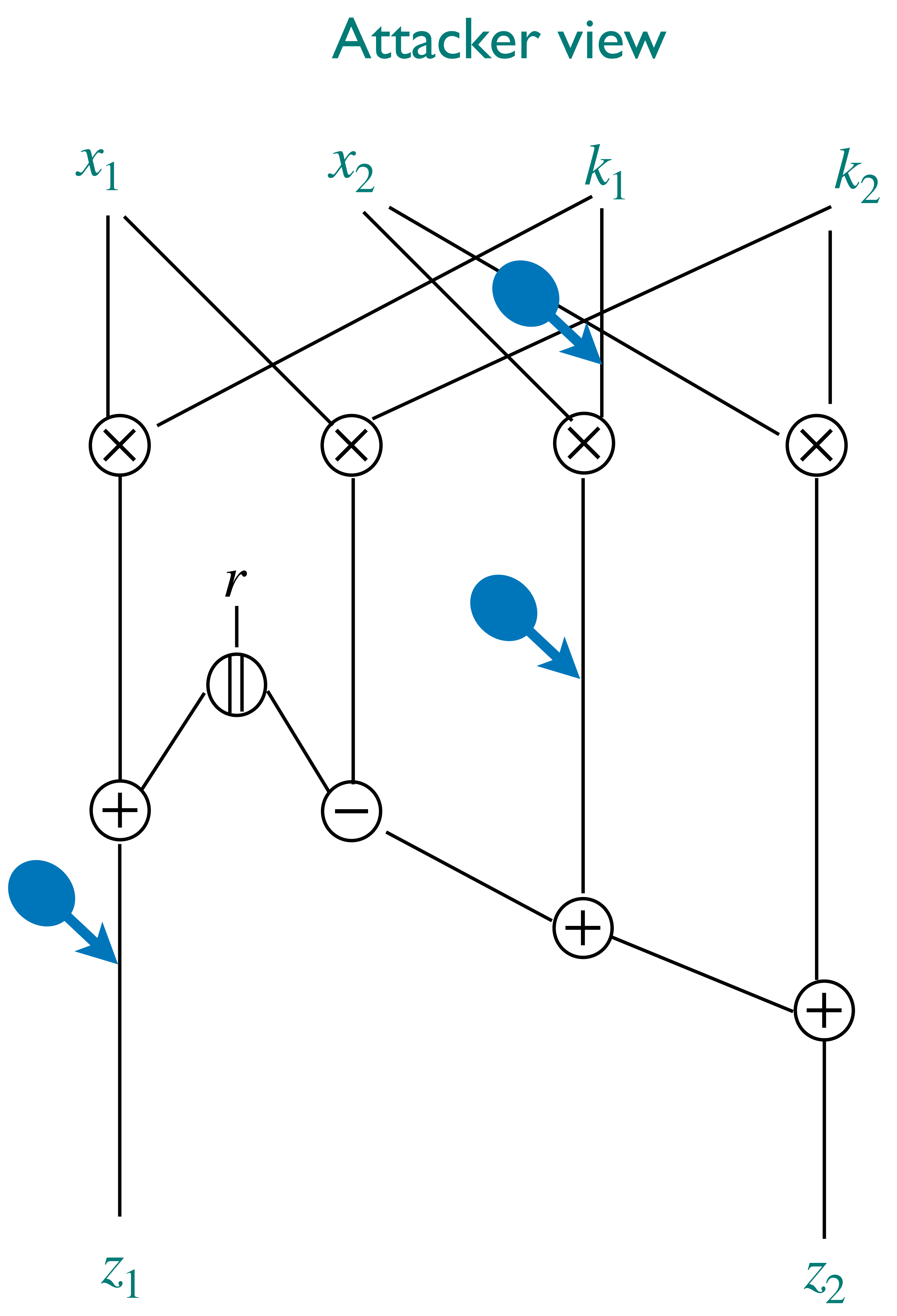
Random probing model



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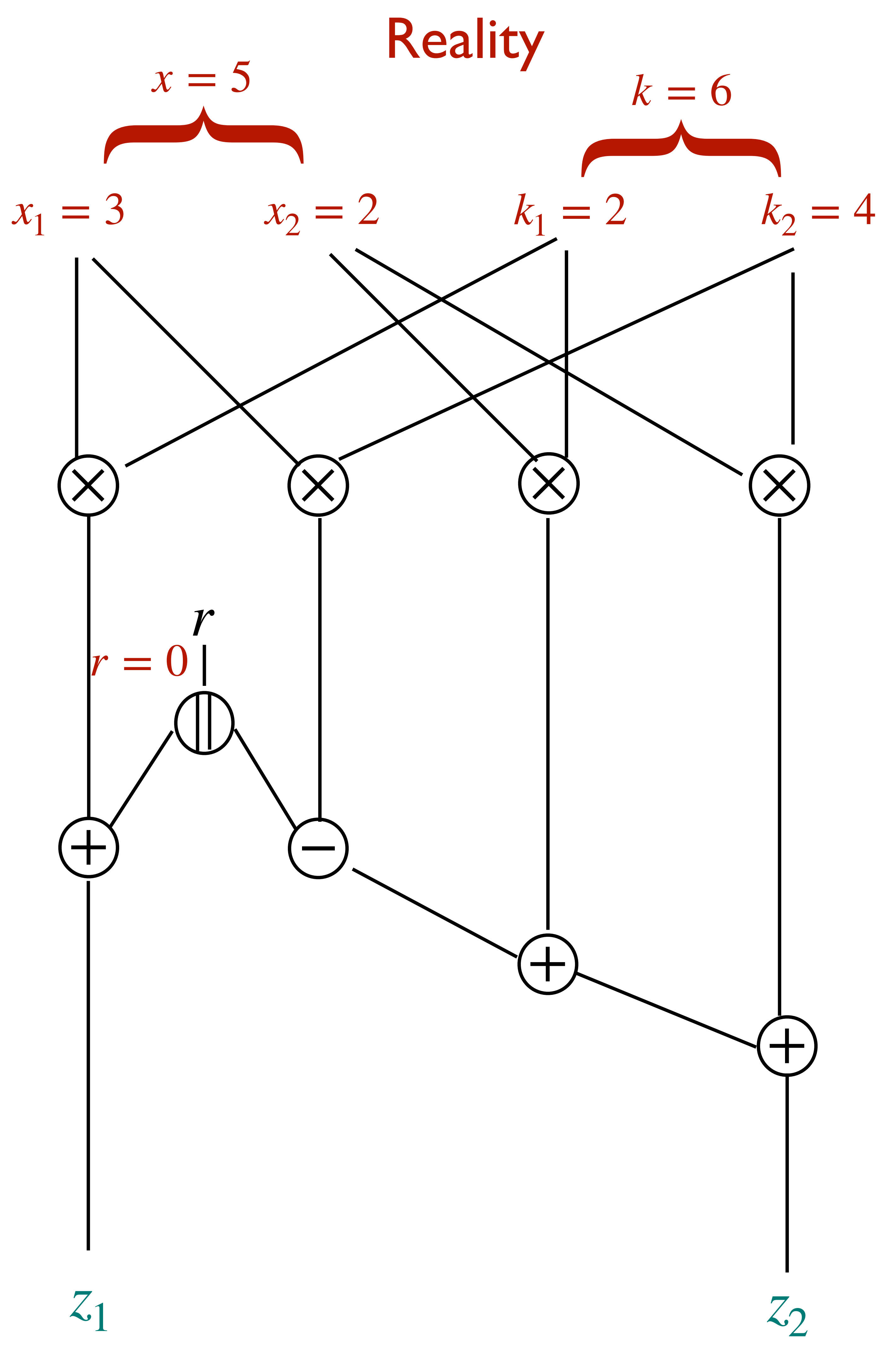

$\mathscr{W} = \{x_1k_1 + r, x_2k_1, k_1\}$ with proba $p^3(1-p)^{16}$

out $\leftarrow \{\$^1, \$^2 \times \$^3, \$^3\}$

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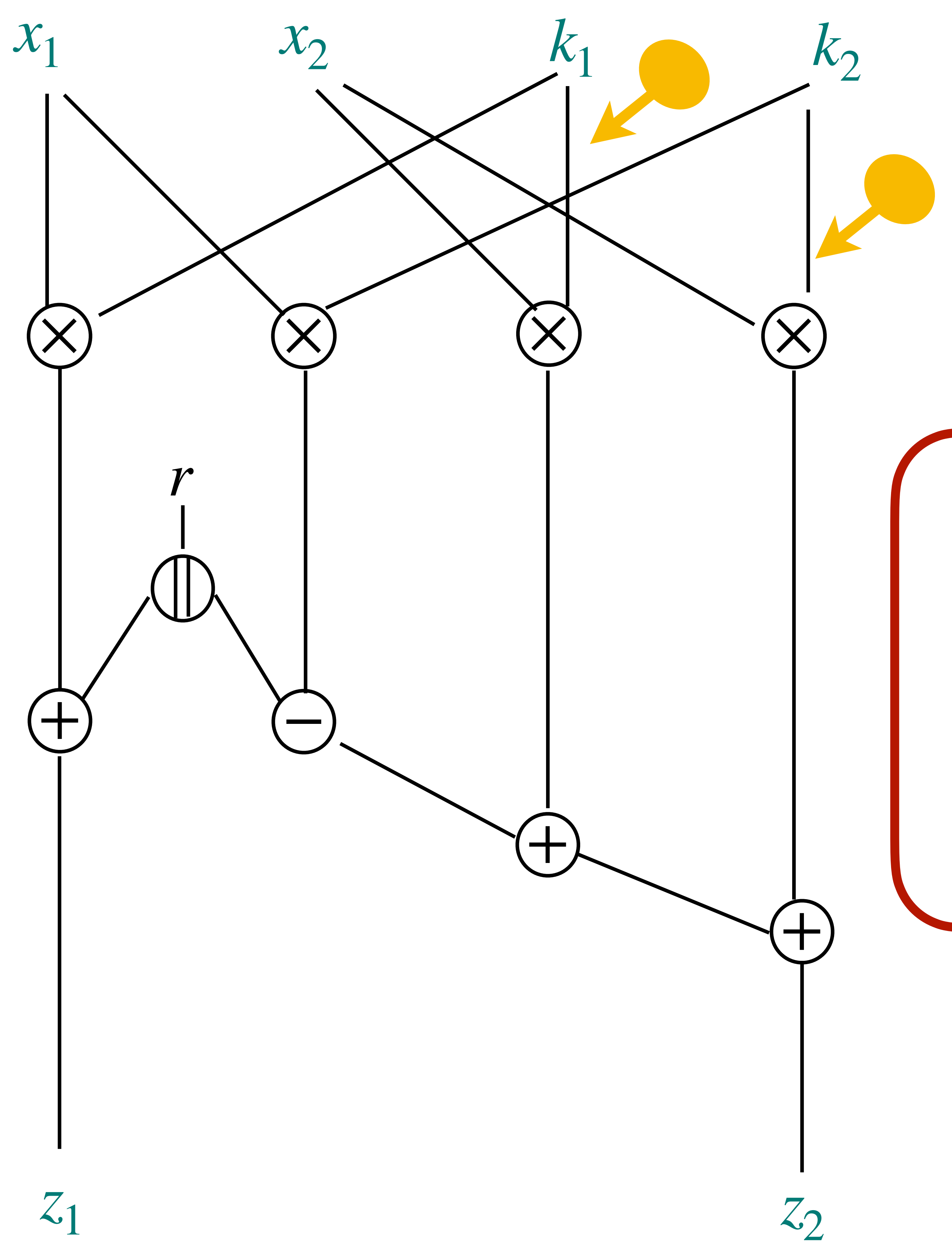
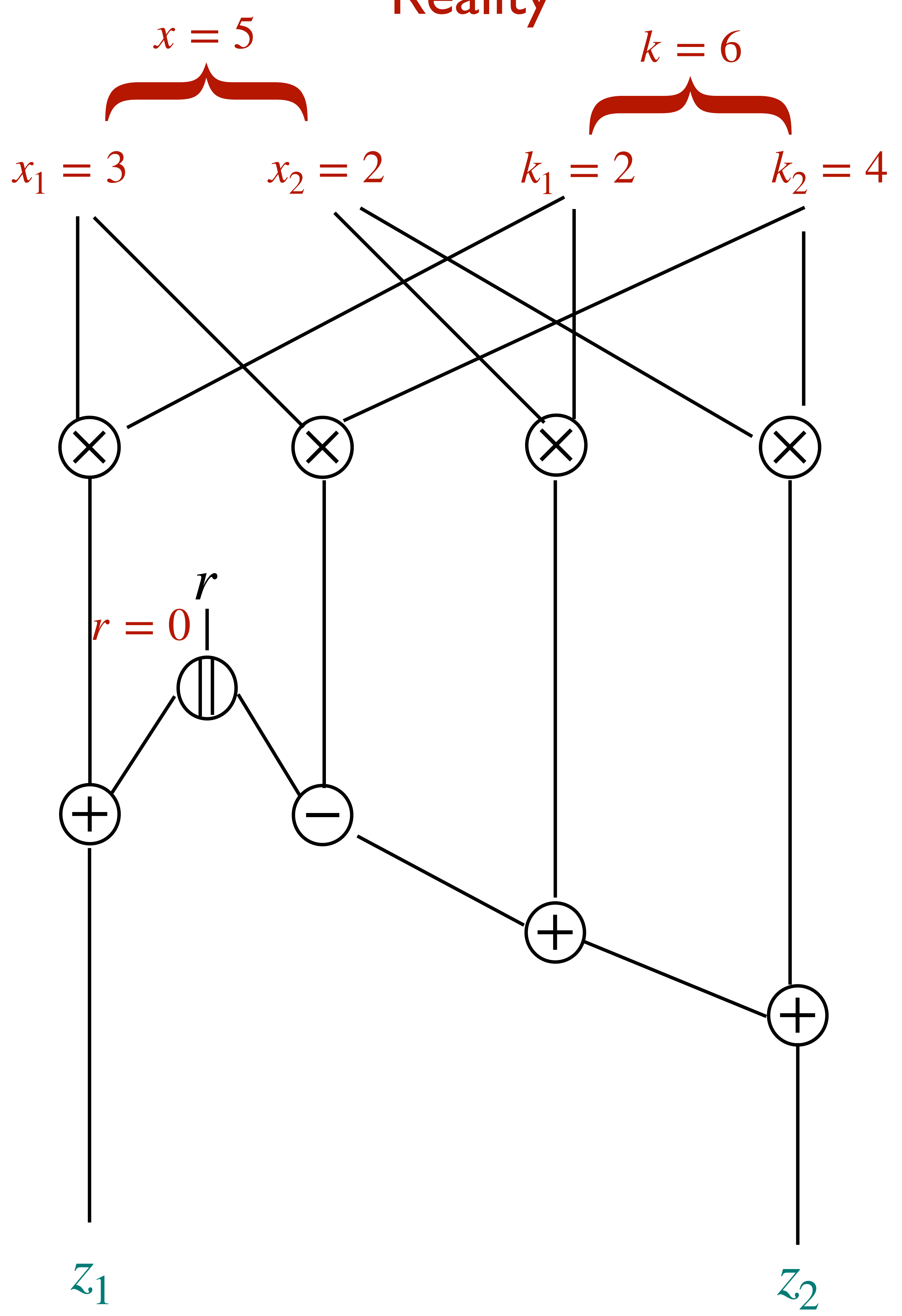
Attacker view



Random probing model

Reality



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$\mathscr{W} = \{k_1, k_2\}$ with proba $p^2(1-p)^{17}$

