Thwarting Higher-Order SCA with Additive and Multiplicative Masking

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Context

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Cryptographic Algorithm: **perfect** from a logical point of view **but** processing leaks information

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Side Channel Analysis (SCA): analyzes the physical leakage to recover the secret

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Countermeasure?

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Order?

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d^{th}-order SCA (dO-SCA): d intermediate values targeted

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d^{th}-order SCA (dO-SCA): d intermediate values targeted

d^{th}-order Masking: renders any vector of d intermediate values independent from the secret

d^{th}-order masking:

- Every secret-dependent variable x is shared into $d+1$ variables:

$$x = x_0 \perp {x_1}^{-1} \perp \ldots \perp {x_d}^{-1} \qquad (1)$$

- A group operation $\perp$

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  Additive $\longrightarrow$ $x_0 \leftarrow x \oplus x_1 \oplus \ldots \oplus x_d$

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- The masked variable: $x_0 \leftarrow x \perp x_1 \perp \ldots \perp x_d$

  Additive $\longrightarrow$ $x_0 \leftarrow x \oplus x_1 \oplus \ldots \oplus x_d$

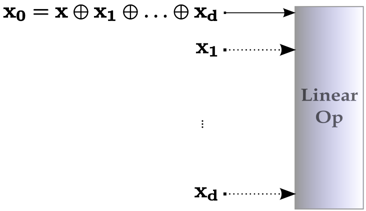
  Multiplicative $\longrightarrow$ $x_0 \leftarrow x \otimes x_1 \otimes \ldots \otimes x_d$, $\quad x, x_i \neq 0$

Masking Propagation

Additive masking and linear operation.

$\mathbf{x_0} = \mathbf{x} \oplus \mathbf{x_1} \oplus \ldots \oplus \mathbf{x_d}$

Additive masking and linear operation.



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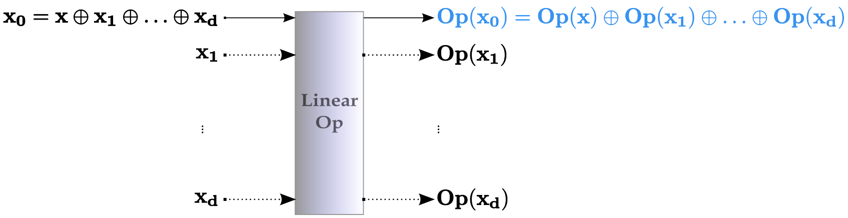

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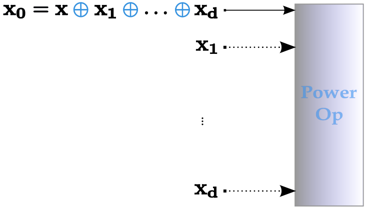
Additive masking and power operation.



Masking Propagation

Additive masking and power operation.

$$\mathbf{x_0 = x \oplus x_1 \oplus \ldots \oplus x_d} \longrightarrow \text{Power Op} \longrightarrow \mathbf{Op(x_0) \neq Op(x) \oplus Op(x_1) \oplus \ldots \oplus Op(x_d)}$$

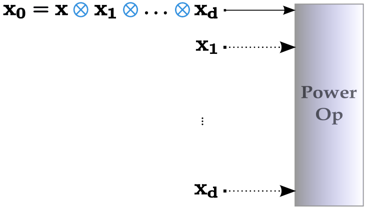
$$\mathbf{x_1} \dashrightarrow \text{Power Op} \dashrightarrow \mathbf{Op(x_1)}$$

$$\vdots \qquad\qquad \vdots$$

$$\mathbf{x_d} \dashrightarrow \text{Power Op} \dashrightarrow \mathbf{Op(x_d)}$$

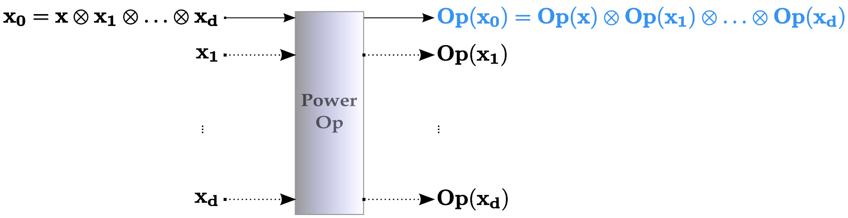
Masking Propagation

Multiplicative masking and power operation.



