Combined Fault and Leakage Resilience: Composability, Constructions and Compiler

Sebastian Berndt Thomas Eisenbarth Sebastian Faust Marc Gourjon
Maximilian Orlt Okan Seker

Fault and Side-Channel Attacks

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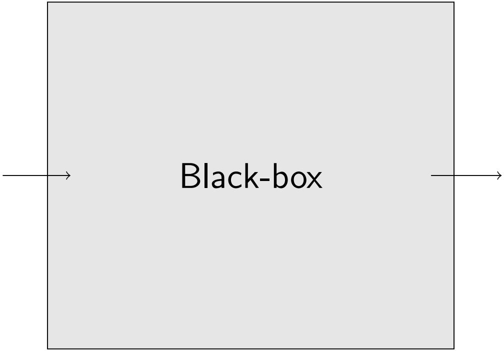
Classical setting: Black-box model



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- Adversary learns Input/Output

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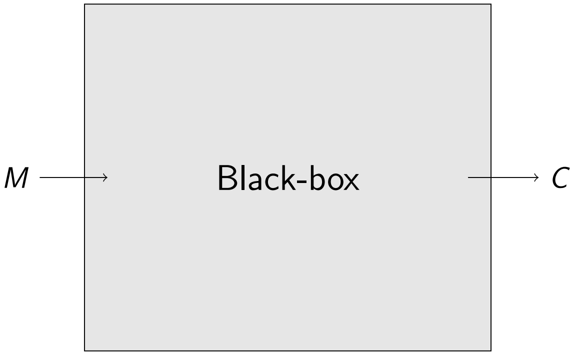

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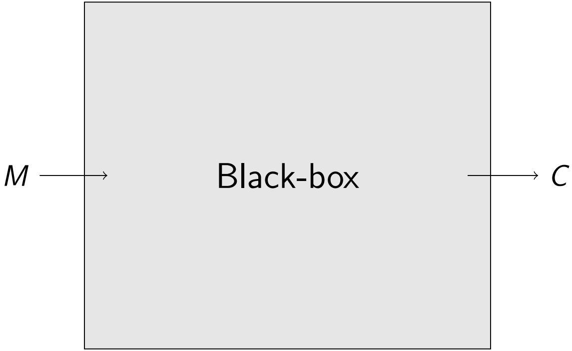

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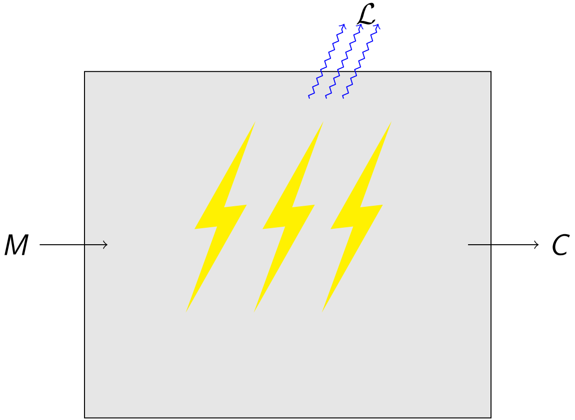

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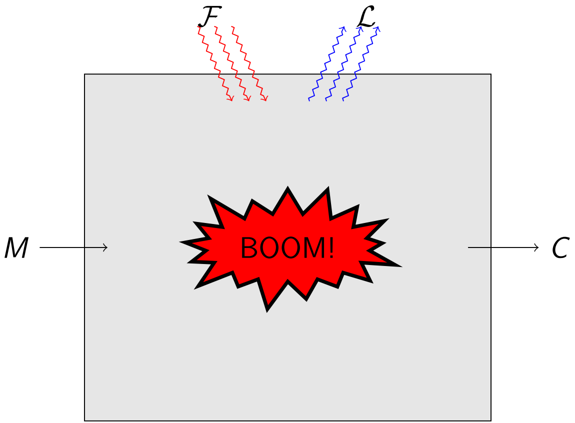
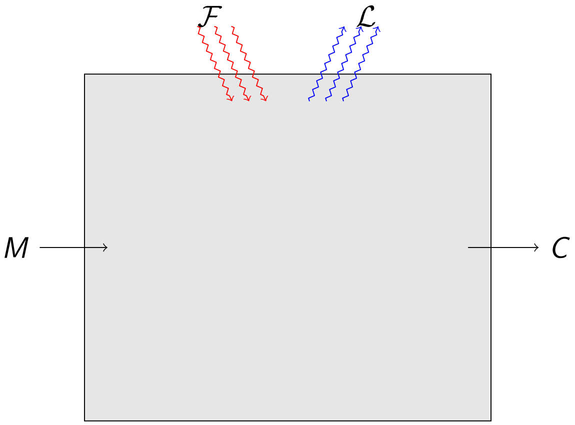
  E.g. Electromagnetic Pulses



Security Model



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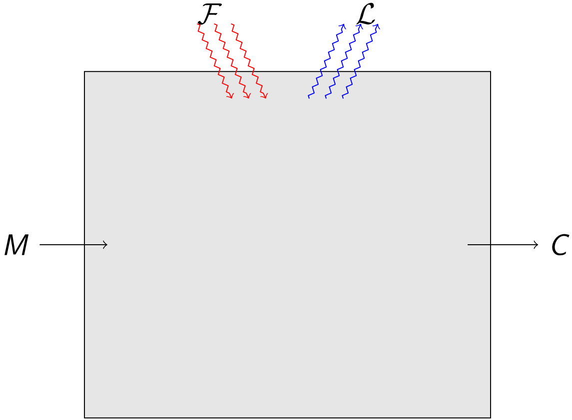