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Random probing model

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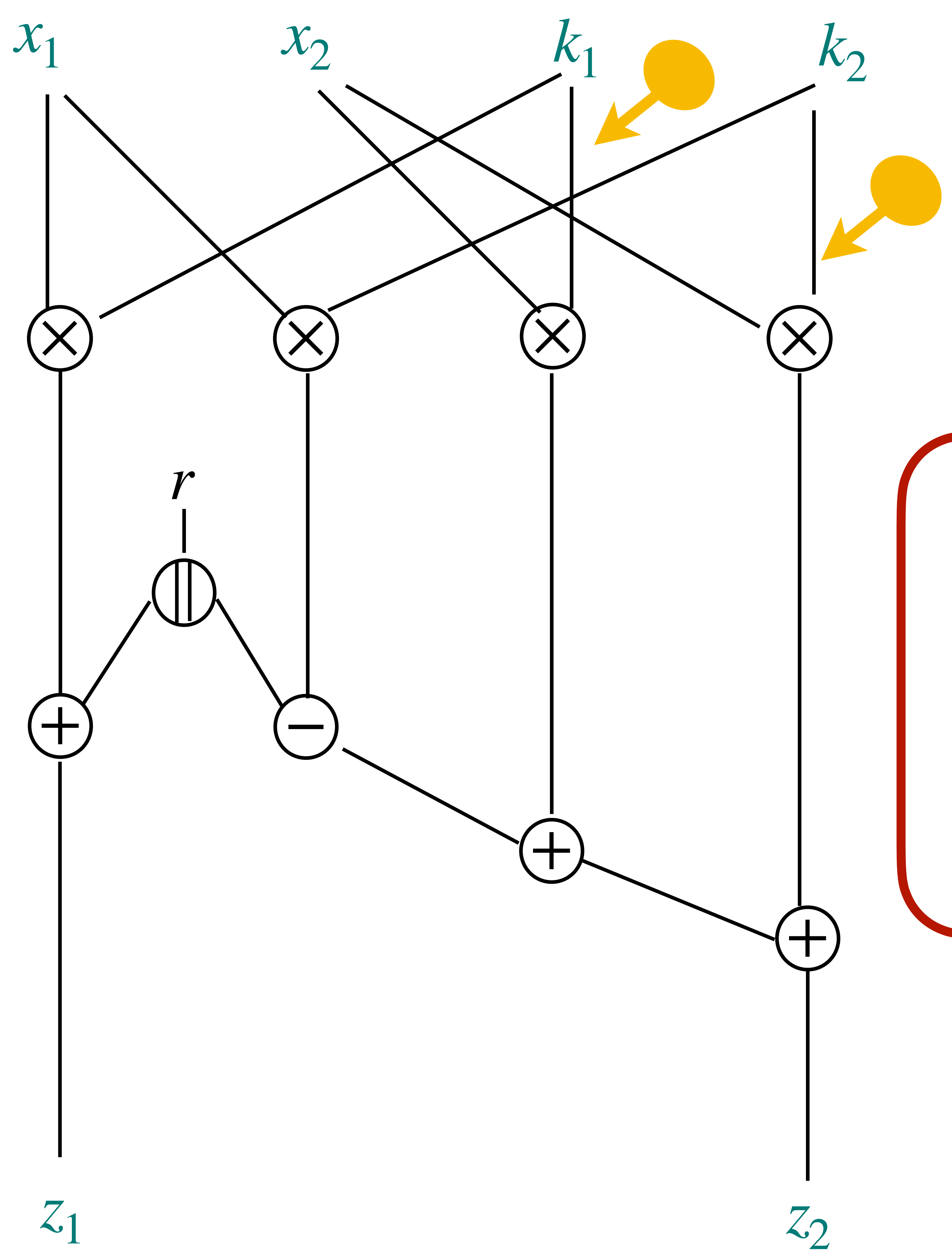

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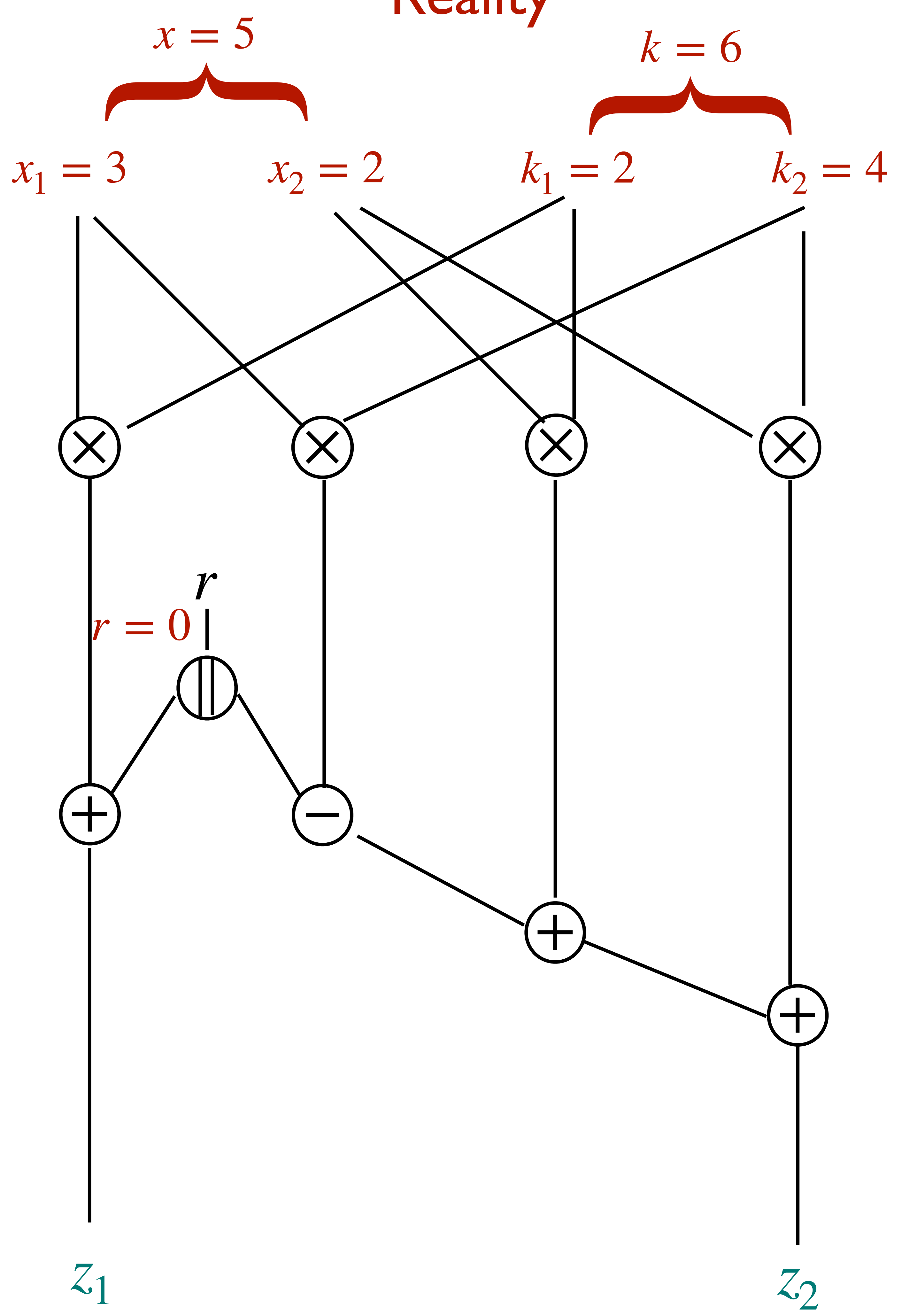

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…except with probability ϵ.

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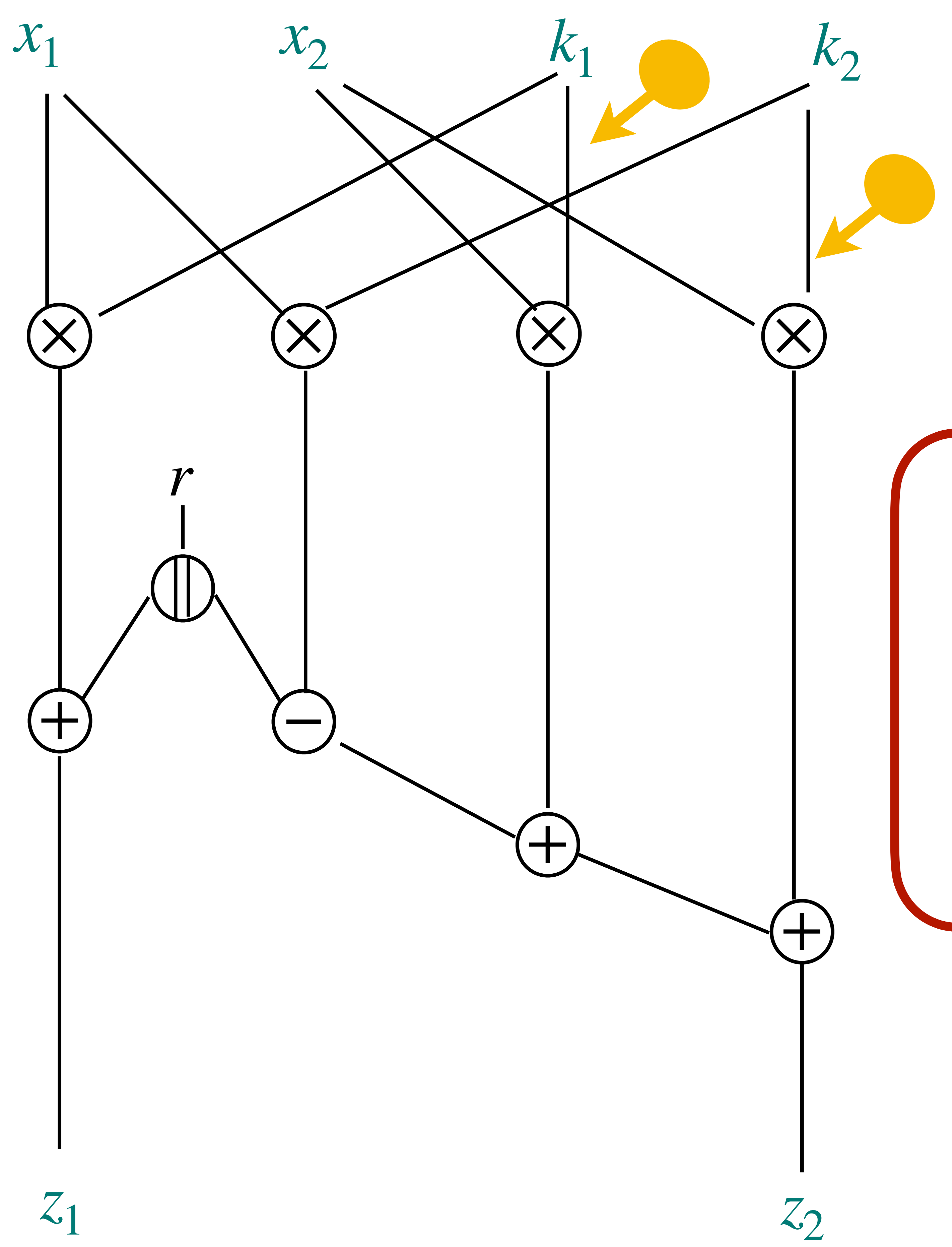

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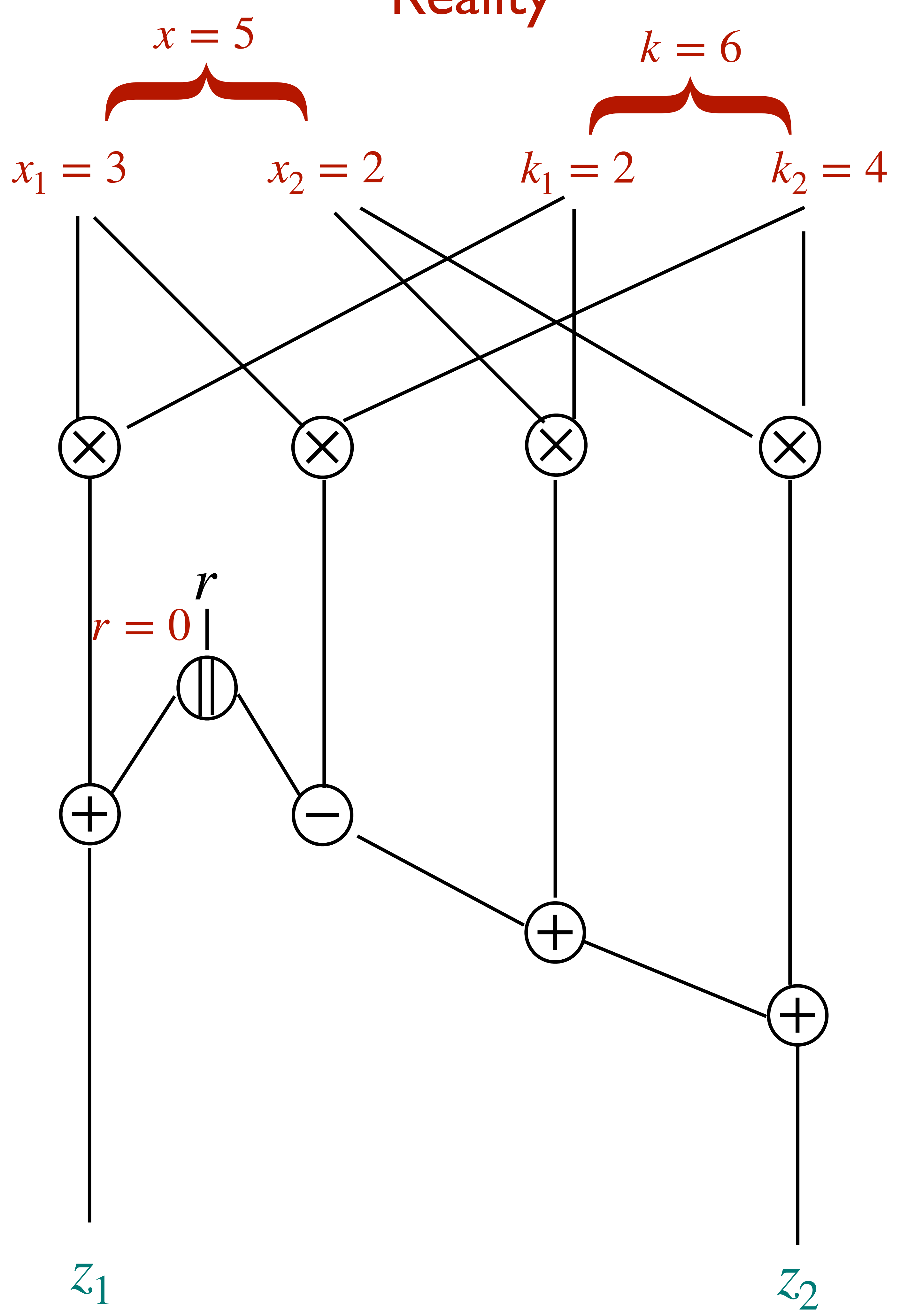
$\epsilon = 2^{-128} \implies p \geq$ some bound