Masking Propagation

Multiplicative masking and power operation.



How to apply masking on block ciphers implementations which mix affine transformations and power functions?

Application

How to apply masking on block ciphers implementations which mix affine transformations and power functions?

Related Works for $d \geq 2$:

$d = 2$: [RivainDottaxProuff08]
[SchrammPaar06]
$d > 2$: [RivainProuff10]

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Our Approach: use multiplicative masking for power functions and additive masking for affine transformations

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[GenelleProuffQuisquater10] for $d = 1$

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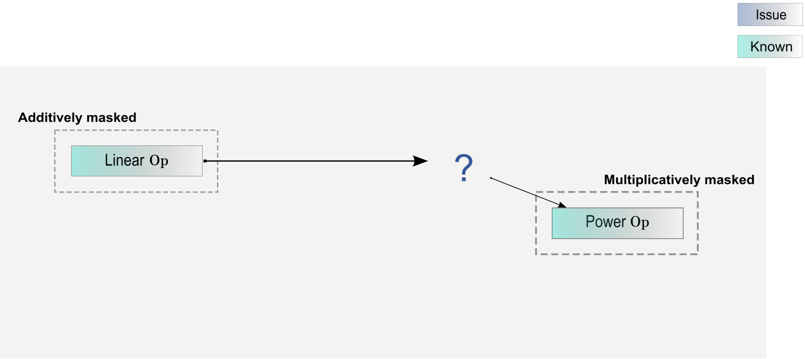

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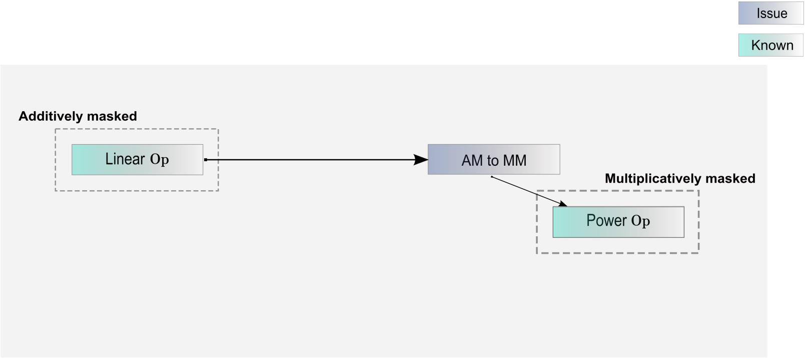

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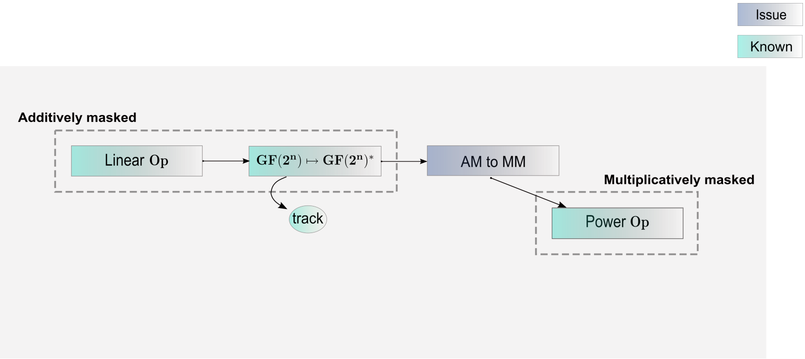

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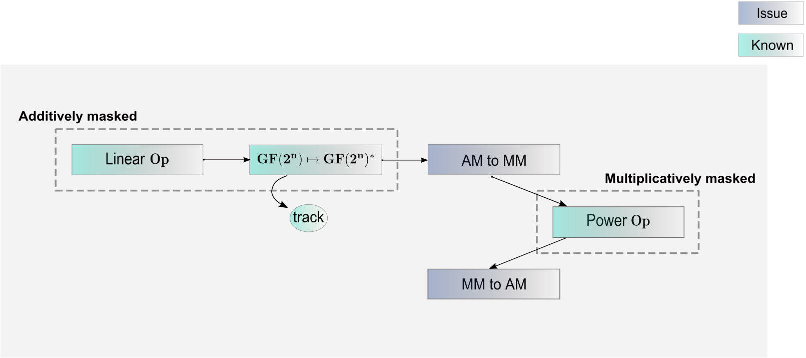