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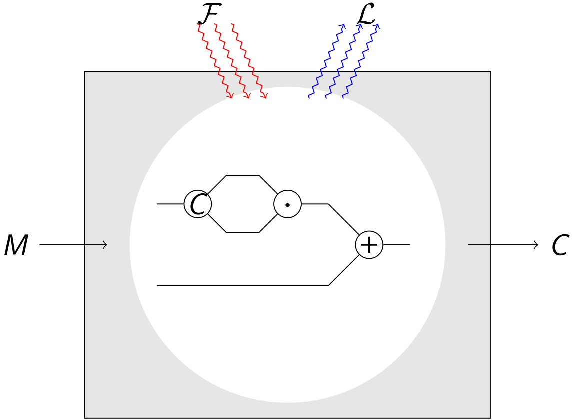

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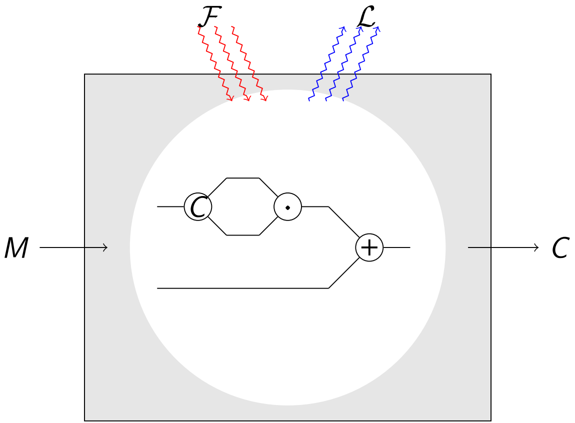

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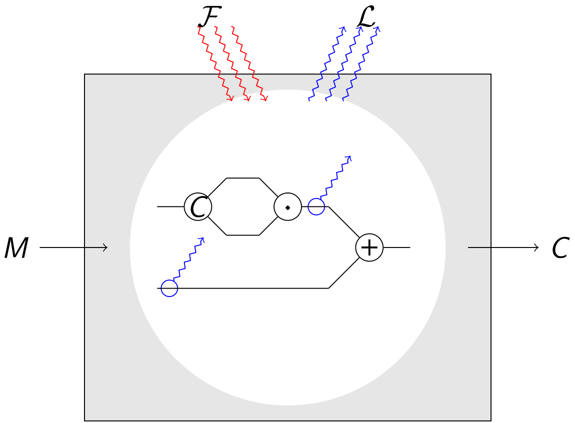

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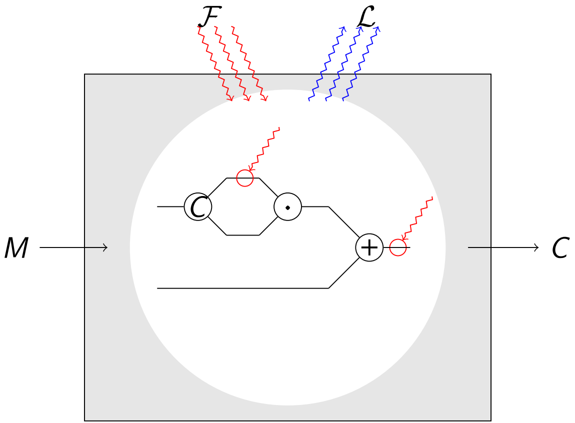

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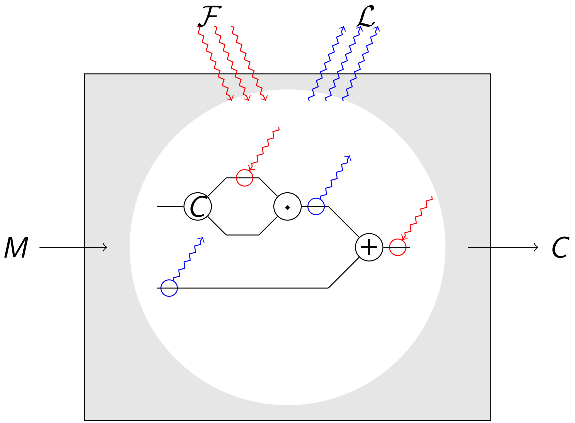

State of the Art: Encodings

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$O(d+e) \leq O(d \cdot e) \Rightarrow$ This work uses Shamir Secret Sharing

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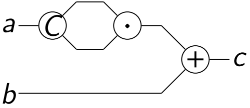


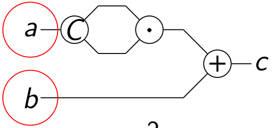
$$c = a^2 + b$$

Countermeasure: Compute on Encodings

- Encode the inputs a and b

a_0

a_1



$$c = a^2 + b$$

$\xrightarrow{\text{Compiler}}$

b_0

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Countermeasure: Compute on Encodings

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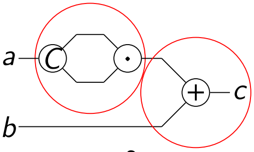
- Only compute on encodings