Reality



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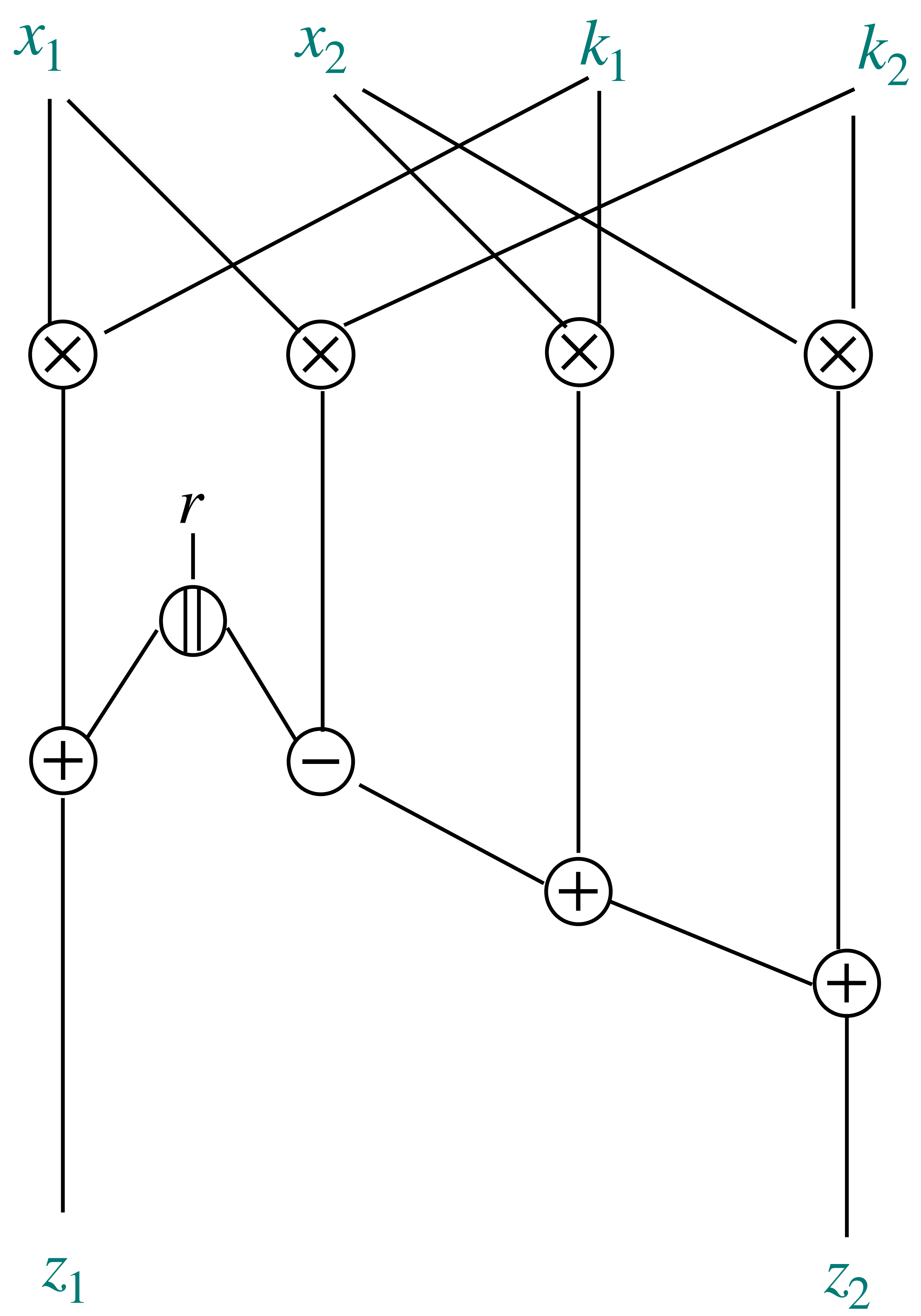
Random Probing Composability

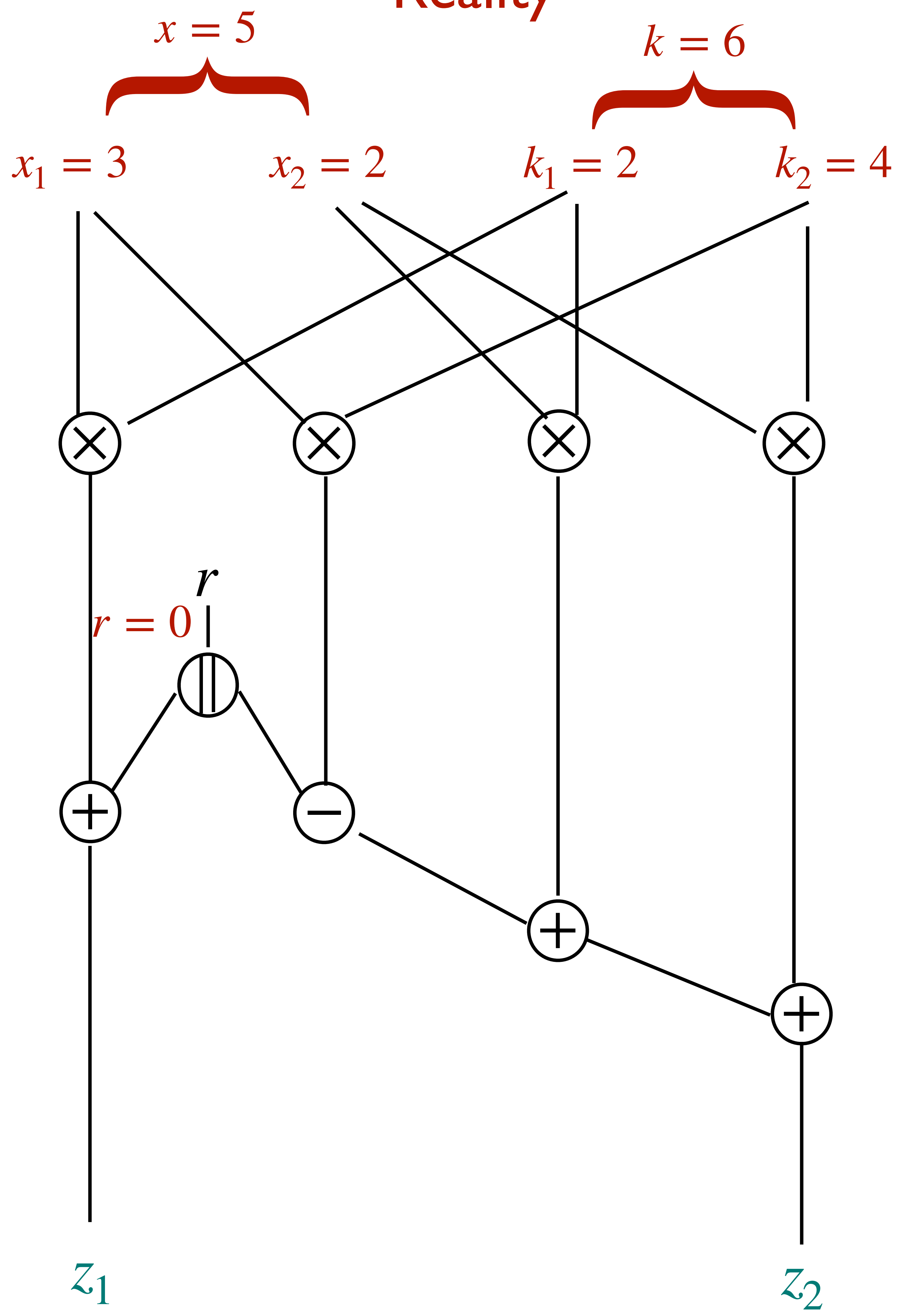
Attacker view



(p, ϵ, t)-threshold RPC

$\mathbb{P}$(« More than t shares of each $[|x|]$ and $[|k|]$ are required to simulate $\mathscr{L}$ + t output shares ») $\leq \varepsilon$

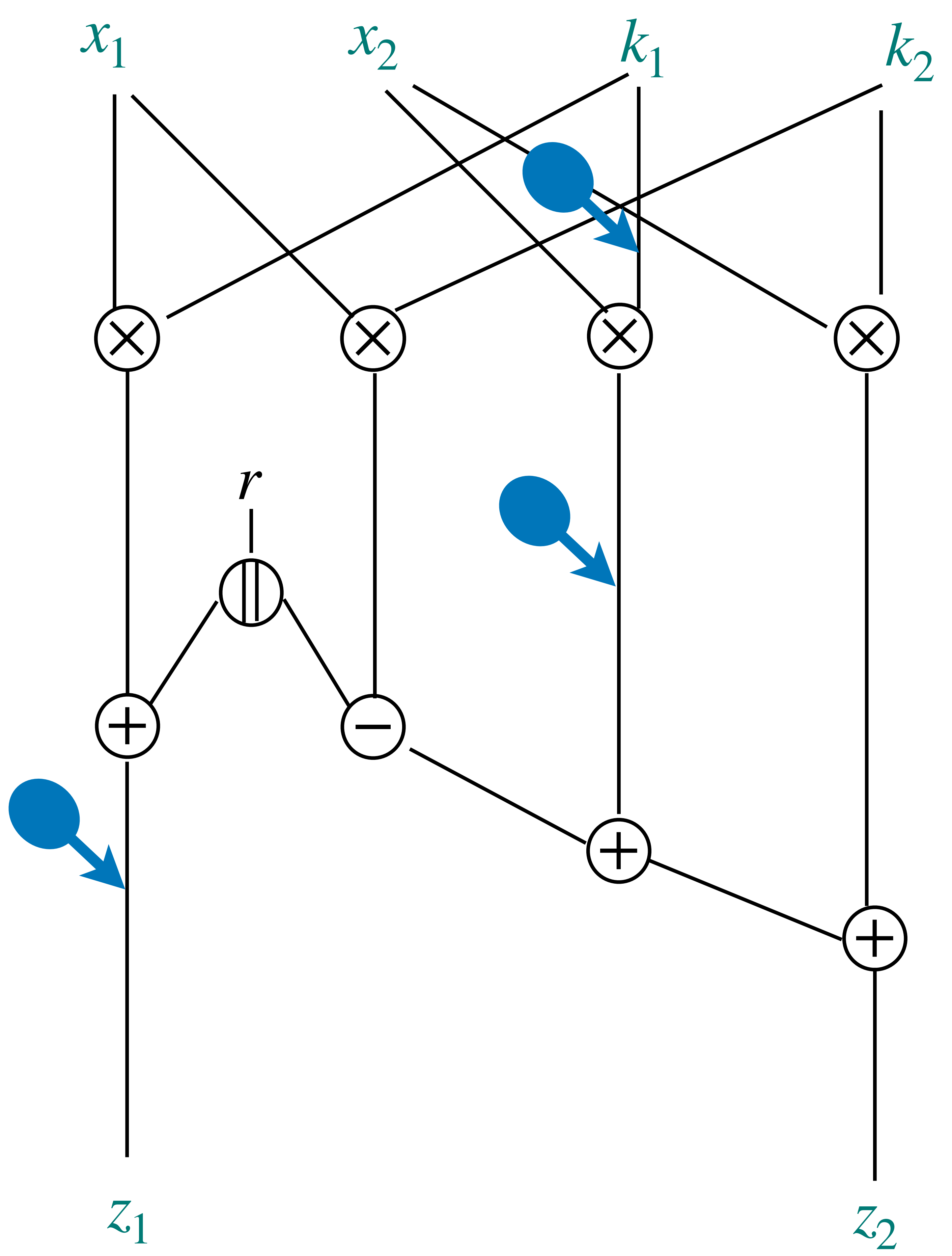
Reality



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

Random Probing Composability

Attacker view



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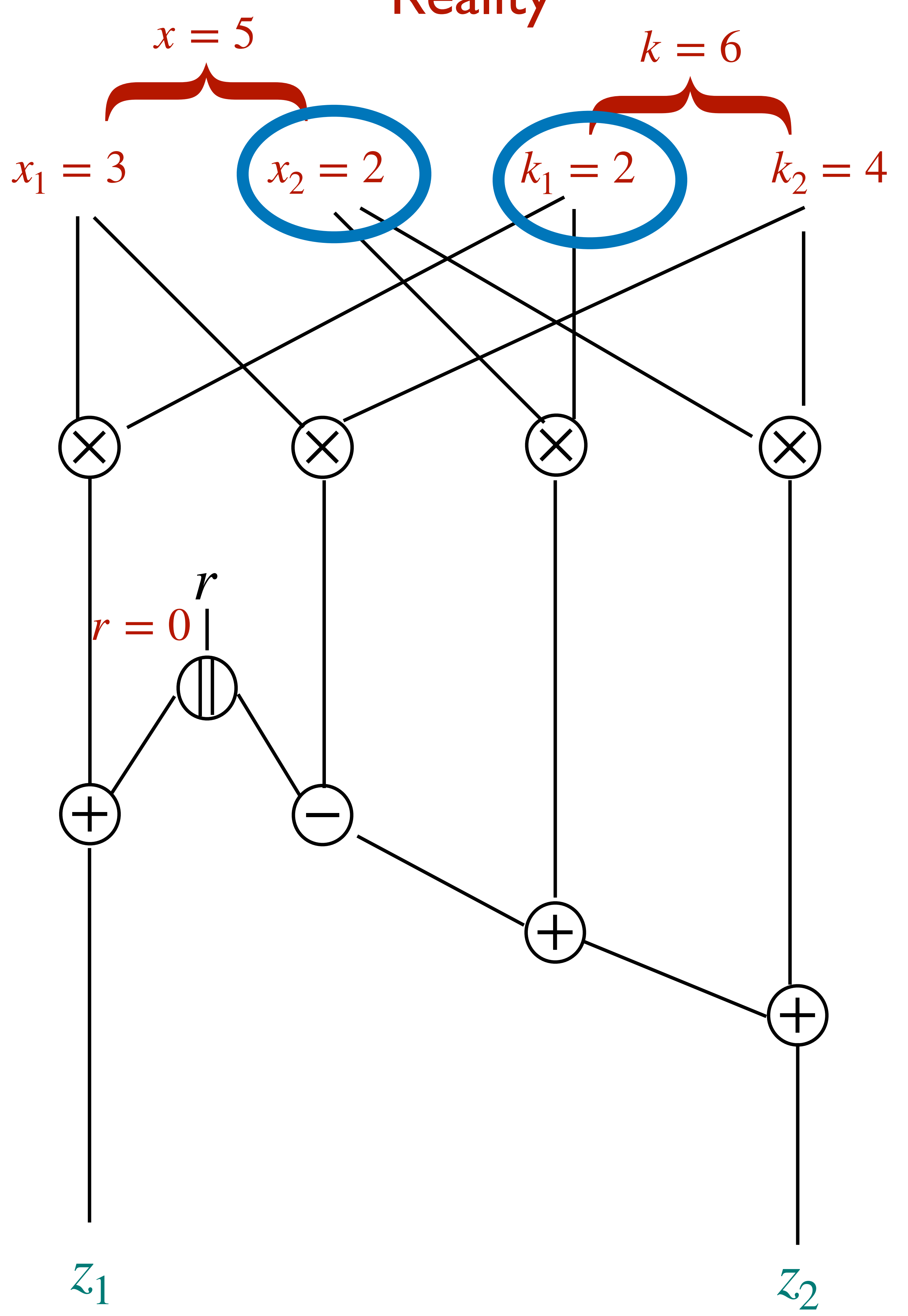