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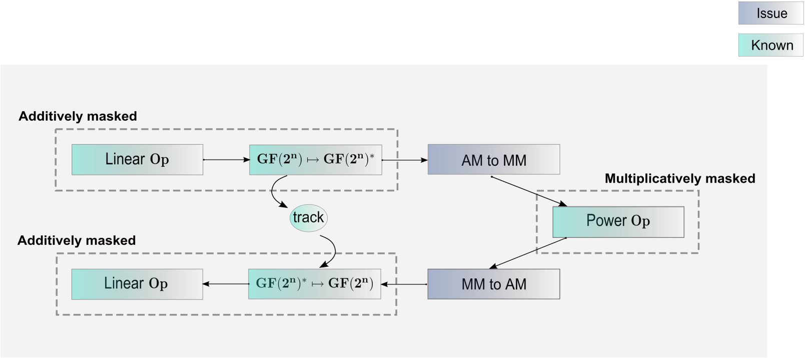

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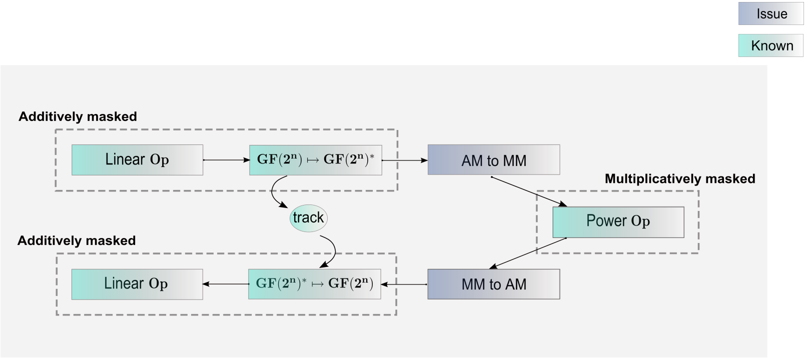

Mapping from $GF(2^n)$ into $GF(2^n)^*$ (and conversely):
[GenelleProuffQuisquater2011]

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Conversion from additive to multiplicative masking (`AMtoMM`), which is d^{th}-**order secure**

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- Additive masks $x_1, \ldots, x_d$ ($\mathcal{S}_{AM}$)
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Goal:

Input **Output**

$$\begin{array}{l} \mathbf{x_0 = x \oplus x_1 \oplus \ldots \oplus x_d}, \\ \mathcal{S}_{\mathbf{AM}} = \{\mathbf{x_1}, \ldots, \mathbf{x_d}\}, \\ \mathcal{S}_{\mathbf{MM}} = \emptyset \end{array} \xrightarrow{\texttt{AMtoMM}} \begin{array}{l} \mathbf{z_0 = x \otimes z_1 \otimes \ldots \otimes z_d}, \\ \mathcal{S}_{\mathbf{AM}} = \emptyset, \\ \mathcal{S}_{\mathbf{MM}} = \{\mathbf{z_1}, \ldots, \mathbf{z_d}\} \end{array}$$

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An Intuitive Attempt

Masked value	Additive masks ($\mathcal{S}_{\mathrm{AM}}$)		Multiplicative masks ($\mathcal{S}_{\mathrm{MM}}$)
$\mathbf{x_0}$	$\mathbf{x_1}$	$\mathbf{x_2}$	$\emptyset$

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$\oplus$

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$(\mathbf{x_0} \oplus \mathbf{x_1}) \otimes \mathbf{z_1}$			

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$\mathbf{(x_0 \oplus x_1) \otimes z_1}$		$\mathbf{x_2 \otimes z_1}$	$\mathbf{z_1}$

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$\mathbf{(x_0 \oplus x_1) \otimes z_1 \otimes z_2}$		$\mathbf{x_2 \otimes z_1 \otimes z_2}$	$\mathbf{z_1}$	$\mathbf{z_2}$

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$x_0 \otimes z_1$	$x_1 \otimes z_1$	$x_2 \otimes z_1$	z_1	
$(x_0 \oplus x_1) \otimes z_1$		$x_2 \otimes z_1$	z_1	
$(x_0 \oplus x_1) \otimes z_1 \otimes z_2$		$x_2 \otimes z_1 \otimes z_2$	z_1	z_2
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$(x_0 \oplus x_1) \otimes z_1 \otimes z_2$		$x_2 \otimes z_1 \otimes z_2$	z_1	z_2
$(x_0 \oplus x_1 \oplus x_2) \otimes z_1 \otimes z_2$	$\emptyset$		$\mathbf{z_1}$	$\mathbf{z_2}$
$\mathbf{x \otimes z_1 \otimes z_2}$				

Three intermediate values:

- x_d,
- $x_d \otimes z_1 \otimes \ldots \otimes z_d$
- $x \otimes z_1 \otimes \ldots \otimes z_d$

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Conversion algorithm is secure when $d = 1$ or $d = 2$, but not when $d > 2$.