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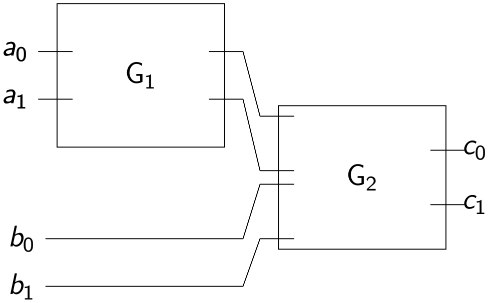

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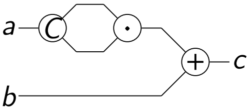

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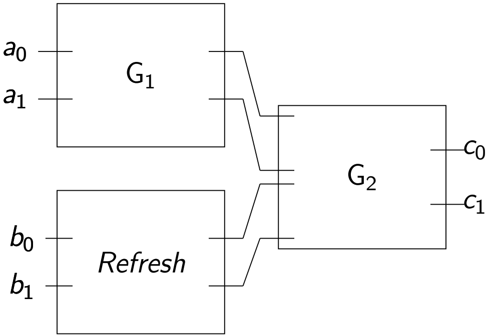

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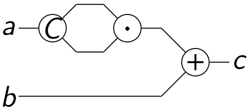

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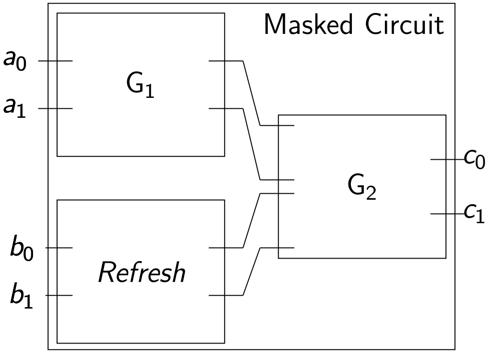

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Compiler secure against d probes and e faults

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Improved Security: This work even allows $d/2$ probes in each gadget.

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Mult., Add. & Ref.

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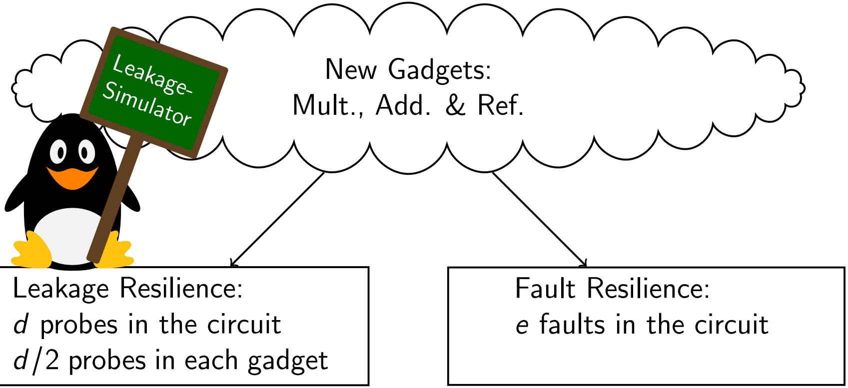

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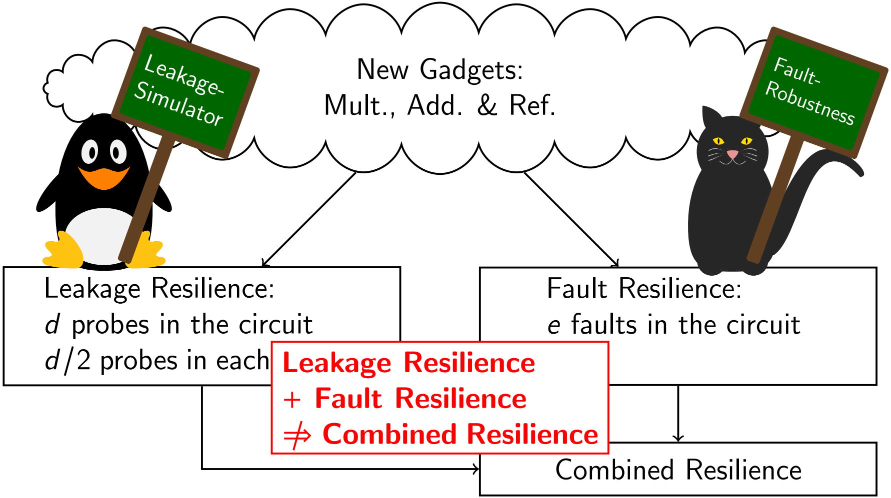

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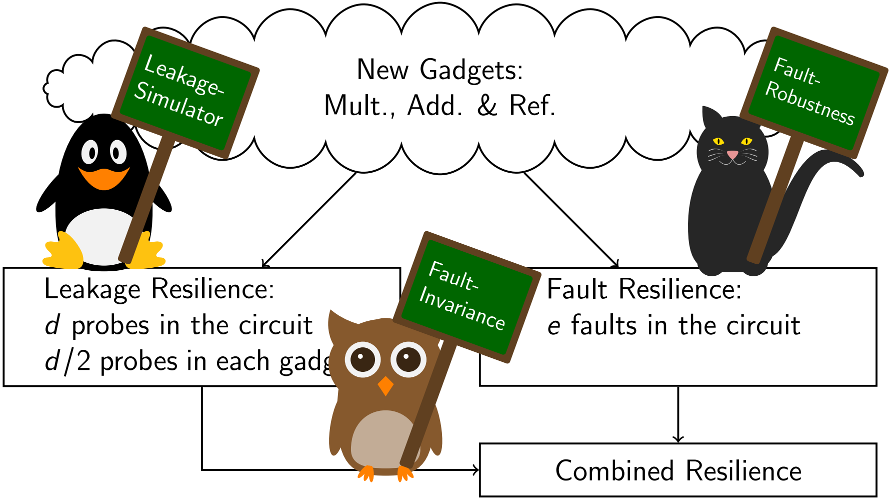