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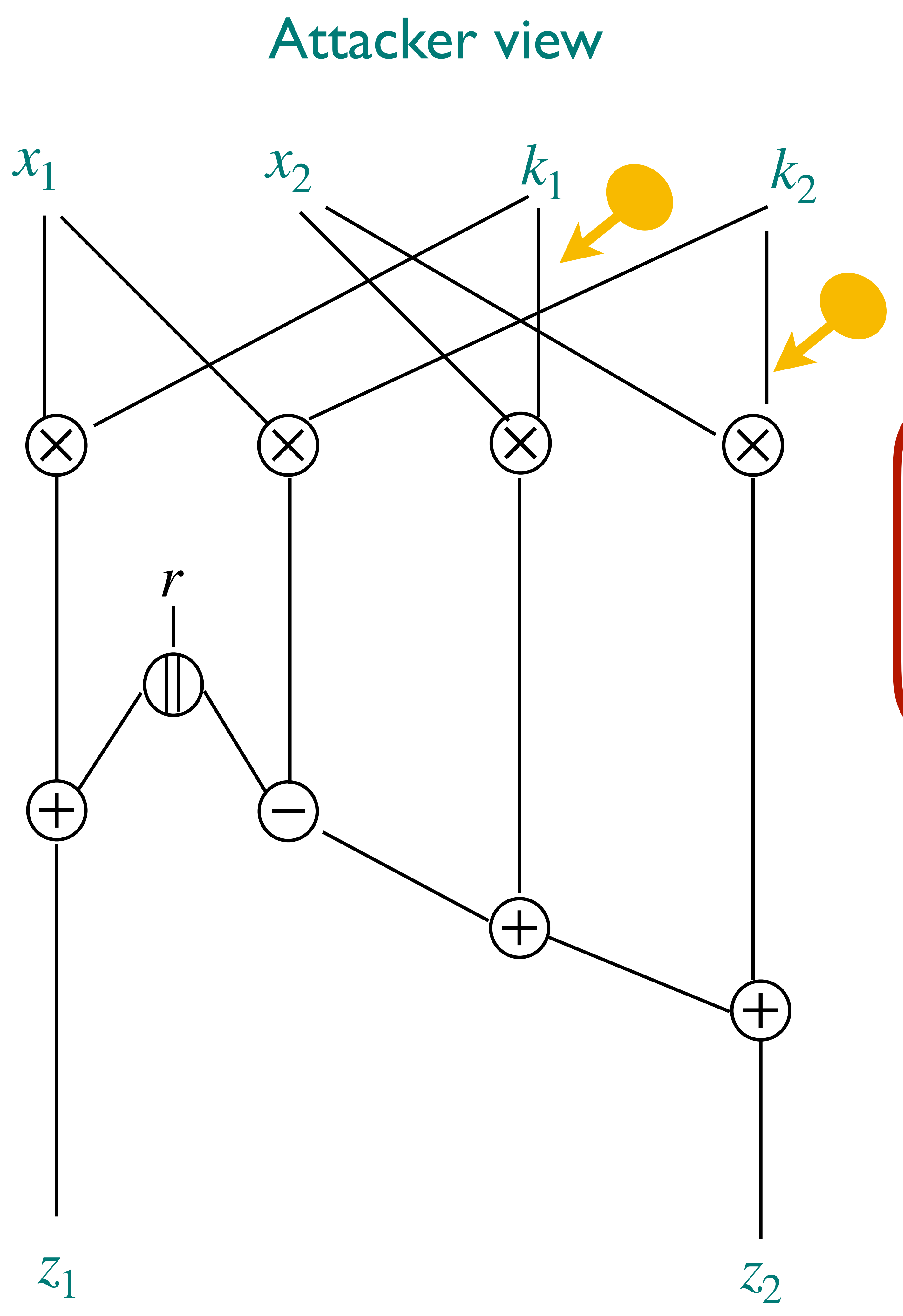
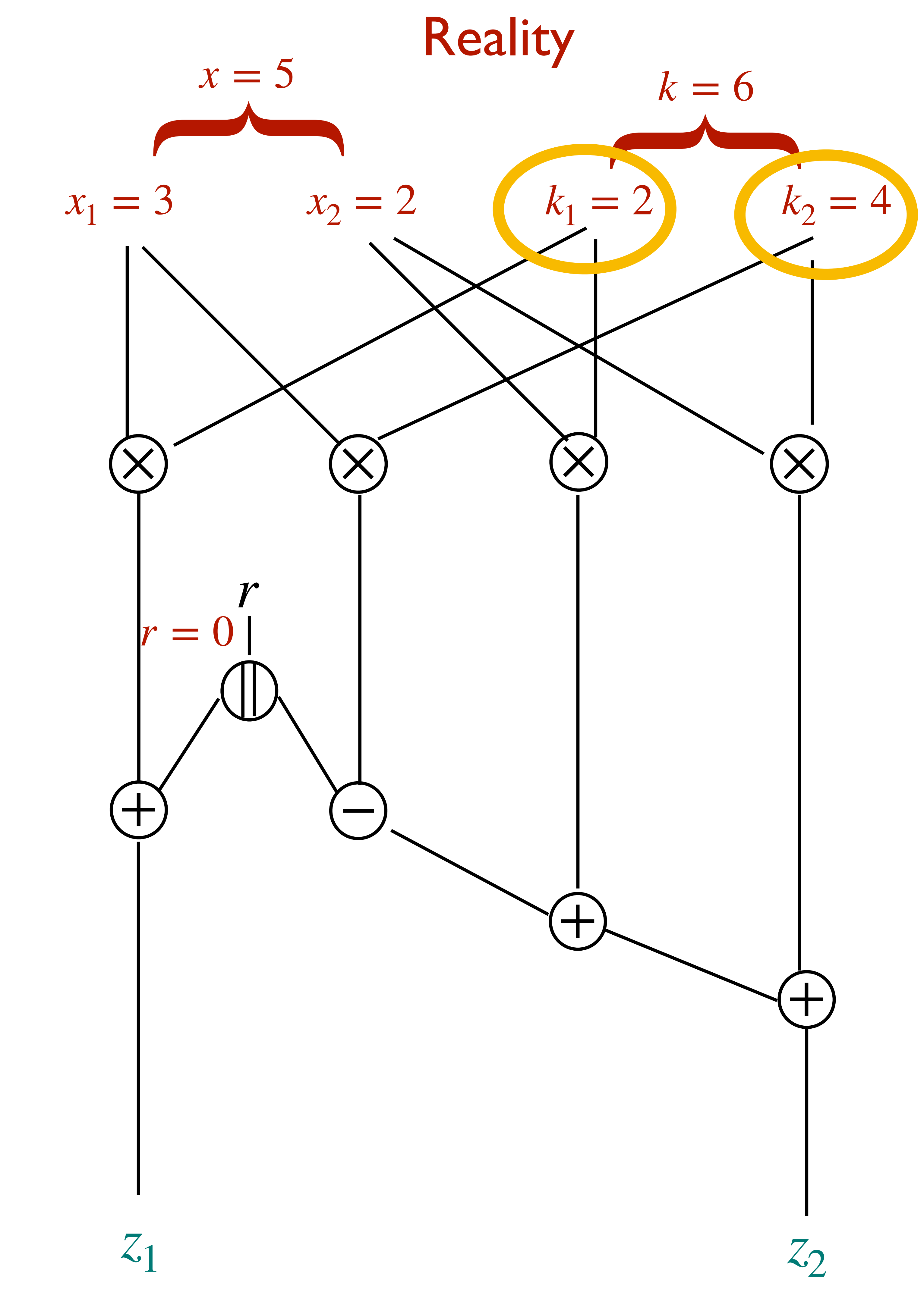


(p, ϵ, t)-threshold RPC

$\mathbb{P}$(« More than t shares of each $[|x|]$ and $[|k|]$ are required to simulate $\mathscr{L}$ + t output shares ») $\leq \varepsilon$

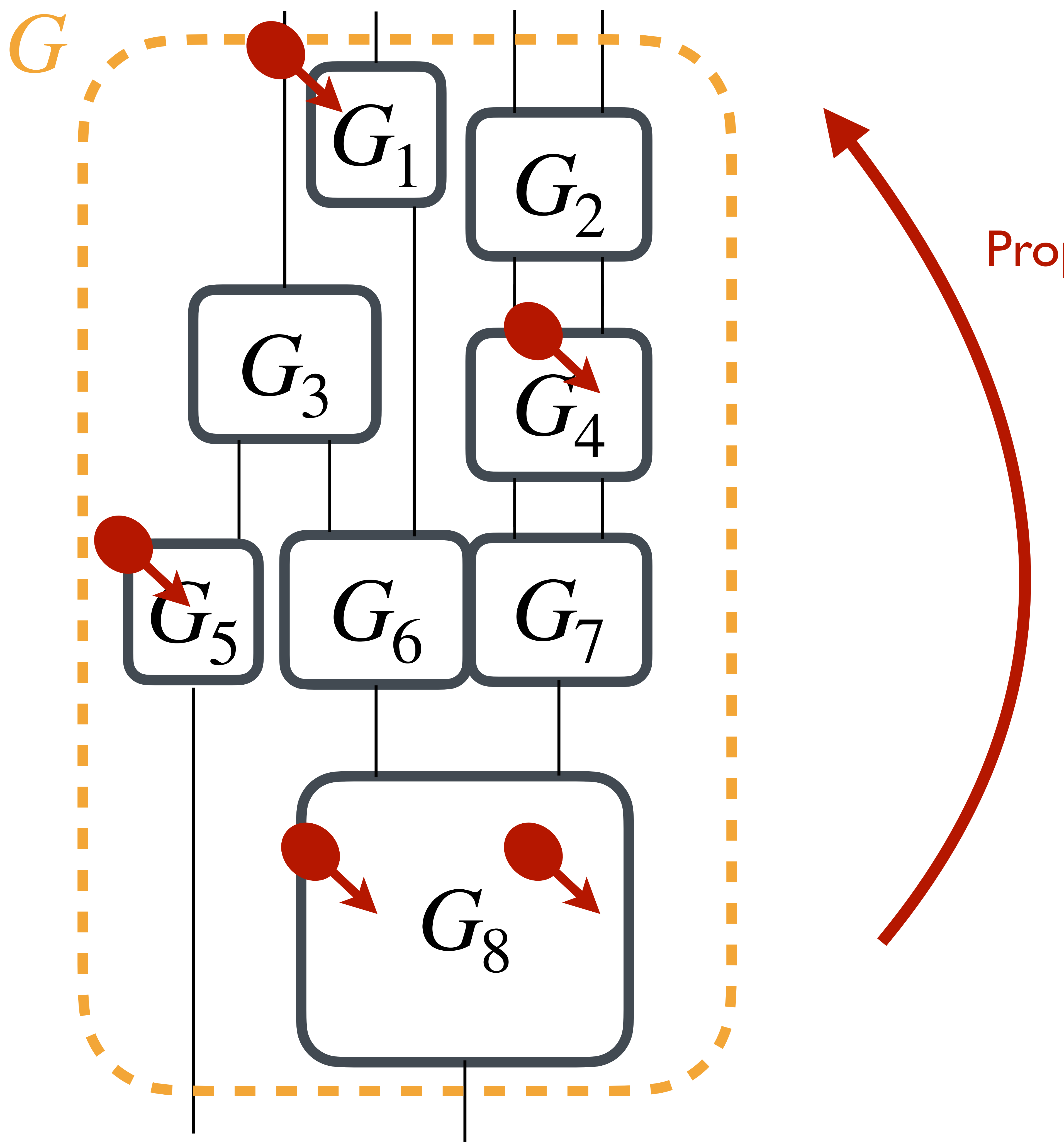


$\mathscr{W} = \{k_1, k_2\}$ with proba $p^2(1-p)^{17}$

out $\leftarrow \{k_1, k_2\}$

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

Composition with threshold RPC



<u>Threshold RPC:</u>

Propagation of the leakage and the outputs to the inputs

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

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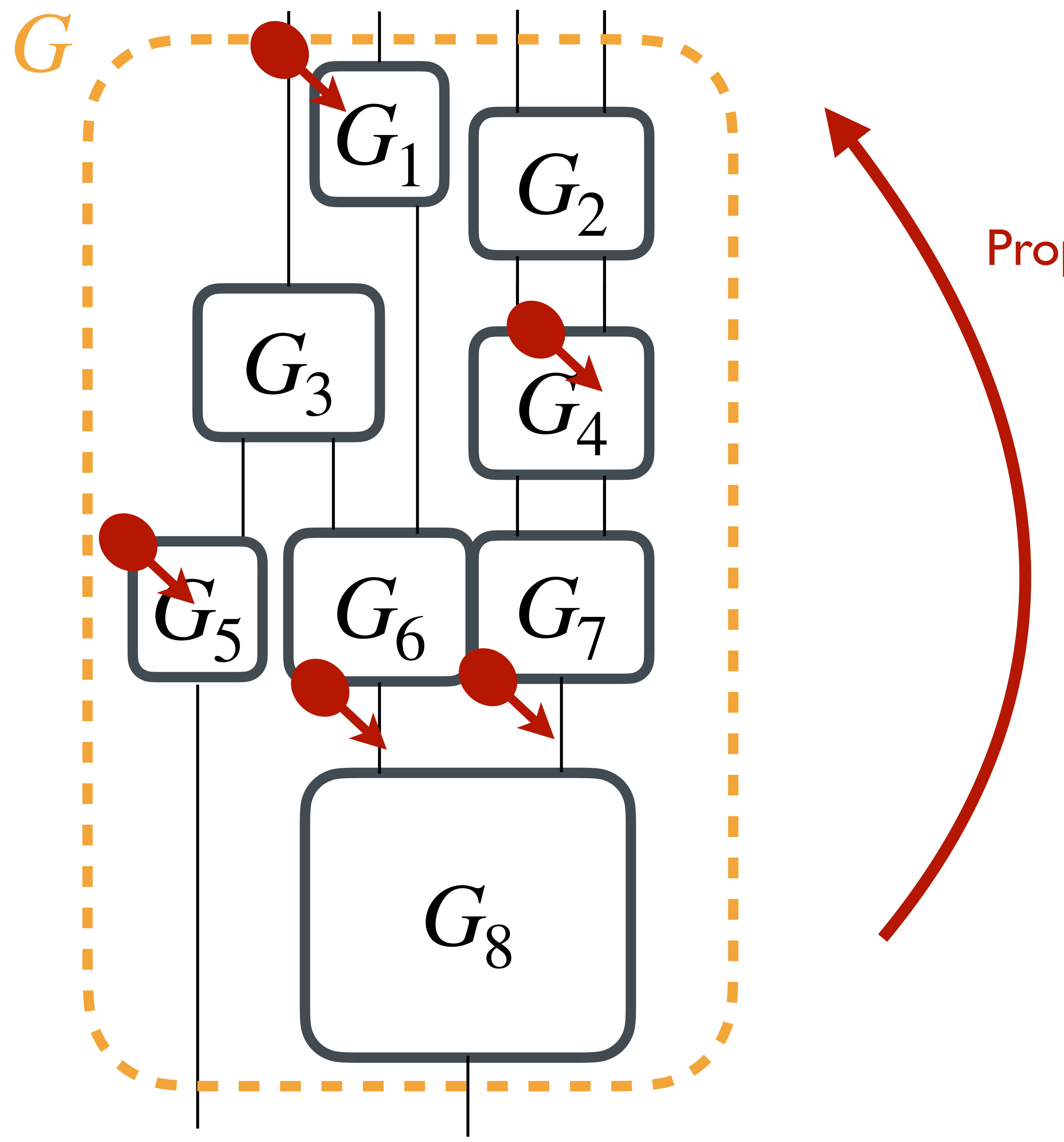

