Side-channel Masking with Pseudo-Random Generator

Eurocrypt 2020

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IDEMIA augmented identity

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Motivation: side-channel attacks

High-order masking : randomness cost

- Number of randoms is high: can become a bottleneck
- **Our goal:** minimize number of calls to TRNG *and* remain secure in the probing model

	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 6$
Rivain-Prouff [RP10]	2880	5760	9600	14400	20160
Belaïd *et. al* [BBP16]	2560	5120	8000	13120	18240
Faust *et. al* [FPS17]	1415	2530	6082	6699	20712
This paper	48	108	192	300	432

Table: number of bytes of true randomness to get t-th order security for AES.

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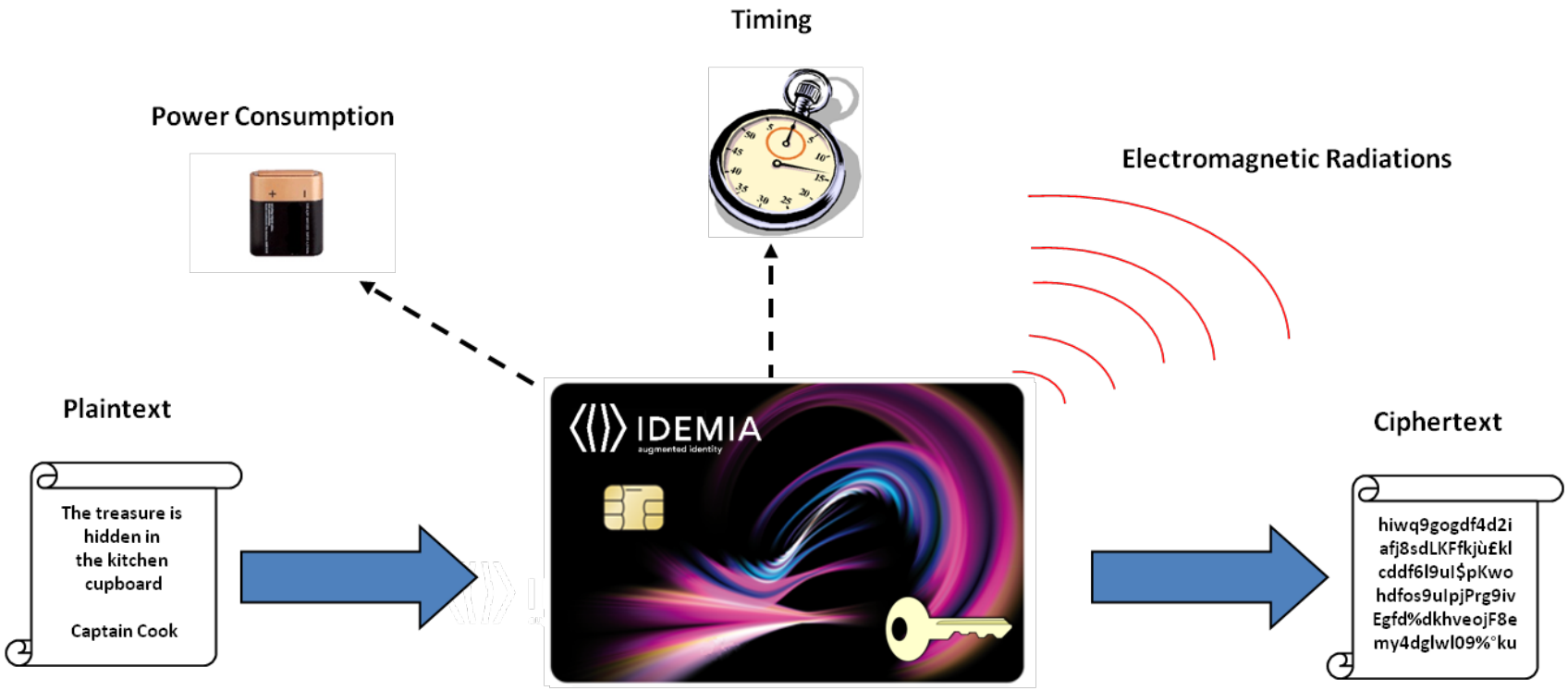
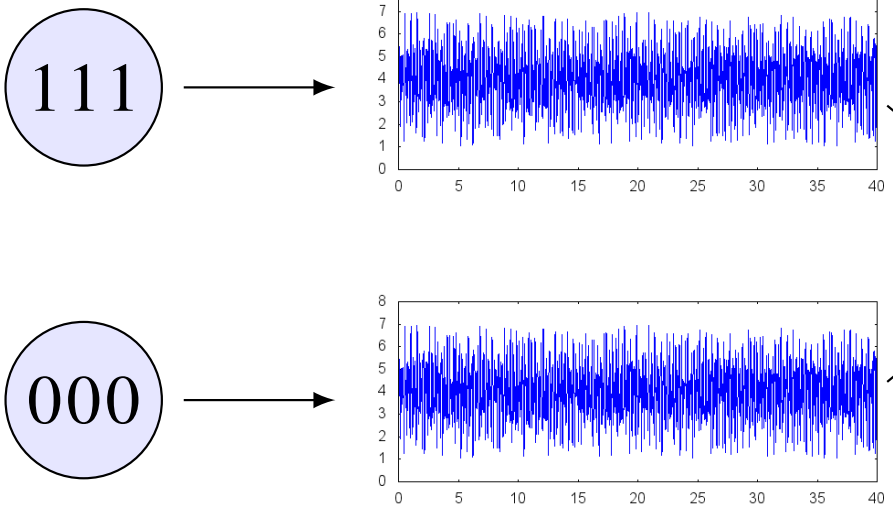