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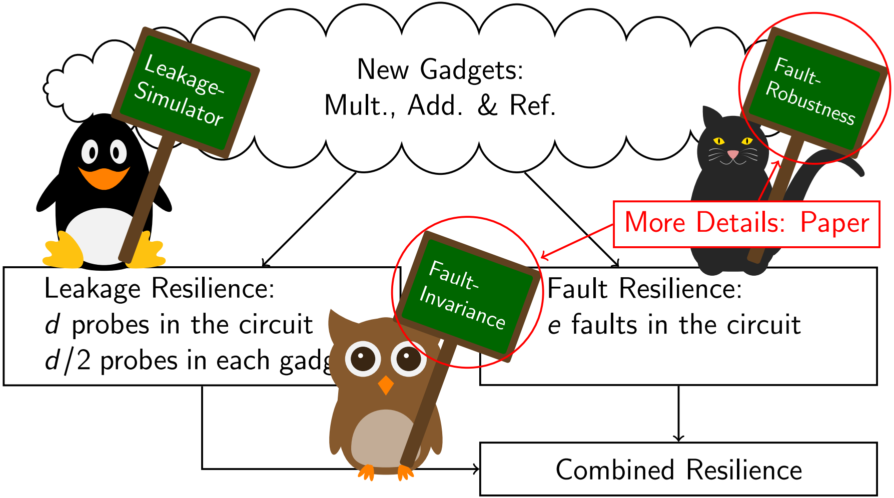

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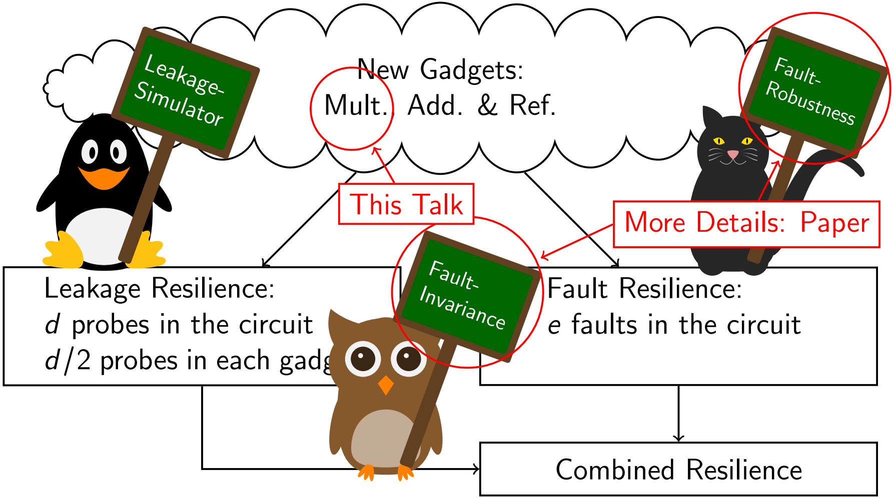

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$r_1 \ldots r_d \leftarrow\!\$\ \mathbb{F}$

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$$s_j \leftarrow \sum_{i=1}^{d} r_i \alpha_j^i + s$$

return $[\![s]\!]_d^n := (s_0, \ldots, s_{n-1})$

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- Fault Resilience: If only e shares of $d + e + 1$ shares are faulted the polynomial has a degree $> d$!

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Probing Attack: Our Paper

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- Compute $c_i \leftarrow a_i + b_i$
- Result $[\![c]\!]_d^n = [\![a + b]\!]_d^n$

$$\left.\right\} \left\{ \begin{array}{c} (\sum_{i=1}^{d} r_i x^i + a) + (\sum_{i=1}^{d} r_i x^i + b) \\ = \sum_{i=1}^{d} (r_i + r_i^{!}) x^i + (a + b) \end{array} \right.$$

Refresh of $[\![a]\!]_d^n$

- Generate $[\![b]\!]_d^n \leftarrow \mathsf{Enc}(0)$
- Compute $[\![c]\!]_d^n = [\![a + b]\!]_d^n$

Probing Attack: Our Paper
Fix: d Refreshes in a row

Fixed SotA Compiler with $n = 2d + e + 1$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

- Compute $c_i \leftarrow a_i \cdot b_i$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

- Compute $c_i \leftarrow a_i \cdot b_i$
- Result $[\![c]\!]_{2d}^n = [\![a \cdot b]\!]_{2d}^n$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