Security

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Conversion algorithm is secure when $d = 1$ or $d = 2$, but not when $d > 2$.

Idea: mask at order 1 some additional intermediate values in such that propagation stays straightforward.

Our Proposal (AMtoMM)

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$x_0 \otimes z_1$	$\mathbf{x_1 \otimes z_1}$	$x_2 \otimes z_1$	z_1
	$\mathbf{x_1 \otimes z_1 \oplus m_1}$ $\mathbf{m_1}$		

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$\mathbf{x_0 \otimes z_1}$	$\mathbf{x_1 \otimes z_1 \oplus m_1}$	$\mathbf{m_1}$	$\mathbf{x_2 \otimes z_1}$	$\mathbf{z_1}$

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x_0	x_1		x_2	$\emptyset$
$x_0 \otimes z_1$	$x_1 \otimes z_1$		$x_2 \otimes z_1$	z_1
$\mathbf{x_0 \otimes z_1} \xleftarrow{\oplus}$	$\mathbf{x_1 \otimes z_1 \oplus m_1}$	$\mathbf{m_1}$	$\mathbf{x_2 \otimes z_1}$	$\mathbf{z_1}$

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$\mathrm{x_0 \otimes z_1}$	$\mathrm{x_1 \otimes z_1 \oplus m_1}$	$\mathrm{m_1}$	$\mathrm{x_2 \otimes z_1}$	$\mathrm{z_1}$
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$\mathbf{(x_0 \oplus x_1) \otimes z_1 \otimes z_2 \oplus m_1 \otimes z_2}$		$\mathbf{m_1 \otimes z_2}$	$\mathbf{x_2 \otimes z_1 \otimes z_2}$	$\mathbf{z_1}$	$\mathbf{z_2}$

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$(x_0 \oplus x_1) \otimes z_1 \otimes z_2 \oplus m_1 \otimes z_2$		$m_1 \otimes z_2$	$x_2 \otimes z_1 \otimes z_2$	z_1	z_2
	$\oplus$				
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Our Proposal (AMtoMM)

Masked value	Additive masks ($\mathcal{S}_{\mathrm{AM}}$)			Multiplicative masks ($\mathcal{S}_{\mathrm{MM}}$)	
x_0	x_1		x_2	$\emptyset$	
$x_0 \otimes z_1$	$x_1 \otimes z_1$		$x_2 \otimes z_1$	z_1	
$x_0 \otimes z_1$	$x_1 \otimes z_1 \oplus m_1$	m_1	$x_2 \otimes z_1$	z_1	
$(x_0 \oplus x_1) \otimes z_1 \otimes z_2 \oplus m_1 \otimes z_2$		$m_1 \otimes z_2$	$x_2 \otimes z_1 \otimes z_2$	z_1	z_2
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$(x_0 \oplus x_1 \oplus x_2) \otimes z_1 \otimes z_2$		$\emptyset$		$\mathbf{z_1}$	$\mathbf{z_2}$
$\mathbf{x \otimes z_1 \otimes z_2}$					

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Sum-up: AES mixes affine transformations and a power function

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- *table re-computation* [Messerges00]
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For $d = 2$:

- *double re-computation* [SchrammPaar06]
- *single re-computation* [RivainDottaxProuff08]
- *secure exponentiation* [RivainProuff10]

For $d = 3$:

- *secure exponentiation* [RivainProuff10]

Comparison of AES implementations

Method	Cycles (10^3)	Memory (bytes)
Unprotected Implementation		
No Masking	2	32
$d = 1$		
table re-computation	10	256
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Conclusion

Our countermeasure:

- dO-SCA resistant (proved)
- best trade-off timing/memory consumptions
- applicable at order 2 and 3 for today products

Thank you!
Questions?