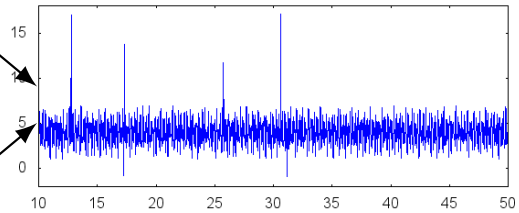
Differential Power Analysis [KJJ99]

Group by predicted
SBox output bit

Average trace



Differential trace



Countermeasure

Masking countermeasure

Let x be a sensitive variable:

- Generate a random r (different for each execution)
- Mask x using r : $x' = x \oplus r$
- Manipulate x' (instead of x) and r independently

r is random $\Longrightarrow$ x' is random $\Longrightarrow$ no information on x leaks

☞ True only in case of one leakage point

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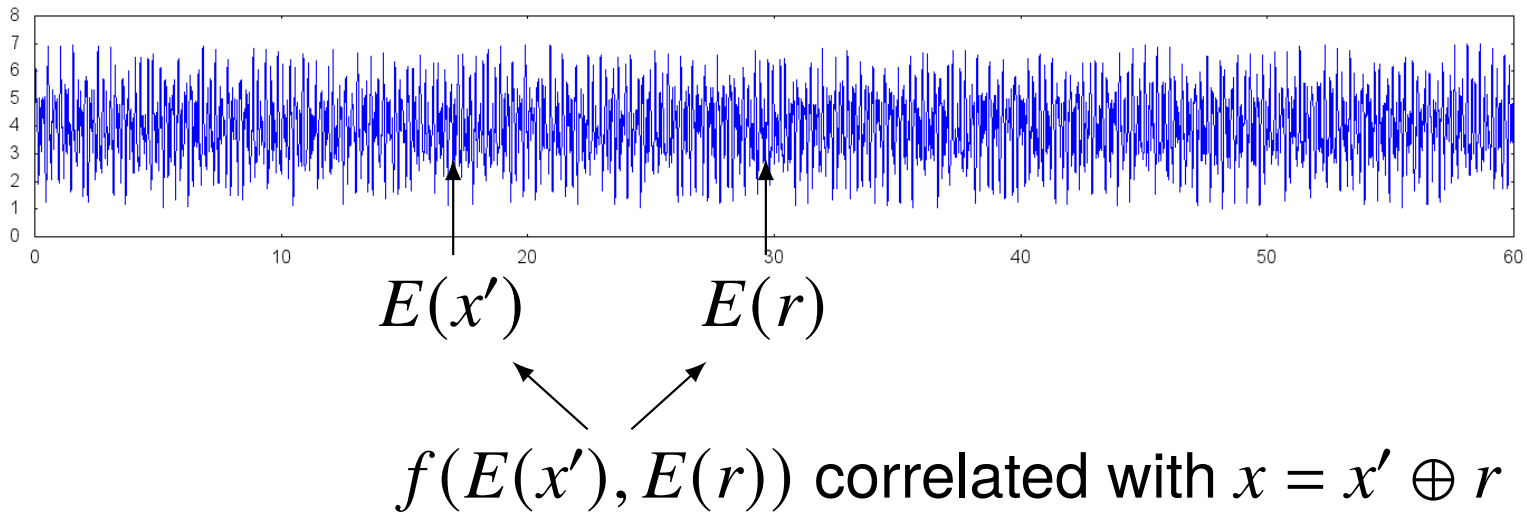
Differential Power Analysis (second-order)