- Compute $c_i \leftarrow a_i \cdot b_i$
- Result $[\![c]\!]_{2d}^n = [\![a \cdot b]\!]_{2d}^n$

$$\left.\vphantom{\begin{array}{c} \\ \\ \\ \\ \end{array}}\right\} \quad \left\{ \begin{array}{c} (\sum_{i=1}^{d} r_i x^i + a) \cdot (\sum_{i=1}^{d} r_i x^i + b) \\ = \sum_{i=1}^{2d} (r_i'') x^i + (a \cdot b) \end{array} \right.$$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

- Compute $c_i \leftarrow a_i \cdot b_i$
- Result $[\![c]\!]_{2d}^n = [\![a \cdot b]\!]_{2d}^n$
- Reduce $[\![c]\!]_{2d}^n$ down to $[\![c]\!]_d^n$

$$\left.\vphantom{\begin{array}{c}1\\1\\1\\1\end{array}}\right\} \left\{ \begin{array}{c} (\sum_{i=1}^{d} r_i x^i + a) \cdot (\sum_{i=1}^{d} r_i x^i + b) \\ = \sum_{i=1}^{2d} (r_i'') x^i + (a \cdot b) \end{array} \right.$$

Fixed SotA Compiler with $n = 2d + e + 1$

Multiplication of $[\![a]\!]_d^n$ and $[\![b]\!]_d^n$

- Compute $c_i \leftarrow a_i \cdot b_i$
- Result $[\![c]\!]_{2d}^n = [\![a \cdot b]\!]_{2d}^n$
- Reduce $[\![c]\!]_{2d}^n$ down to $[\![c]\!]_d^n$
- Problem: Requires $n = 2d + e + 1$

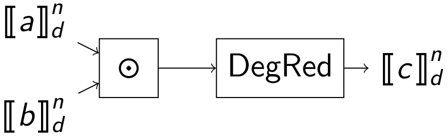
$$\left(\sum_{i=1}^{d} r_i x^i + a\right) \cdot \left(\sum_{i=1}^{d} r_i x^i + b\right) = \sum_{i=1}^{2d} (r_i'') x^i + (a \cdot b)$$

Compiler with $n = d + e + 1$

Compiler with $n = d + e + 1$

Instead of

- Compute $[\![c]\!]^n_{2d} = [\![a \cdot b]\!]^n_{2d}$
- Reduce $[\![c]\!]^n_{2d}$ down to $[\![c]\!]^n_d$



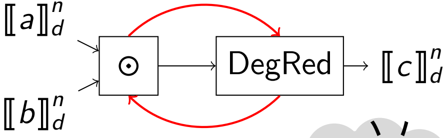
Compiler with $n = d + e + 1$

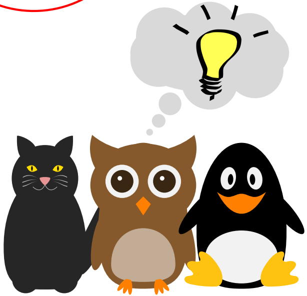
Instead of

- Compute $\llbracket c \rrbracket^n_{2d} = \llbracket a \cdot b \rrbracket^n_{2d}$
- Reduce $\llbracket c \rrbracket^n_{2d}$ down to $\llbracket c \rrbracket^n_{d}$

Reverse the steps

- Reduce $\llbracket a \rrbracket^n_{d}$, $\llbracket b \rrbracket^n_{d}$ down to $\llbracket a \rrbracket^n_{d/2}$, $\llbracket b \rrbracket^n_{d/2}$
- Compute $\llbracket c \rrbracket^n_{d} = \llbracket a \cdot b \rrbracket^n_{d}$





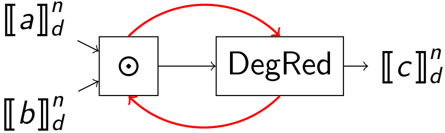
Compiler with $n = d + e + 1$

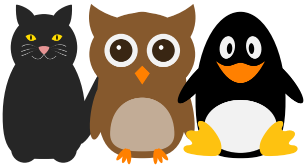
Instead of

- Compute $[\![c]\!]^n_{2d} = [\![a \cdot b]\!]^n_{2d}$
- Reduce $[\![c]\!]^n_{2d}$ down to $[\![c]\!]^n_d$

Reverse the steps

- Reduce $[\![a]\!]^n_d$, $[\![b]\!]^n_d$ down to $[\![a]\!]^n_{d/2}$, $[\![b]\!]^n_{d/2}$
- Compute $[\![c]\!]^n_d = [\![a \cdot b]\!]^n_d$
- Problem d probes in $[\![a]\!]^n_{d/2}$ reveal a





Compiler with $n = d + e + 1$

Instead of

- Compute $[\![c]\!]^n_{2d} = [\![a \cdot b]\!]^n_{2d}$
- Reduce $[\![c]\!]^n_{2d}$ down to $[\![c]\!]^n_{d}$