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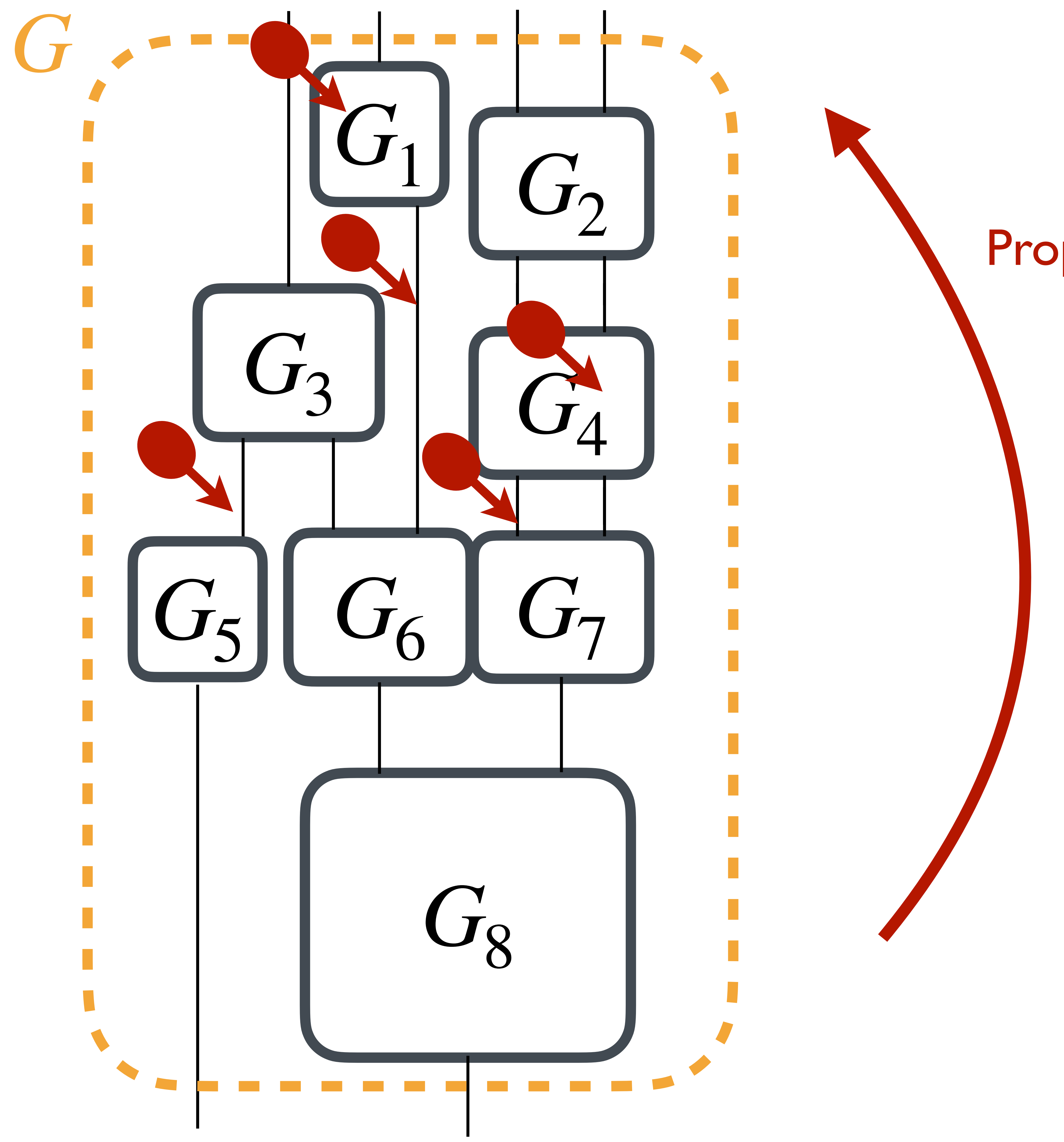

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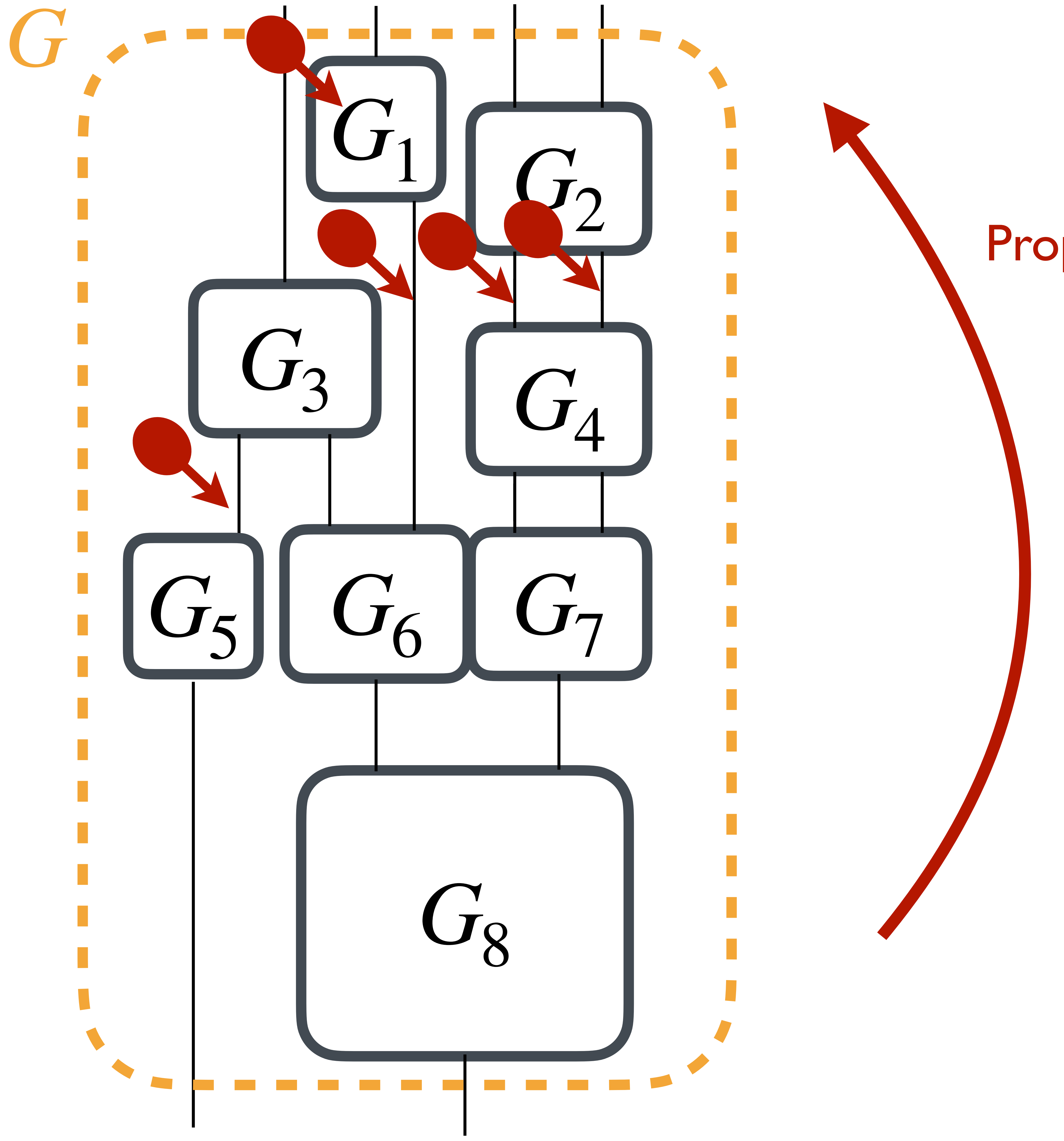

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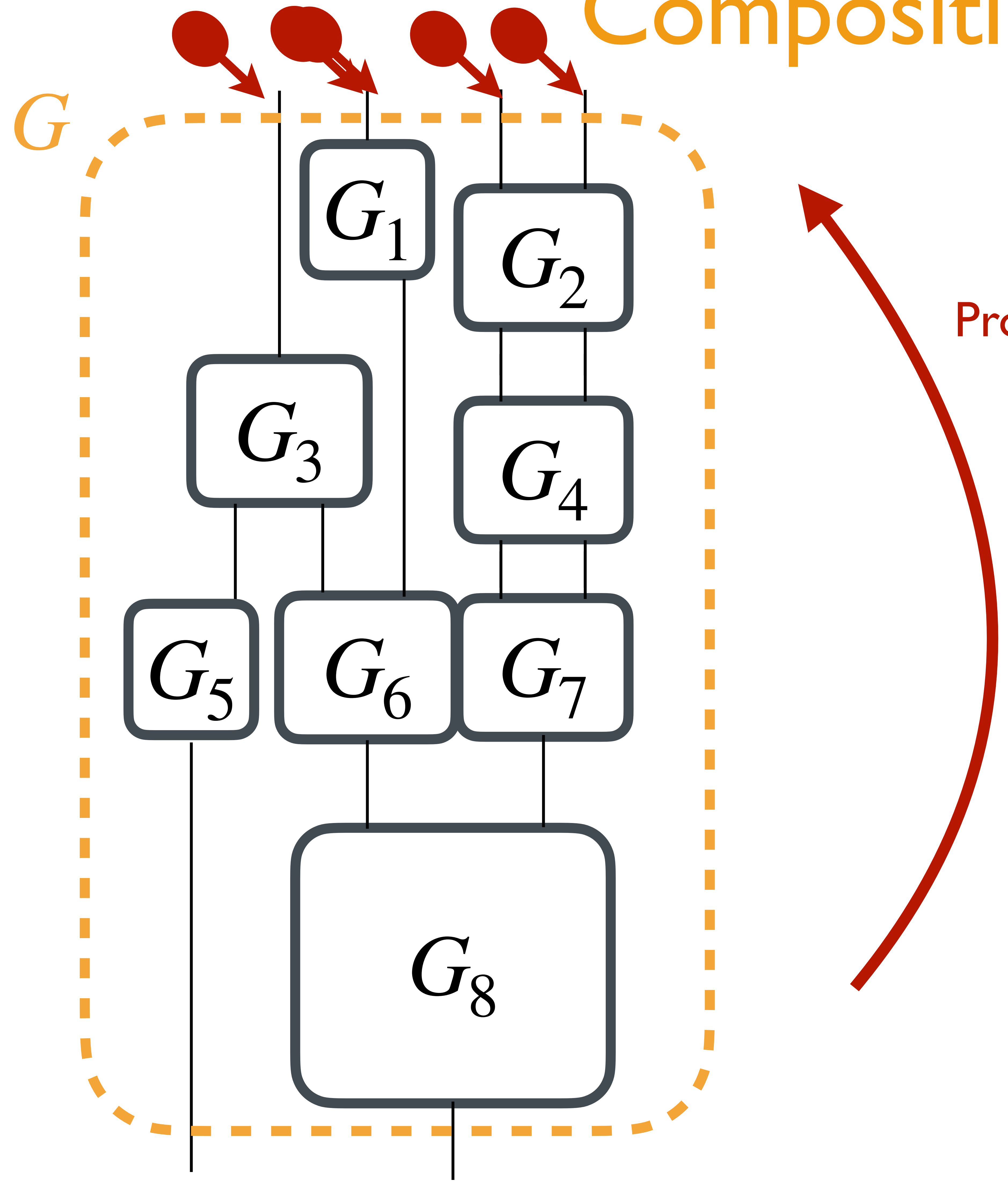

Threshold RPC:

Propagation of the leakage and the outputs to the inputs

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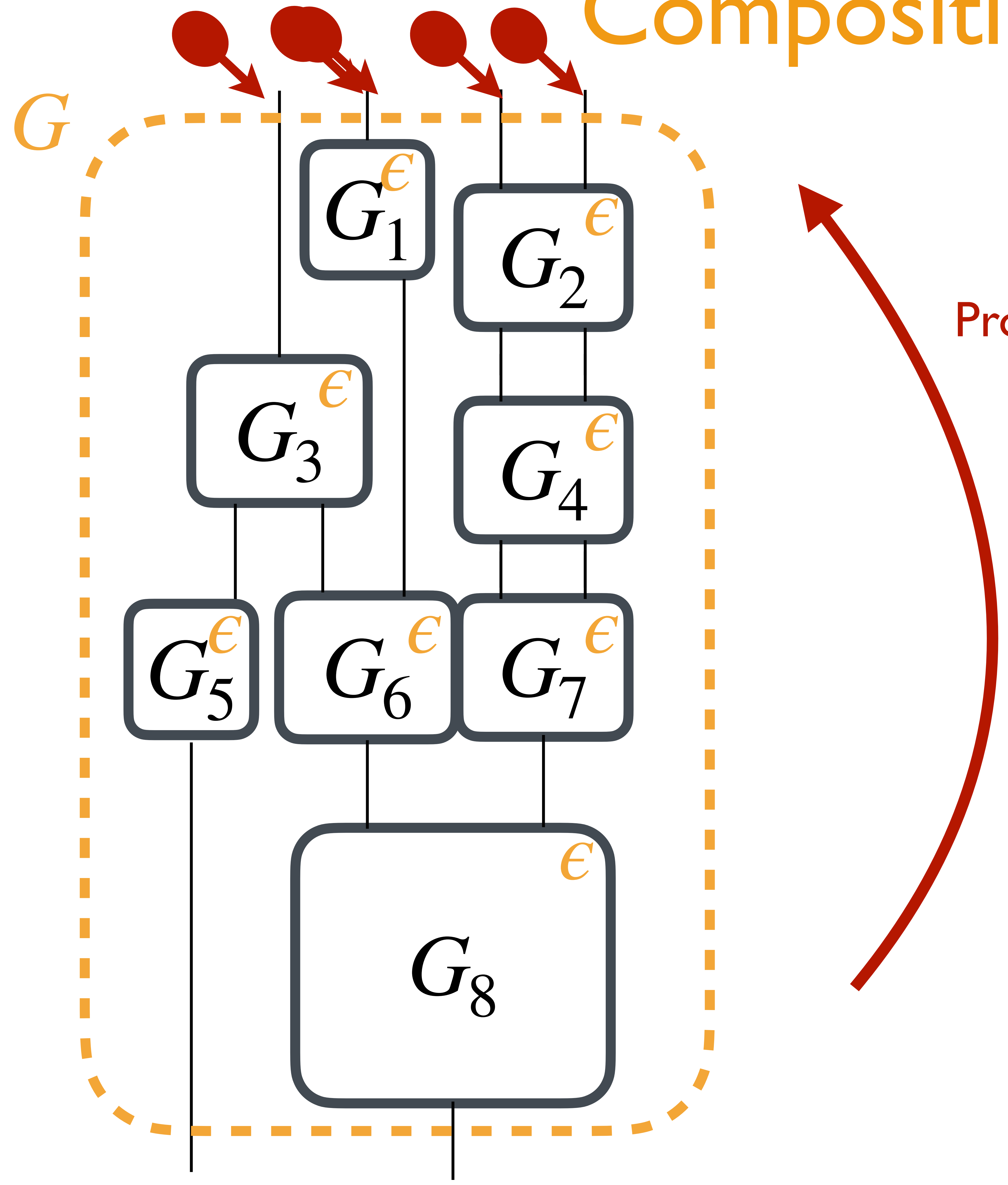
Composition with threshold RPC