- Manipulation of $x' = x \oplus r$



- Second-order attack
  - requires more curves but can be practical

Solution: Higher-Order Boolean Masking

Basic principle

Each sensitive variable x is shared into n variables:

$$x = x_1 \oplus x_2 \oplus \cdots \oplus x_n$$

- Generate $n-1$ random variables $x_1, x_2, \ldots, x_{n-1}$
- Initially let $x_n = x \oplus x_1 \oplus x_2 \oplus \cdots \oplus x_{n-1}$

Security against DPA attack of order $n-1$

- Any subset of $n-1$ shares is uniformly and independently distributed

  $\Longrightarrow$ If we probe at most $n-1$ shares x_i, we learn nothing about x

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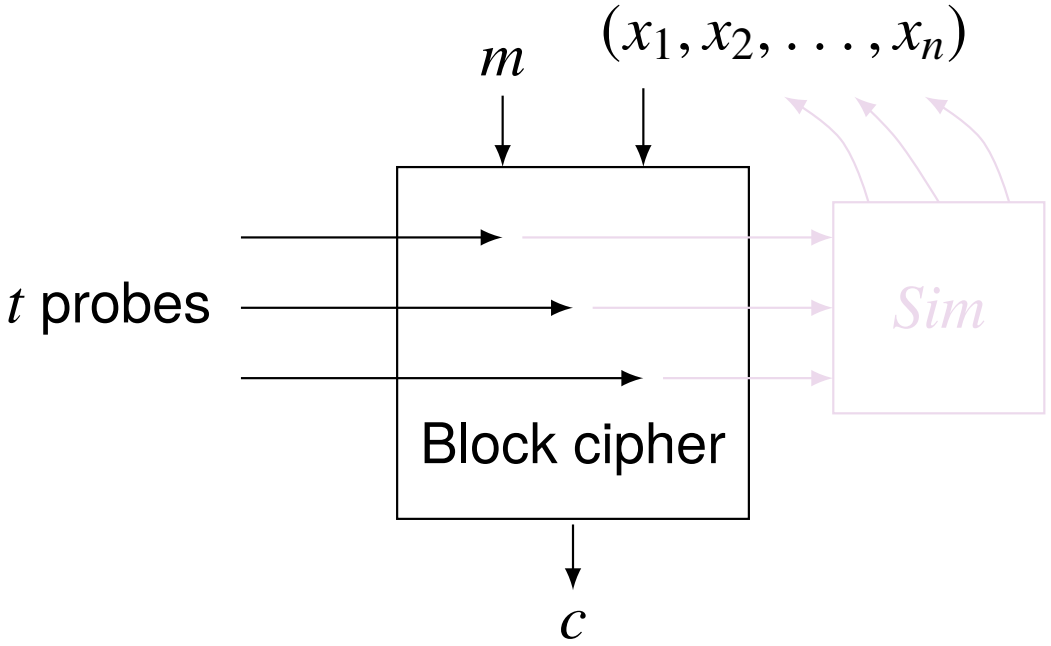
ISW Security Model