Reverse the steps

- Reduce $[\![a]\!]^n_{d}$, $[\![b]\!]^n_{d}$ down to $[\![a]\!]^n_{d/2}$, $[\![b]\!]^n_{d/2}$
- Compute $[\![c]\!]^n_{d} = [\![a \cdot b]\!]^n_{d}$
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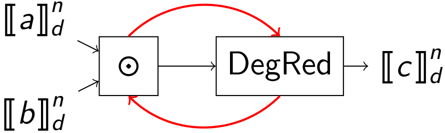
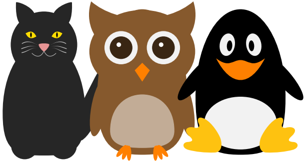
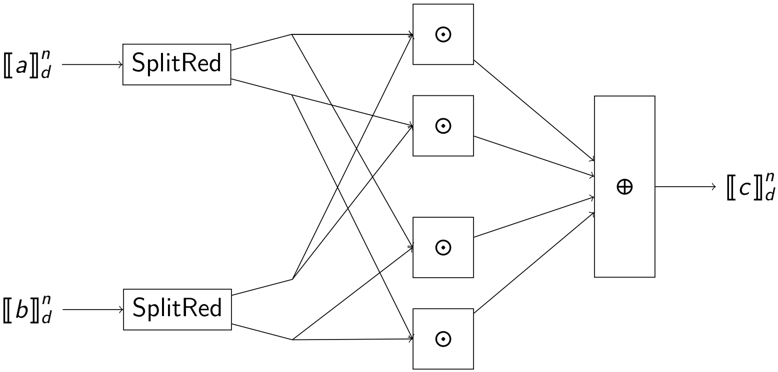


Solution: SplitRed splits $[\![a]\!]^n_{d}$ into $[\![a']\!]^n_{d}$ and $[\![a'']\!]^n_{d}$ with $[\![a']\!]^n_{d} + [\![a'']\!]^n_{d} = [\![a]\!]^n_{d/2}$