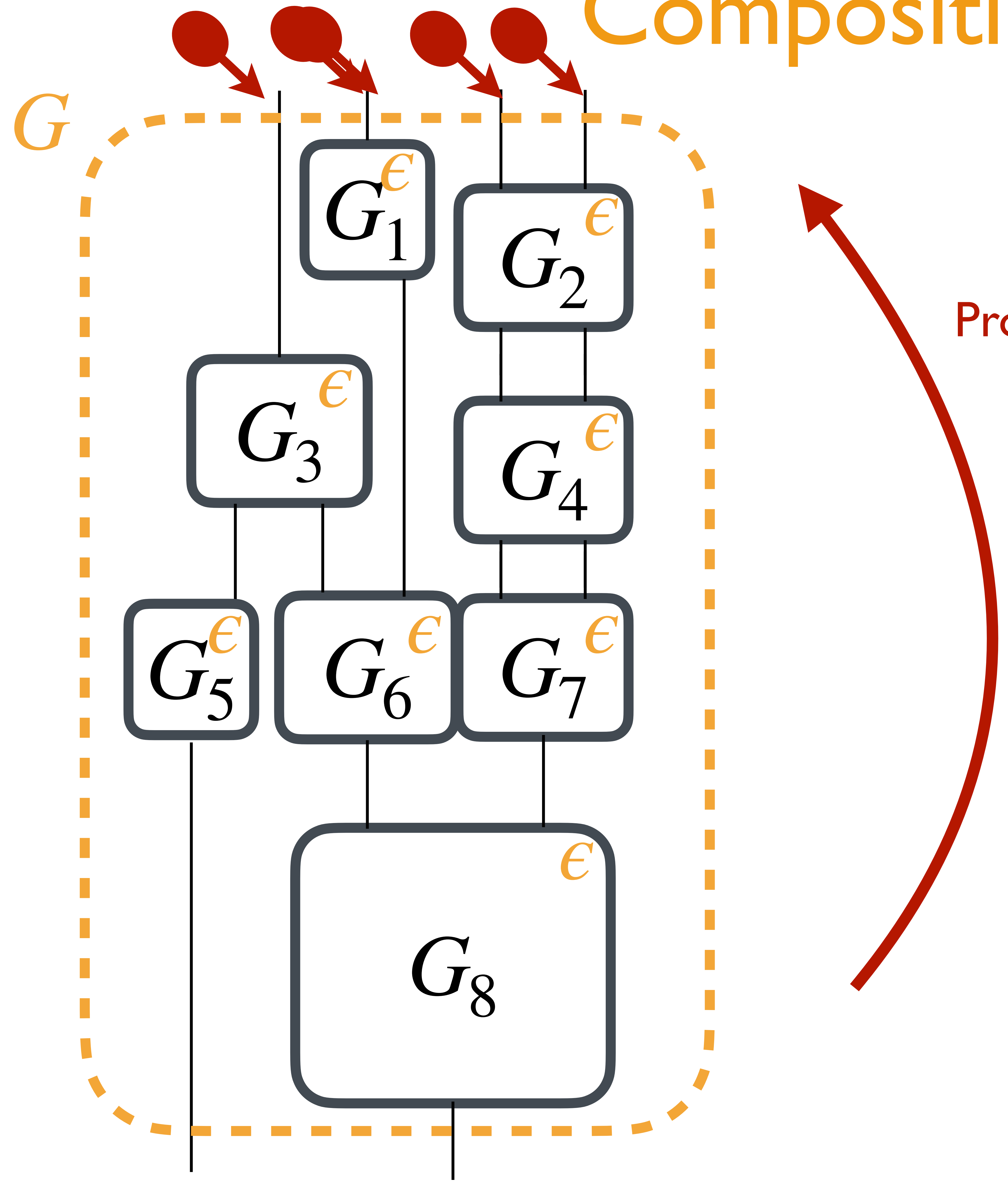
Threshold RPC:

Propagation of the leakage and the outputs to the inputs

Except with probability ϵ!

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

Composition with threshold RPC



Threshold RPC:

Propagation of the leakage and the outputs to the inputs

Except with probability ϵ!

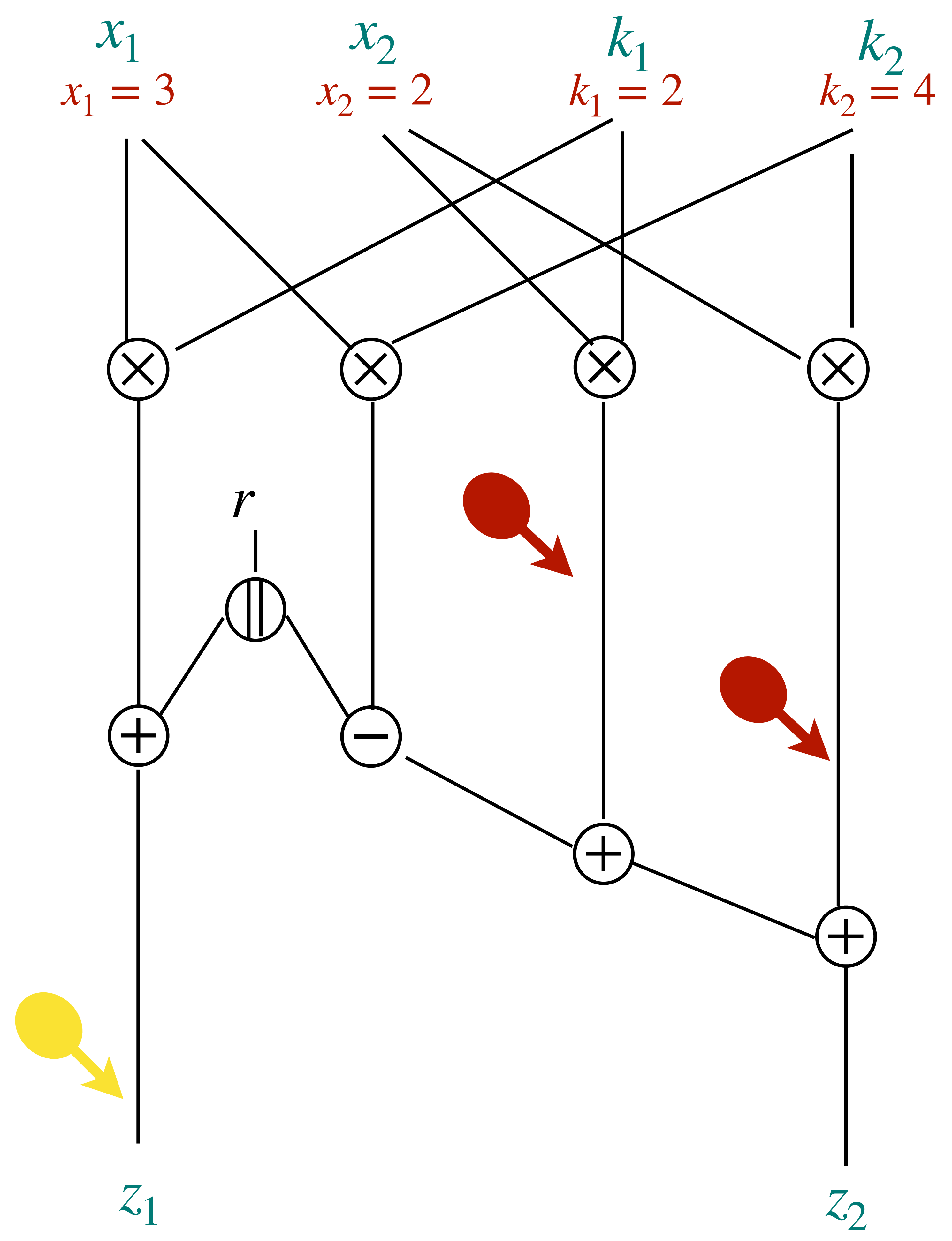
Composition

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

$$\epsilon' \leq 8\epsilon.$$

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

Tighter Compositions



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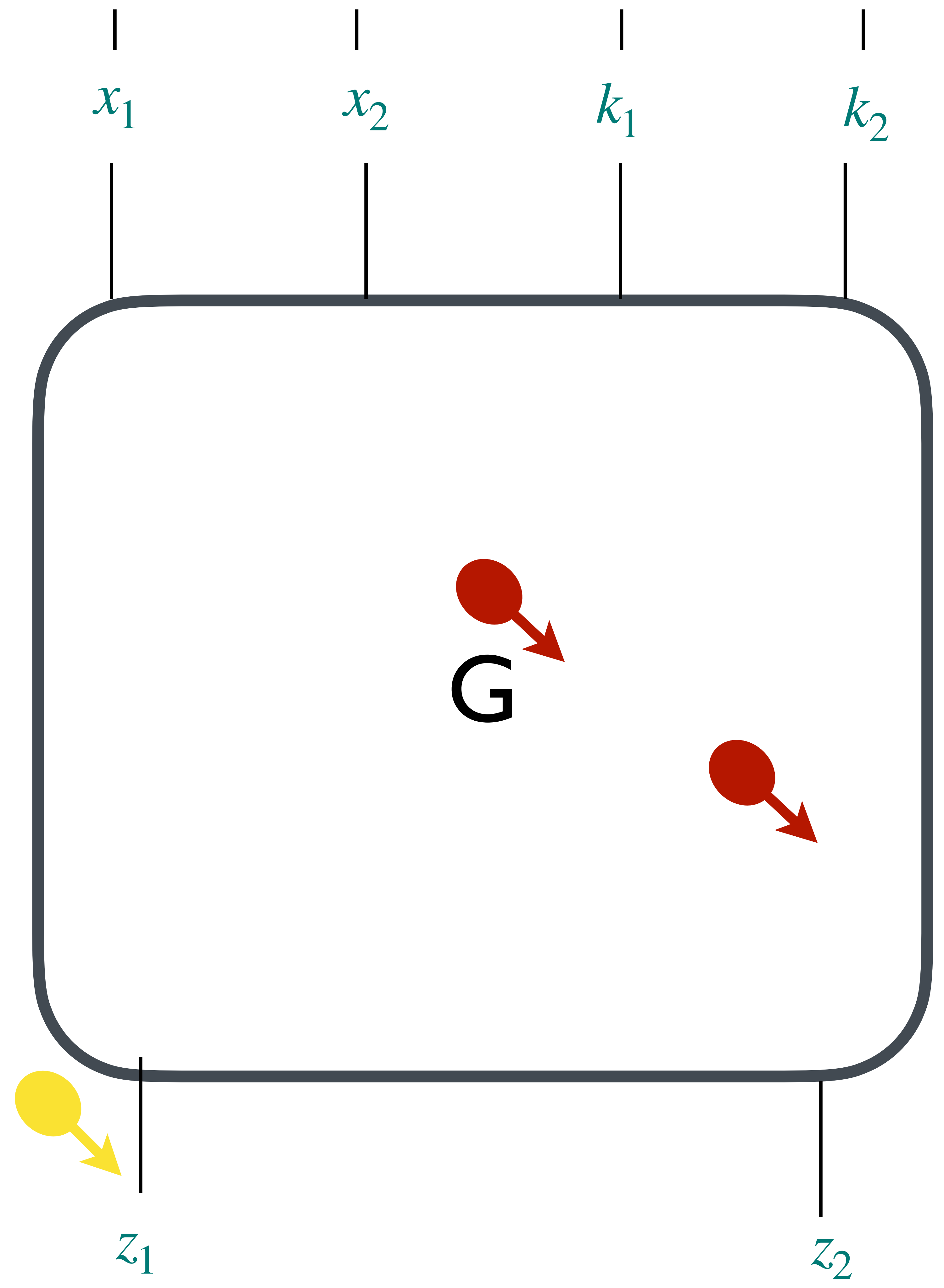
[CFOS21] G. Cassiers, S. Faust, M. Orlt and F-X. Standaert. *Towards Tight Random Probing Security* published in Crypto 2021

Tighter Compositions



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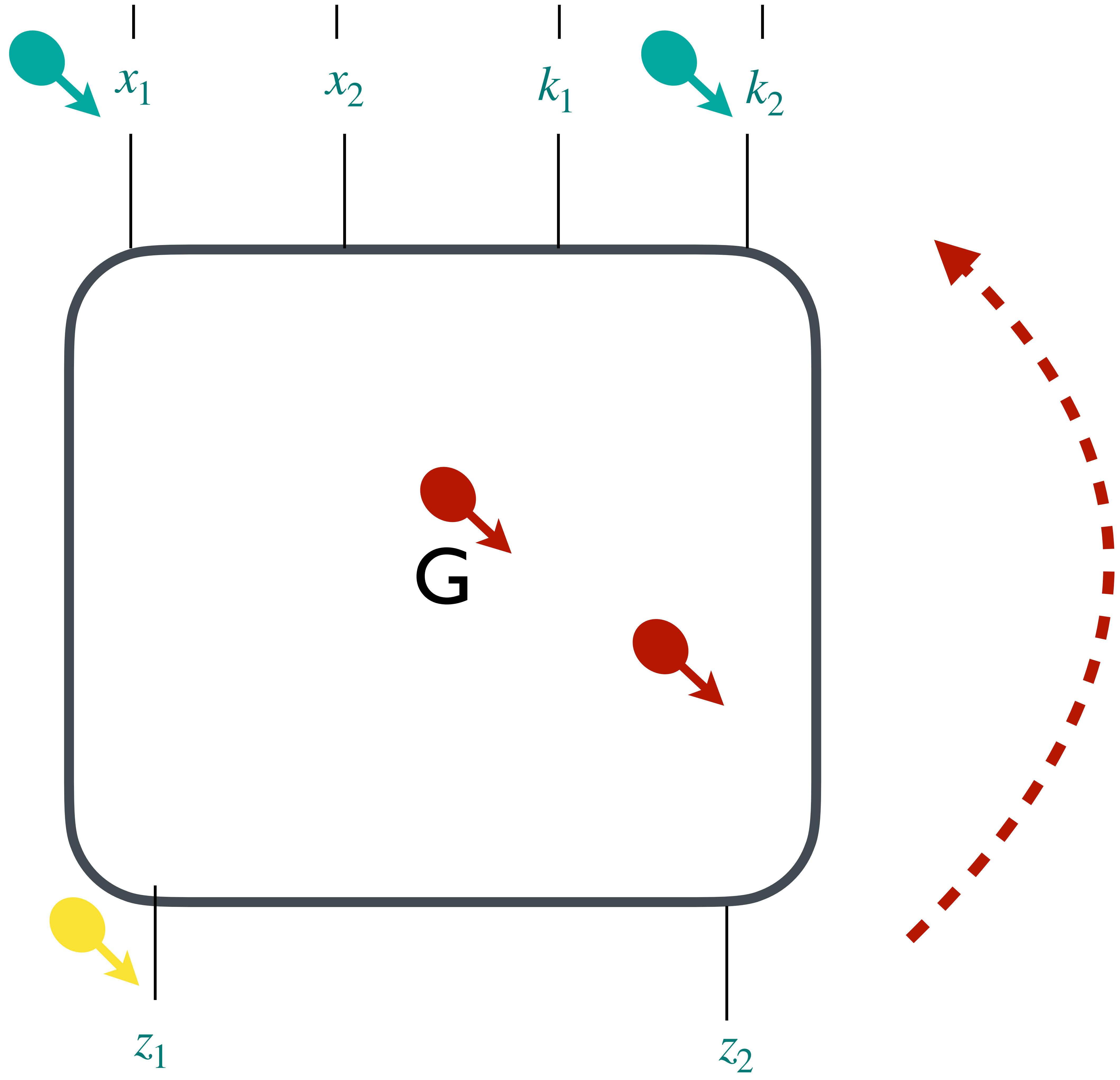