- Proof of security in the Probing Model [ISW03]:



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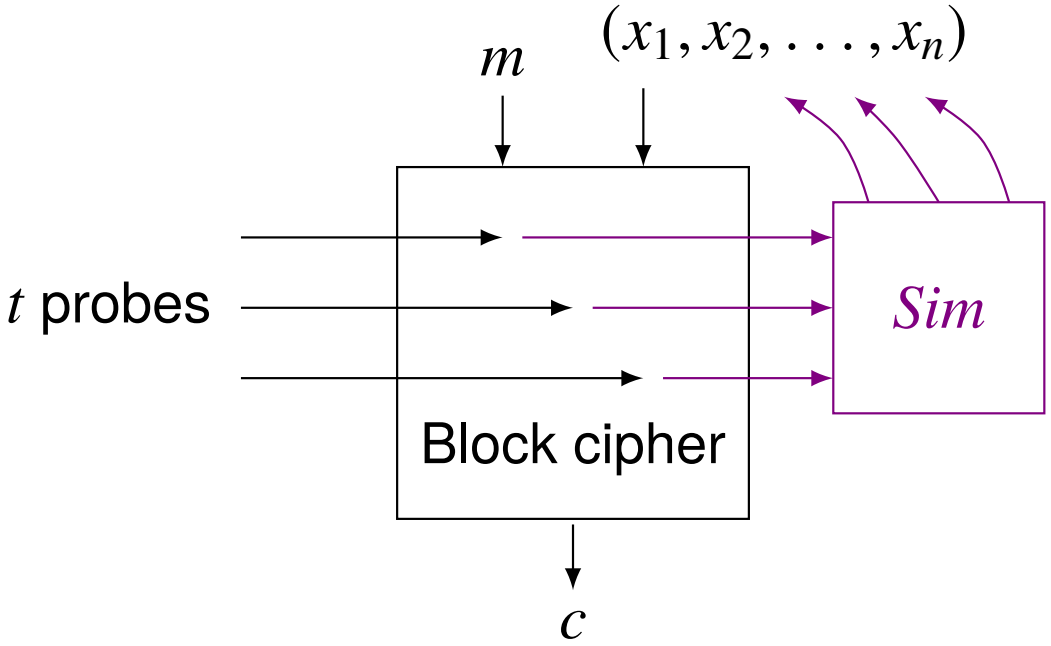

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  - $\Rightarrow$ The adversary learns nothing from the t probes

Linear Operations

Computation of $a \oplus b$

- **Inputs:** $(a_i)_i$ and $(b_i)_i$ such that
  - $a_1 \oplus a_2 \oplus \cdots \oplus a_n = a$
  - $b_1 \oplus b_2 \oplus \cdots \oplus b_n = b$
- **Output:** $(c_i)_i$ such that
  - $(a_1 \oplus b_1) \oplus (a_2 \oplus b_2) \oplus \cdots \oplus (a_n \oplus b_n) = a \oplus b$

    $\Rightarrow \quad c_1 \oplus c_2 \oplus \cdots \oplus c_n = a \oplus b$

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Secure Multiplication in High-Order Masking Schemes

Secure Computation of $a \times b$

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Ishai-Sahai-Wagner private circuit [ISW03]

- Secure against t probes for $n = 2t + 1$ shares.
- Number of operations: $\mathcal{O}(t^2)$
- Requires $\mathcal{O}(t^2)$ randoms per multiplication.