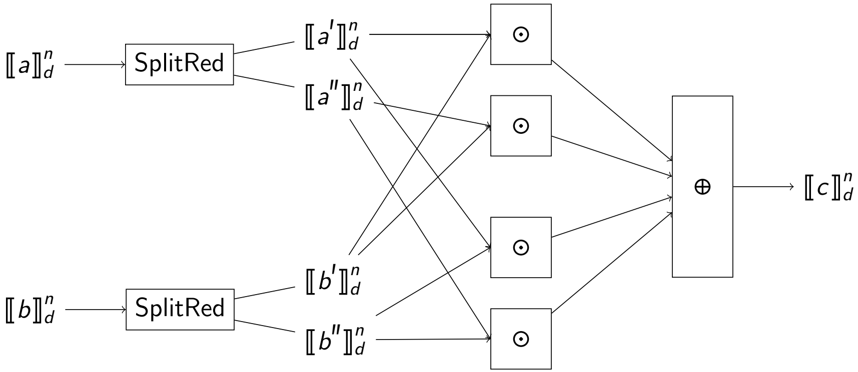


The Multiplication

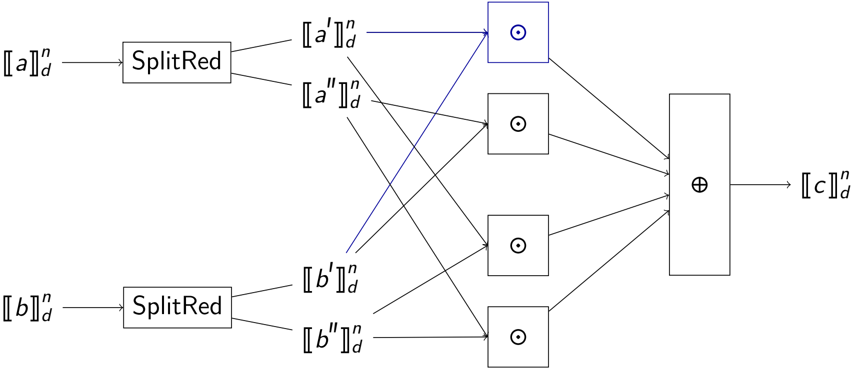
The Multiplication



The Multiplication

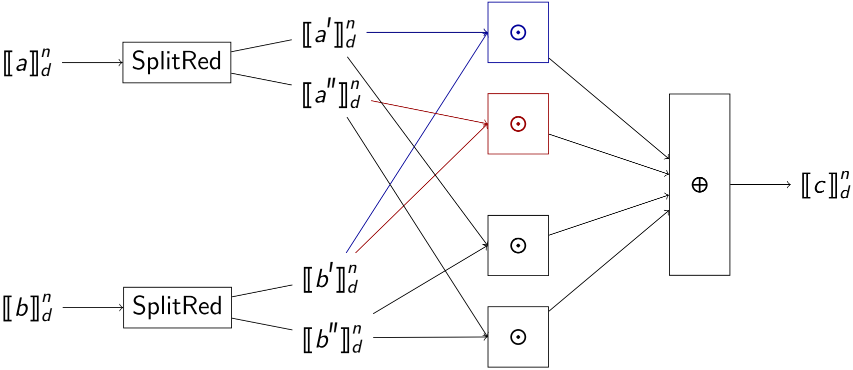


The Multiplication



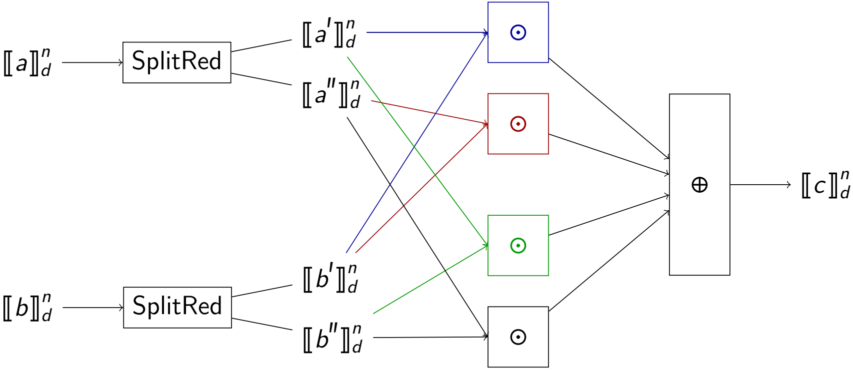
$$[\![a']\!]^n_d \cdot [\![b']\!]^n_d$$

The Multiplication



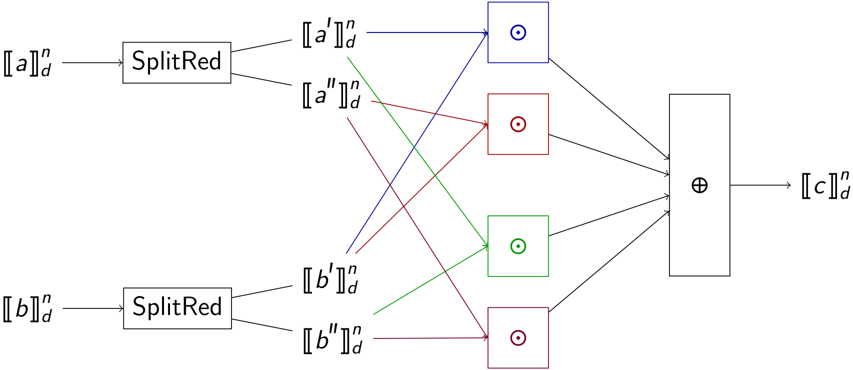
$[\![a']\!]_d^n \cdot [\![b']\!]_d^n \quad [\![a'']\!]_d^n \cdot [\![b']\!]_d^n$

The Multiplication



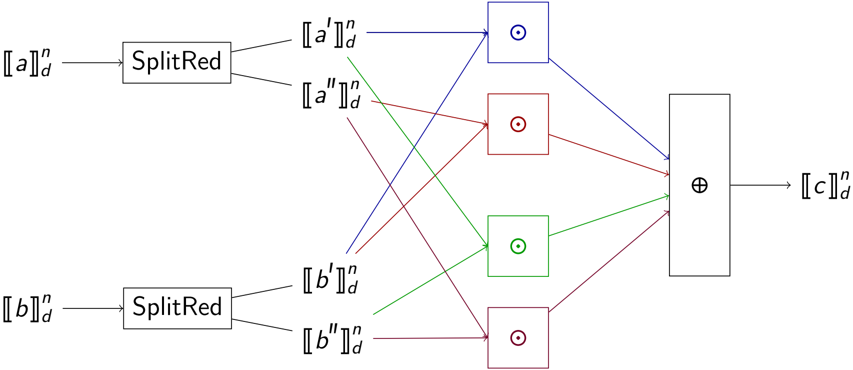
$[\![a']\!]_d^n \cdot [\![b']\!]_d^n \quad [\![a'']\!]_d^n \cdot [\![b']\!]_d^n \quad [\![a']\!]_d^n \cdot [\![b'']\!]_d^n$

The Multiplication



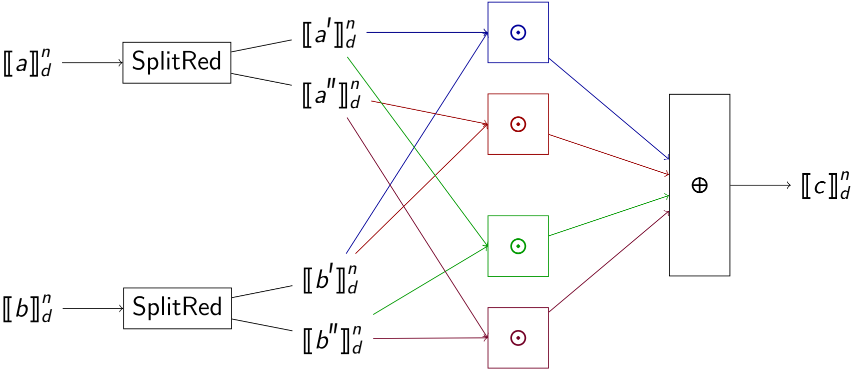
$[\![a']\!]_d^n \cdot [\![b']\!]_d^n \quad [\![a'']\!]_d^n \cdot [\![b']\!]_d^n \quad [\![a']\!]_d^n \cdot [\![b'']\!]_d^n \quad [\![a'']\!]_d^n \cdot [\![b'']\!]_d^n$

The Multiplication



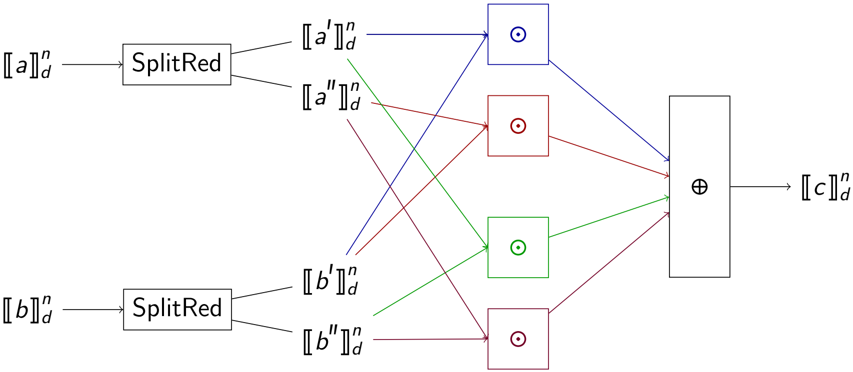
$$[\![c]\!]^n_d = \quad [\![a']\!]^n_d \cdot [\![b']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b']\!]^n_d + [\![a']\!]^n_d \cdot [\![b'']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b'']\!]^n_d$$