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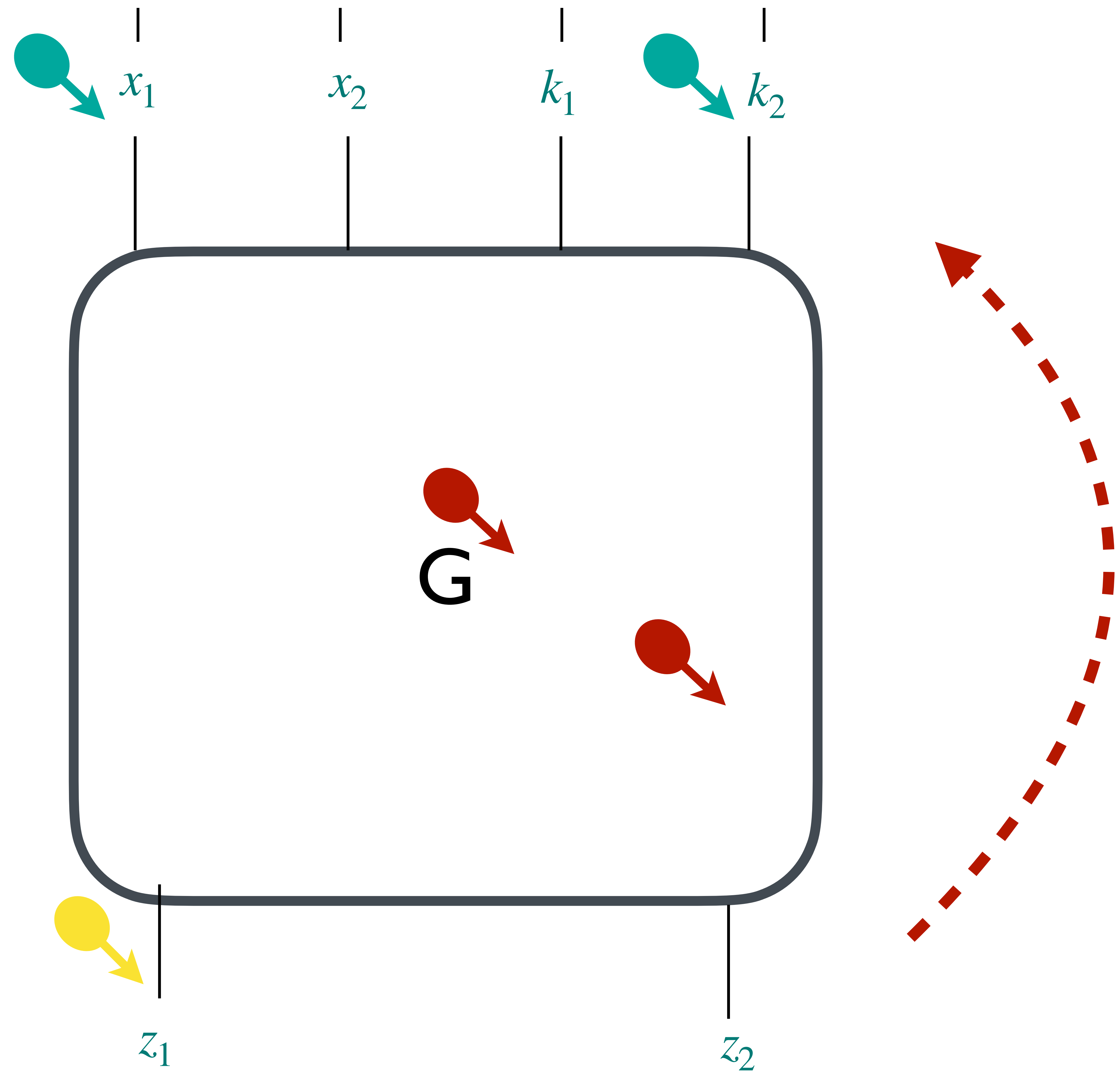
Tighter Compositions

	Threshold RPC	General RPC	Cardinal RPC
🟢	$\leq t$	All the sets	All the cardinals
🟡	$> t$	All the sets	All the cardinals



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1) The random probing model

2) Composition in the random probing model

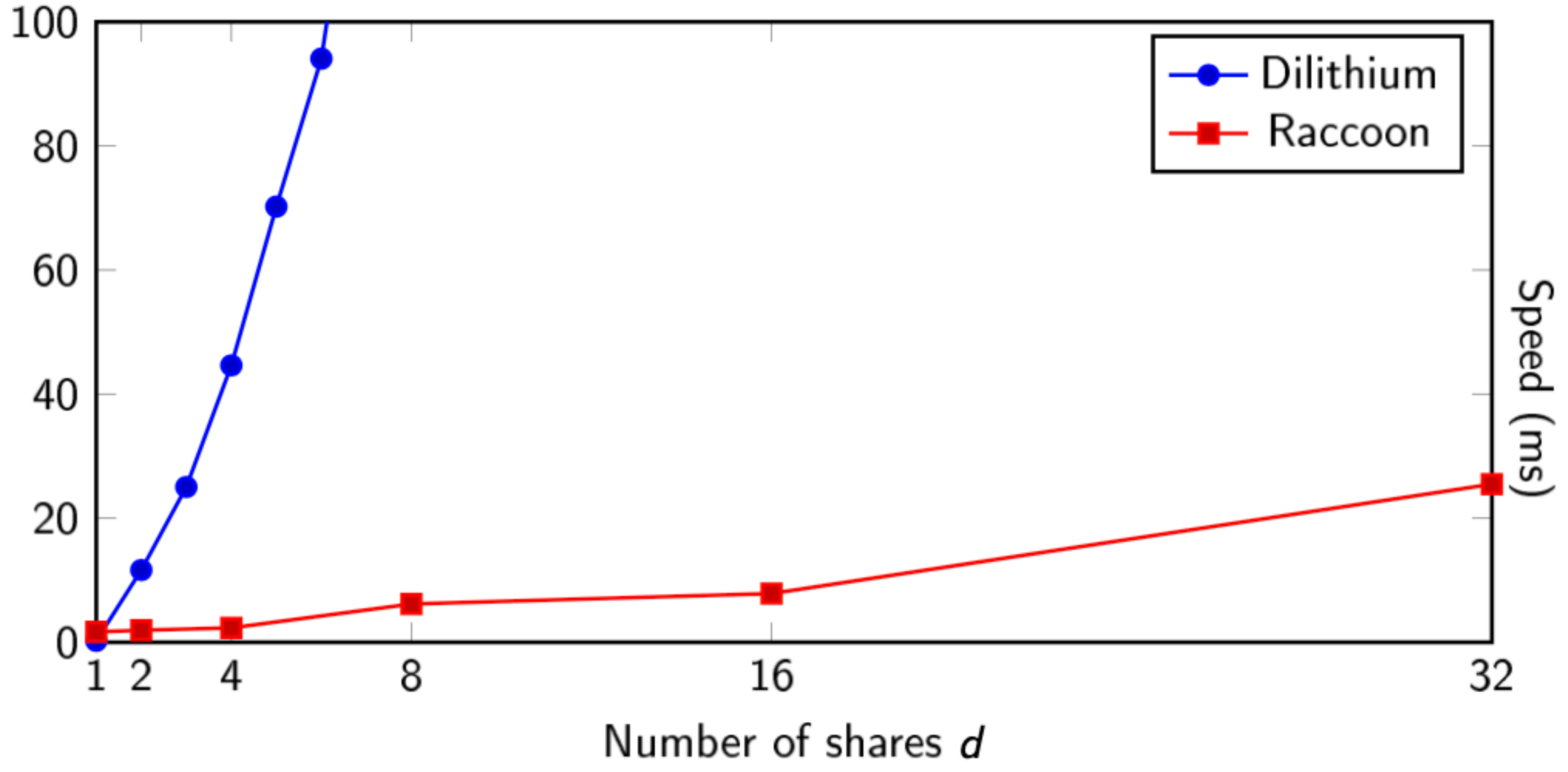
3) Random-probing Raccoon

1) The random probing model

2) Composition in the random probing model

3) Random-probing Raccoon

Raccoon Signature Scheme



Raccoon 128-16

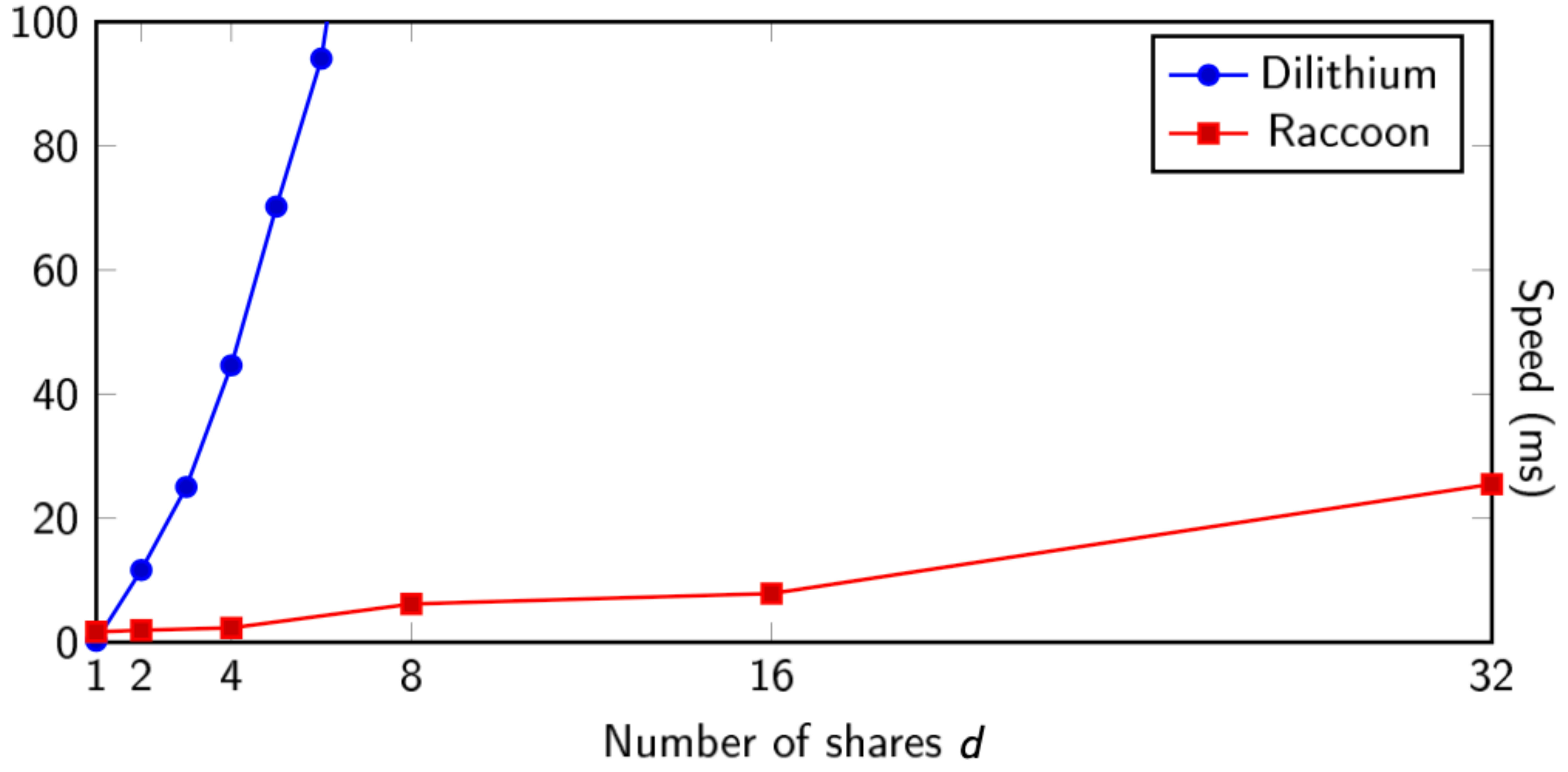
q	549824583172097
n	512
k	5
l	4
d	16
T	2

➡ 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

Raccoon Signature Scheme



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

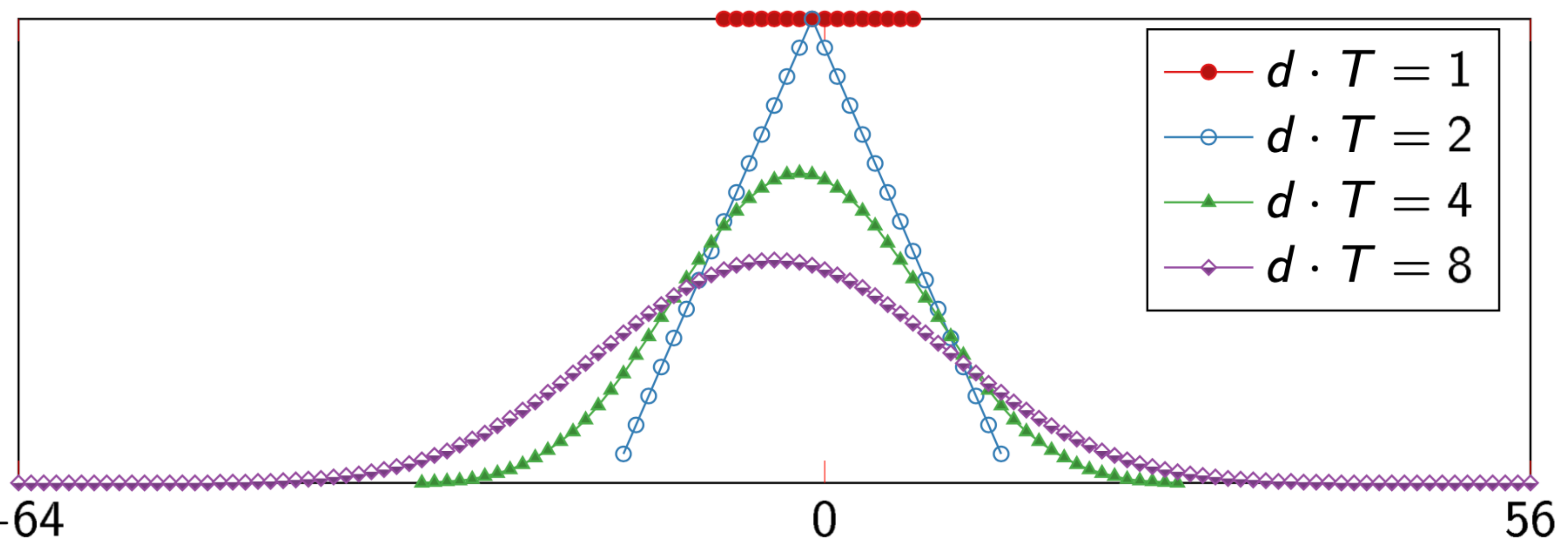
Random Probing Raccoon

KeyGen

1. Generate a large matrix $\mathbf{A} \in \mathscr{R}_q^{k\times\ell}$
2. $[\![s]\!] = (0,\dots,0)$
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. $[\![r]\!] = \text{Refresh}(0,\dots,0)$
2. Add noise to $[\![r]\!]$
3. Compute the commitment $[\![w]\!] = \mathbf{A} \cdot [\![r]\!]$
4. Add noise to $[\![w]\!]$
5. Decode $[\![w]\!]$ to w
6. Compute the challenge $c = \text{H}(w, \text{msg}, \text{vk})$
7. Compute the response $[\![z]\!] = [\![s]\!] \cdot c + [\![r]\!]$
8. Decode $[\![z]\!]$ to z
   No Rejection Sampling
9. The signature is sig = (c, z)

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 $[\![s]\!]$
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6. Decode $[\![t]\!]$ to t
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Signature

1. $[\![r]\!] =$ Refresh$(0,\ldots,0)$
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8. Decode $[\![z]\!]$ to z
   No Rejection Sampling
9. The signature is sig $=$ (c, z)

« Add noise to »

Add $d\cdot T$ small uniform randoms

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 $(\mathbf{A}, t)$
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Signature

1. $[|r|] = \qquad (0,\ldots,0)$
2. Add noise to $[|r|]$
3. Compute the commitment $[|w|] = \mathbf{A} \cdot [|r|]$
4. Add noise to $[|w|]$
5. Decode $[|w|]$ to w
6. Compute the challenge c = H(w, msg, vk)
7. Compute the response $[|z|] = [|s|] \cdot c + [|r|]$
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Random Probing Raccoon