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Decomposition of the c_i

$$\bigoplus_i c_i = \left(\bigoplus_i a_i\right)\left(\bigoplus_i b_i\right) = \bigoplus_{i,j} a_i b_j$$

Example for $n = 3$

☞ For n shares: requires $n(n-1)/2$ fresh random values

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Secure SBox Computation

Secure Computation of $S(x)$

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[RP10] countermeasure **for AES**: compute $S(x) = x^{254}$

- 4 multiplications over $\mathbb{F}_{2^8}$ with ISW
- 2 mask refreshings

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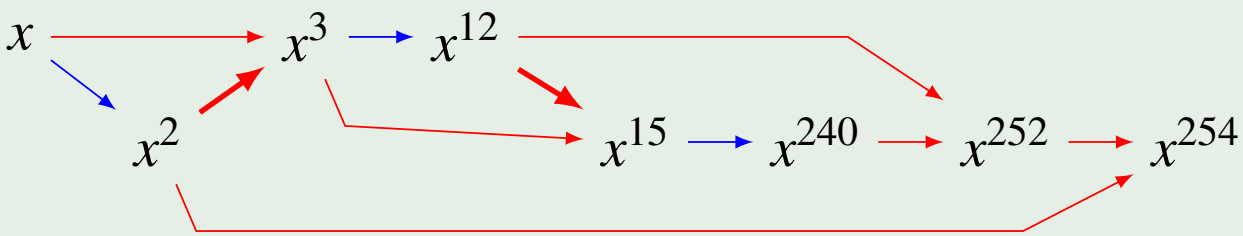

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Reducing randomness complexity

Natural idea

- Use a **TRNG** to generate a seed
- Use a **PRG** to generate all needed randoms

☞ **Security:** The Pseudo-Random Generator (PRG) should also be secure against t-probing attacks

Notion of robust PRG [IKL+13]

- Original ISW: randomness complexity $\mathcal{O}(t^2|C|)$
- New randomness complexity $\mathcal{O}(t^{3+\varepsilon}\log^k|C|)$
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- New randomness complexity $\mathcal{O}(t^2(\log t + \log|C|))$
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r-wise independent PRG

Definition: r-wise independent PRG

- $G : \{0,1\}^n \longrightarrow \{0,1\}^m$ for $m \gg n$
- Any subset of r bits of $G(a)$ is uniformly and independently distributed, for $a \leftarrow U_n$.

Construction based on polynomial evaluation in $\mathbb{F}$

- Generate a random **seed** of r elements from TRNG:
$$\vec{a} = (a_0, \ldots, a_{r-1}) \in \mathbb{F}^r$$
- Evaluate the polynomial
$$h_{\vec{a}}(x) = \sum_{i=0}^{r-1} a_i x^i \in \mathbb{F}$$
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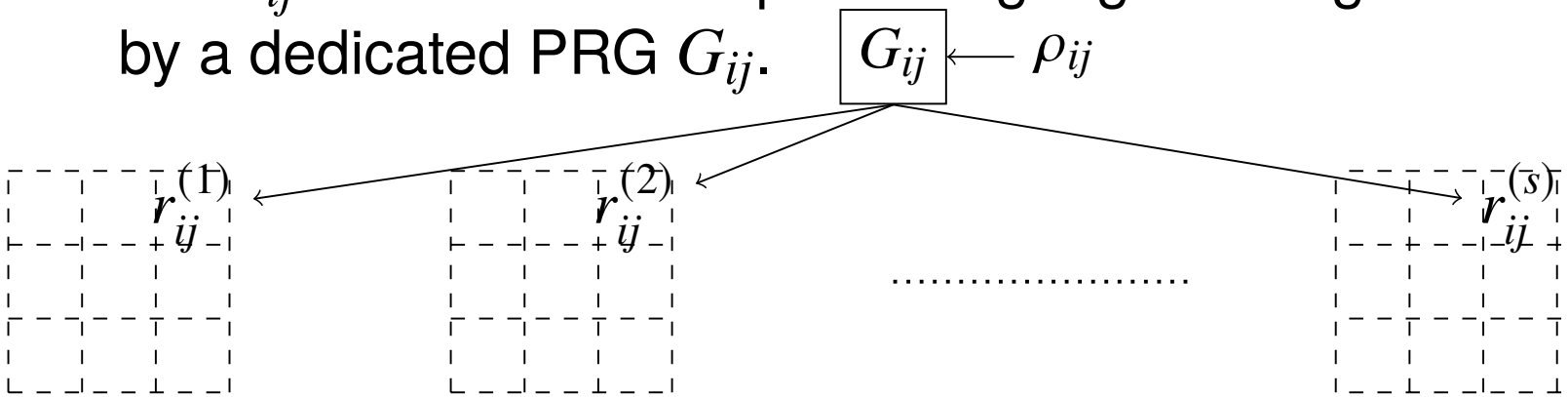
- The r_{ij}'s in all ISW multiplication gadgets are generated by a dedicated PRG G_{ij}.



Security of ISW

- If the attacker probes a given r_{ij}, we can give to the attacker all other $r_{ij}^{(k)}$ for free.
- The attacker has no advantage in probing the PRG G_{ij}, since he could get all $r_{ij}^{(k)}$ with a single probe.
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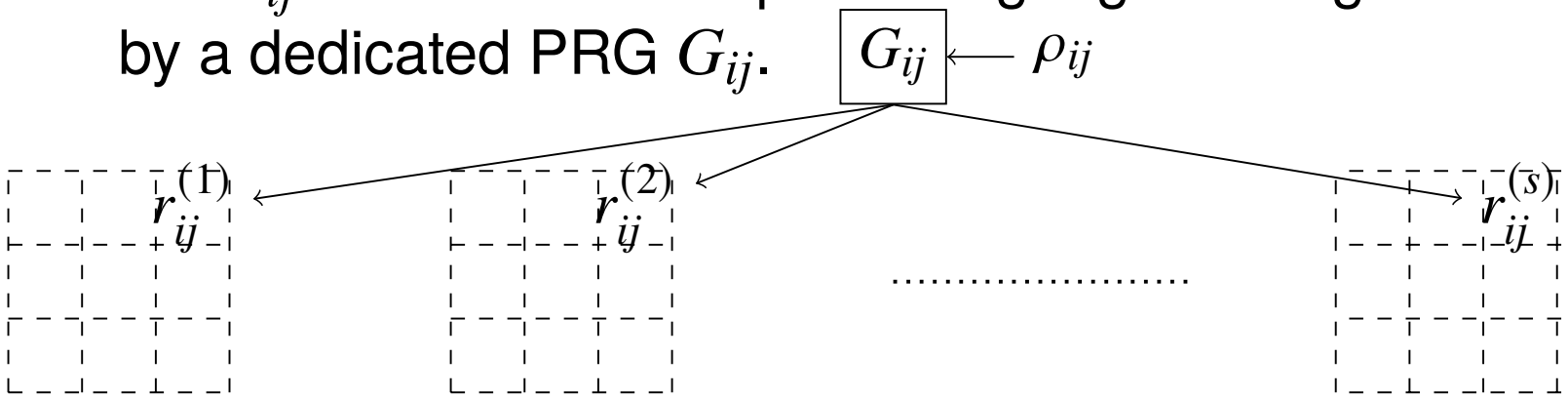