« Add noise to »

Add $d \cdot T$ small uniform randoms

KeyGen

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2. $[|s|] = (0,\ldots,0)$
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8. ⊕ Decode $[|z|]$ to z
   No Rejection Sampling
9. The signature is sig = (c, z)

Random Probing Raccoon

KeyGen

$\oplus$

$\oplus \otimes$

$\oplus$

$\oplus$

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 $[\,|s|\,]$

Signature

$\oplus$

$\oplus \otimes$

$\oplus$

$\oplus$

$\Cup \oplus \otimes$

$\oplus$

1. $[\,|r|\,] = \qquad (0,\ldots,0)$
2. Add noise to $[\,|r|\,]$
3. Compute the commitment $[\,|w|\,] = \mathbf{A} \cdot [\,|r|\,]$
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8. Decode $[\,|z|\,]$ to z

   No Rejection Sampling
9. The signature is sig = (c, z)

« Add noise to »

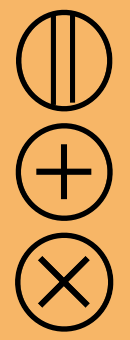
Add $d \cdot T$ small uniform randoms

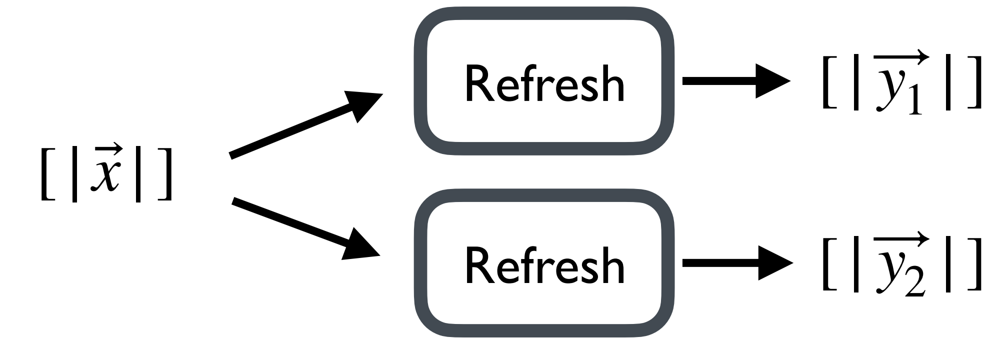
A New Notion

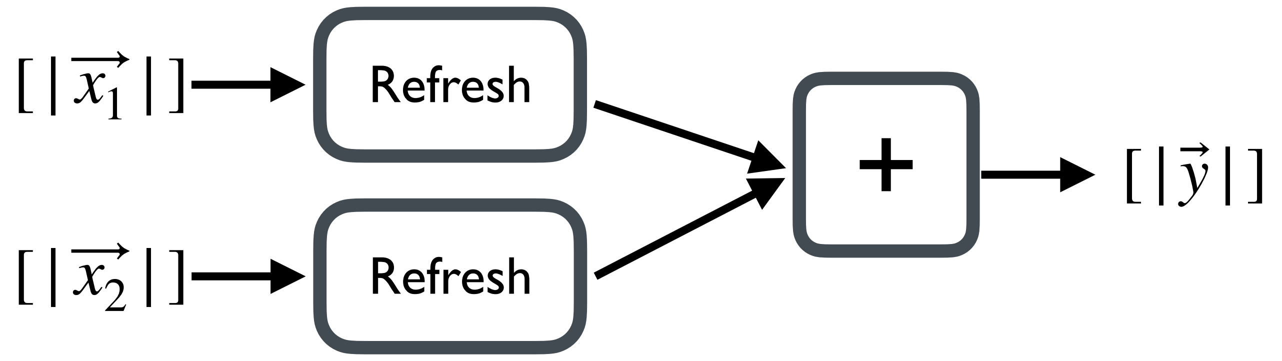
Random Probing Security with Auxiliary Inputs and public Outputs (RPS-AI-O)

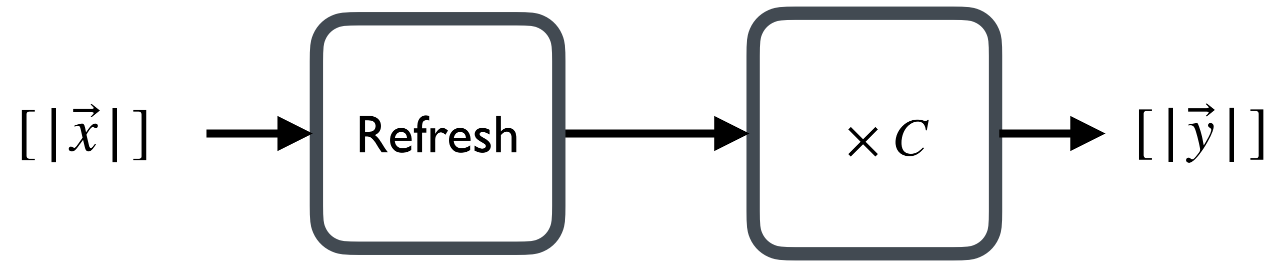
New gadgets

Composable (cardinal or threshold RPC) elementary gates are needed



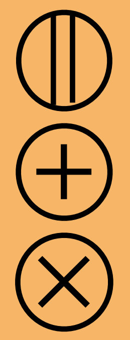


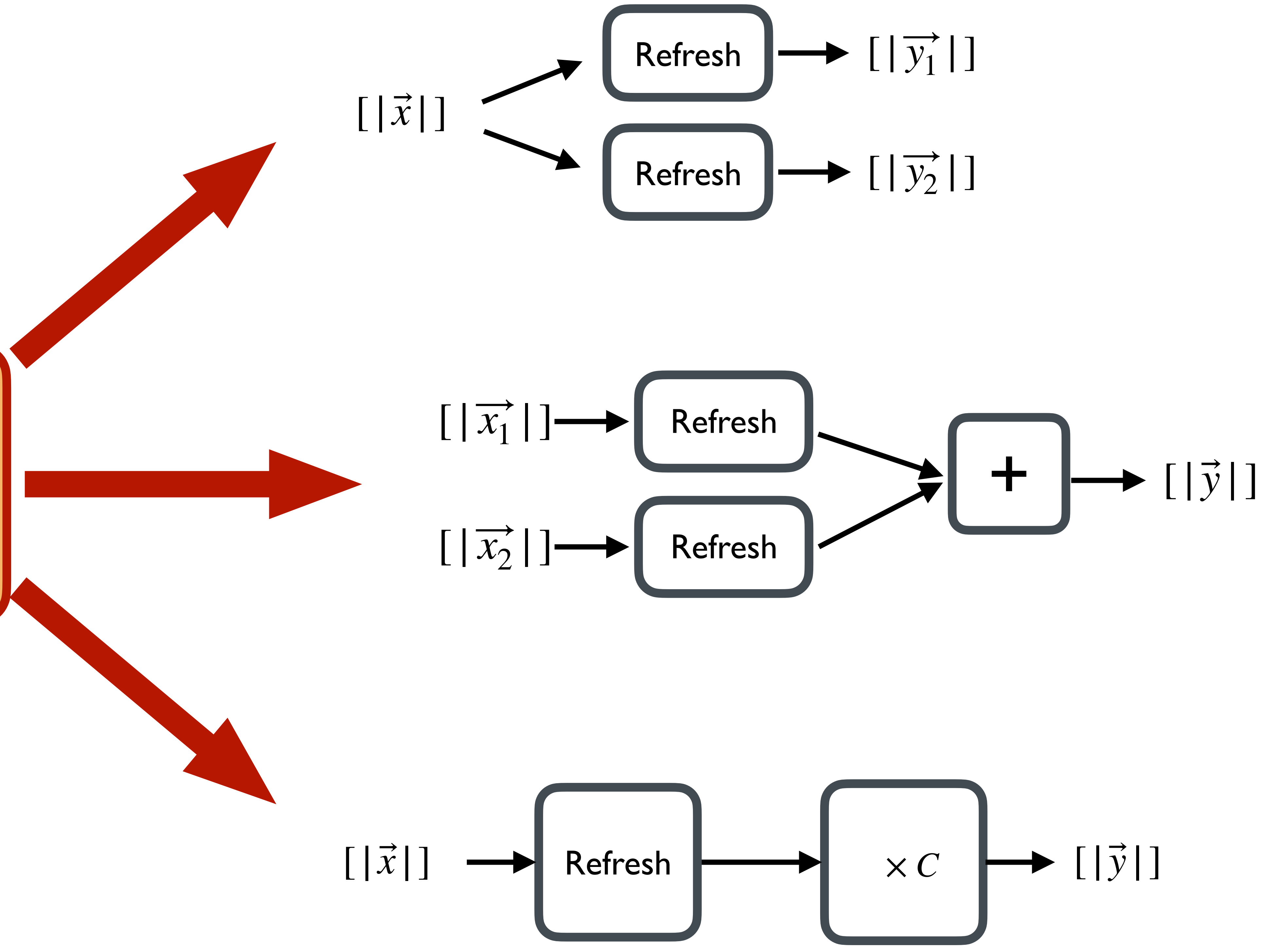




New gadgets

Composable (cardinal or threshold RPC) elementary gates are needed





To be composable, they need to include some refreshes

Refresh ?

New gadgets

Composable (cardinal or threshold RPC) elementary gates are needed

$\varobar$ $\oplus$ $\otimes$

$$\begin{tikzcd}
 & \boxed{\text{Refresh}} \arrow[r] & {[|\vec{y_1}|]} \\
{[|\vec{x}|]} \arrow[ur] \arrow[dr] & & \\
 & \boxed{\text{Refresh}} \arrow[r] & {[|\vec{y_2}|]}
\end{tikzcd}$$

$$\begin{tikzcd}
{[|\vec{x_1}|]} \arrow[r] & \boxed{\text{Refresh}} \arrow[dr] & & \\
 & & \boxed{+} \arrow[r] & {[|\vec{y}|]} \\
{[|\vec{x_2}|]} \arrow[r] & \boxed{\text{Refresh}} \arrow[ur] & &
\end{tikzcd}$$

$$\begin{tikzcd}
{[|\vec{x}|]} \arrow[r] & \boxed{\text{Refresh}} \arrow[r] & \boxed{\times C} \arrow[r] & {[|\vec{y}|]}
\end{tikzcd}$$

Efficient random-probing composable refresh

To be composable, they need to include some refreshes

Refresh ?

New Random Probing Composable Refresh

$$[|z|] = \begin{array}{|c|c|c|c|c|c|c|c|} \multicolumn{1}{c}{1} & \multicolumn{1}{c}{2} & \multicolumn{1}{c}{3} & \multicolumn{1}{c}{4} & \multicolumn{1}{c}{5} & \multicolumn{1}{c}{6} & \multicolumn{1}{c}{7} & \multicolumn{1}{c}{8} \\ \hline 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline \end{array}$$

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

$[|z|] =$

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

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

	1	2	3	4	5	6	7	8
$[\vert z\vert] =$	0	0	0	0	0	0	0	0

1st iteration

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

	1	2	3	4	5	6	7	8
$[\vert z\vert] =$	0	0	r_1	0	0	0	$-r_1$	0

2nd iteration

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

	1	2	3	4	5	6	7	8
$[\vert z\vert] =$	r_2	0	r_1	0	0	0	$-r_1$	$-r_2$

3rd iteration

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

	1	2	3	4	5	6	7	8
$[\vert z\vert] =$	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

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

2nd iteration

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

$[|z|] =$

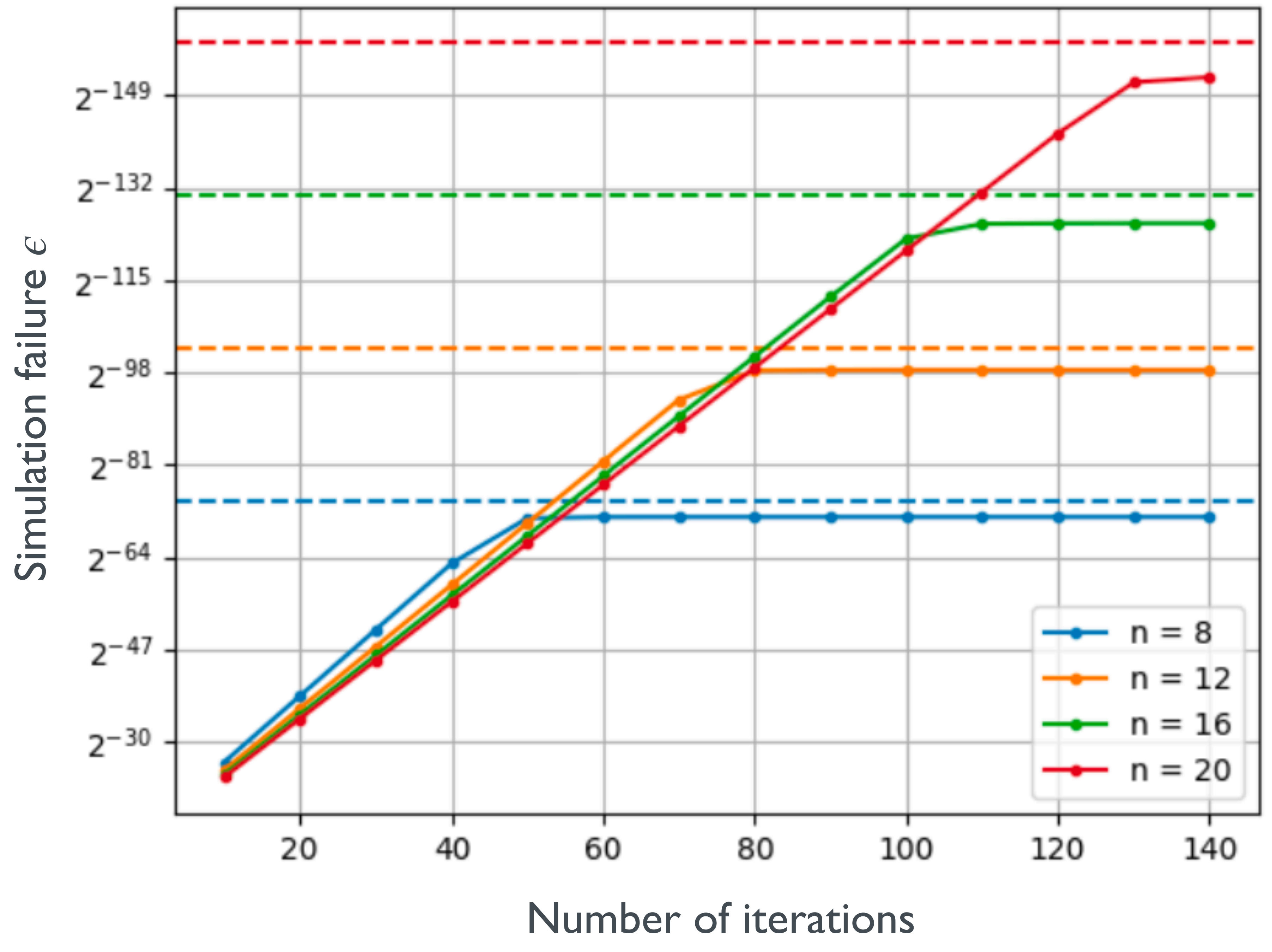
1	2	3	4	5	6	7	8
r_2	0	r_1	0	0	0	$-r_1$	$-r_2$

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	$-r_1$	$-r_2$



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.
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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

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Thank you