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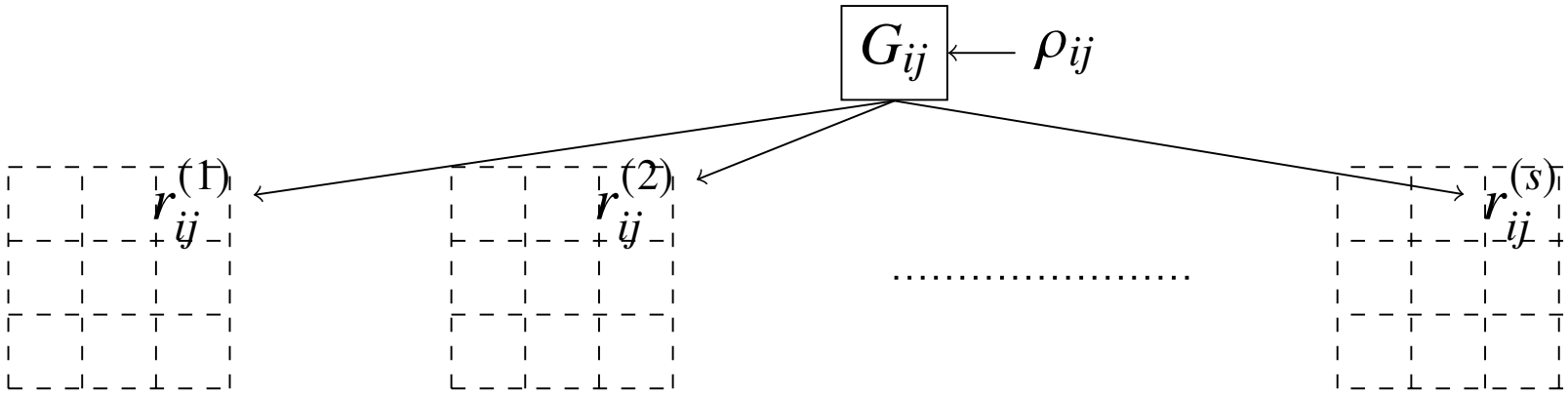
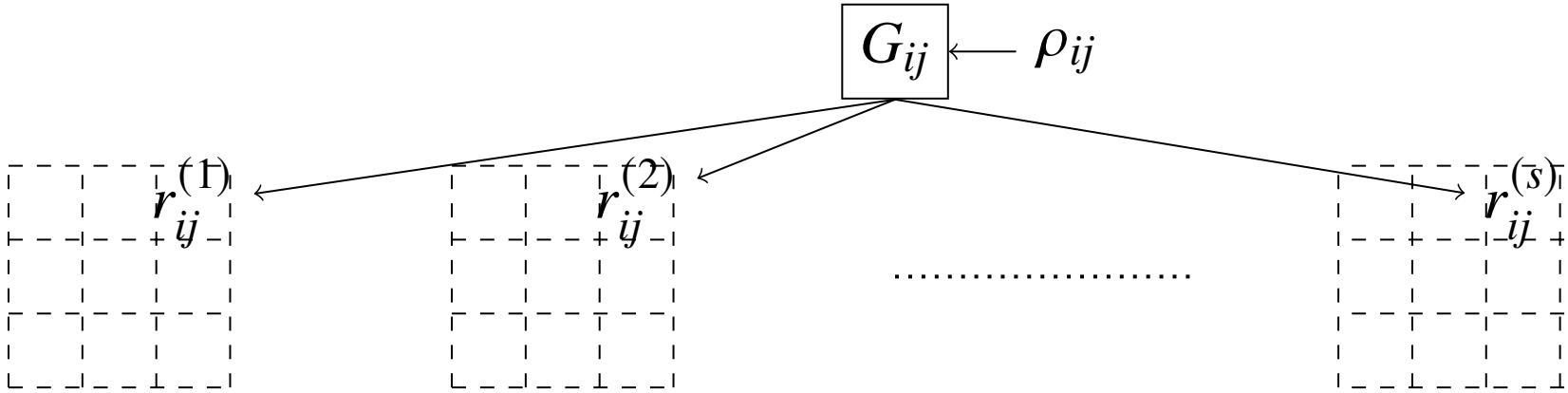


r-wise independence of PRG

- With some mask refreshing, every intermediate variable depends on at most a *single* random $r_{ij}^{(k)}$.
- With t probes, the adversary gets information about at most t randoms $r_{ij}^{(k)}$ generated by the PRG G_{ij}.
- $\Longrightarrow$ we can use a PRG with r-wise independence $r = t$.

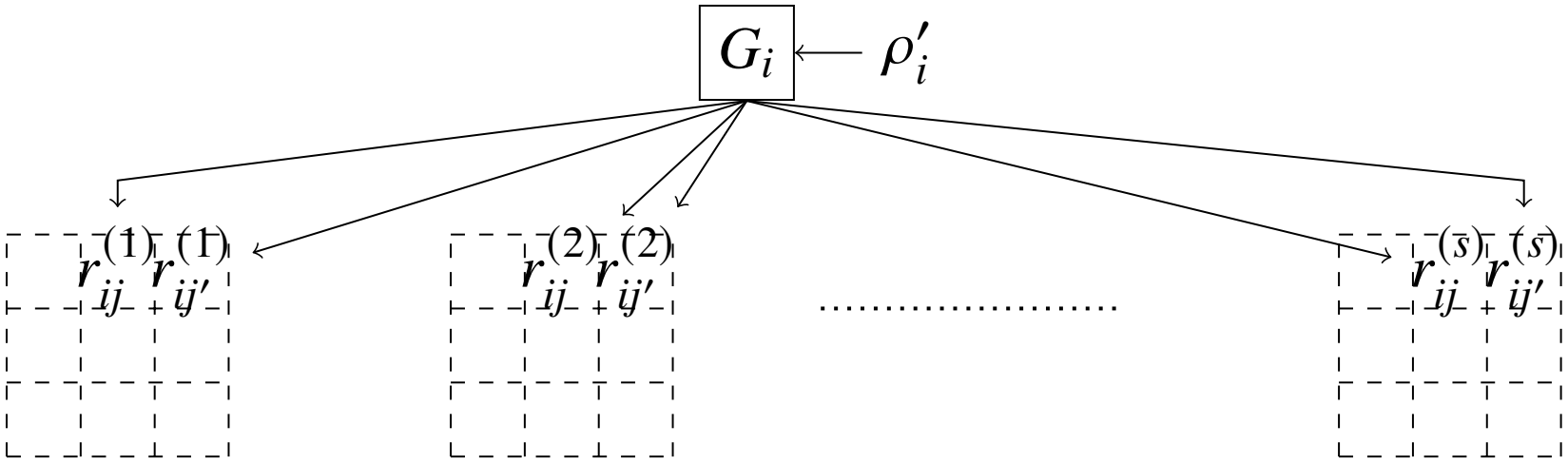
Our technique (3)



Randomness complexity

- There are $\mathcal{O}(t^2)$ randoms r_{ij}, so we need $\mathcal{O}(t^2)$ independent PRGs G_{ij}
- Each PRG requires $r = t$ true randoms in $\mathbb{F}$
  - with $|\mathbb{F}| = \mathcal{O}(|C|)$
- Randomness complexity $\mathcal{O}(t^3 \log |C|)$
  - instead of $\mathcal{O}(t^{3+\varepsilon} \log^k |C|)$ in [IKL13]
  - without expander graphs

Improved randomness complexity



Randomness complexity

- Each PRG G_i now generates the full row of randoms $r_{ij}^{(k)}$
  - We need $\mathcal{O}(t)$ independent PRGs instead of $\mathcal{O}(t^2)$.
- Each PRG requires $r = t$ true randoms in $\mathbb{F}$
  - with $|\mathbb{F}| = \mathcal{O}(t|C|)$
- Randomness complexity $\mathcal{O}(t^2(\log t + \log |C|))$

Application to AES

- Concrete AES implementation of our construction
  - 44 MHz ARM-Cortex M3 processor
  - Slow TRNG: 1500 cycles per TRNG byte.
  - Source code publicly available
- Minimization of TRNG calls

	Rivain-Prouff		Our construction		
	TRNG	MCycles	TRNG	MCycles	ratio
$t = 2$	2880	20.6	**48**	14.1	0.68
$t = 3$	5760	40.2	**108**	34.7	0.86

- Minimization of running time

	Rivain-Prouff		Our construction		
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$t = 2$	2880	20.6	642	9.8	**0.48**
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Conclusion

Reducing randomness complexity of high-order masking

- $\mathcal{O}(t^2|C|)$ in original ISW
- From $\mathcal{O}(t^{3+\varepsilon}\log^k|C|)$ in [IKL+13] with robust PRG
- to $\mathcal{O}(t^2(\log t + \log|C|))$ with r-wise independent PRG
- Simple construction without expander graphs.

Application to AES

- Concrete implementation of AES with PRG.
- Only 48 bytes of TRNG instead of 2880 in [RP10] for $t = 2$.
- Implementation on a real-life processor : 50 % speedup.

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