The Multiplication



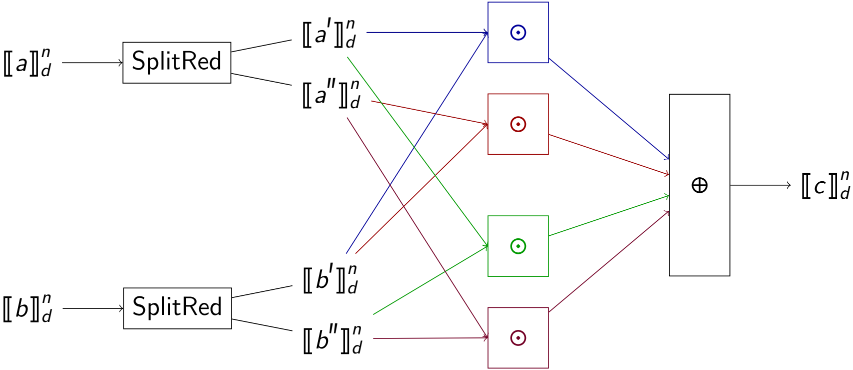
$$
\begin{aligned}
[\![c]\!]^n_d &= [\![a']\!]^n_d \cdot [\![b']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b']\!]^n_d + [\![a']\!]^n_d \cdot [\![b'']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b'']\!]^n_d \\
&= ([\![a']\!]^n_d + [\![a'']\!]^n_d) \cdot ([\![b']\!]^n_d + [\![b'']\!]^n_d)
\end{aligned}
$$

The Multiplication



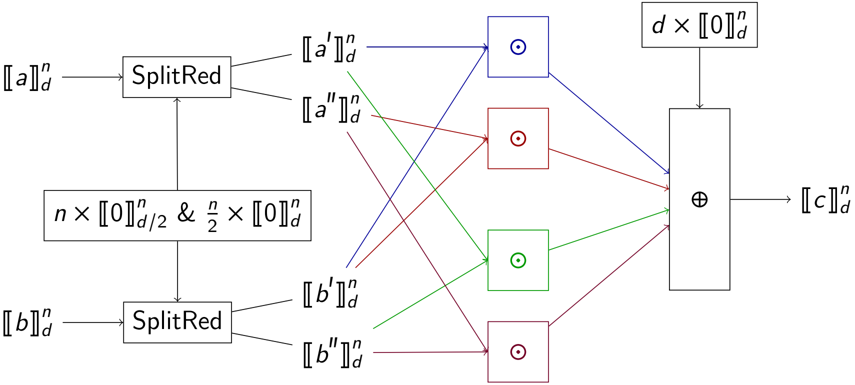
$$\begin{aligned}\llbracket c \rrbracket^n_d &= \llbracket a' \rrbracket^n_d \cdot \llbracket b' \rrbracket^n_d + \llbracket a'' \rrbracket^n_d \cdot \llbracket b' \rrbracket^n_d + \llbracket a' \rrbracket^n_d \cdot \llbracket b'' \rrbracket^n_d + \llbracket a'' \rrbracket^n_d \cdot \llbracket b'' \rrbracket^n_d \\ &= (\llbracket a' \rrbracket^n_d + \llbracket a'' \rrbracket^n_d) \cdot (\llbracket b' \rrbracket^n_d + \llbracket b'' \rrbracket^n_d) = \llbracket a \rrbracket^n_{d/2} \cdot \llbracket b \rrbracket^n_{d/2}\end{aligned}$$

The Multiplication



$$
\begin{aligned}
[\![c]\!]^n_d &= [\![a']\!]^n_d \cdot [\![b']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b']\!]^n_d + [\![a']\!]^n_d \cdot [\![b'']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b'']\!]^n_d \\
&= ([\![a']\!]^n_d + [\![a'']\!]^n_d) \cdot ([\![b']\!]^n_d + [\![b'']\!]^n_d) = [\![a]\!]^n_{d/2} \cdot [\![b]\!]^n_{d/2} = [\![a \cdot b]\!]^n_d
\end{aligned}
$$

The Multiplication



$$
\begin{aligned}
[\![c]\!]^n_d &= [\![a']\!]^n_d \cdot [\![b']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b']\!]^n_d + [\![a']\!]^n_d \cdot [\![b'']\!]^n_d + [\![a'']\!]^n_d \cdot [\![b'']\!]^n_d \\
&= ([\![a']\!]^n_d + [\![a'']\!]^n_d) \cdot ([\![b']\!]^n_d + [\![b'']\!]^n_d) = [\![a]\!]^n_{d/2} \cdot [\![b]\!]^n_{d/2} = [\![a \cdot b]\!]^n_d
\end{aligned}
$$

Security: Fault-Robustness

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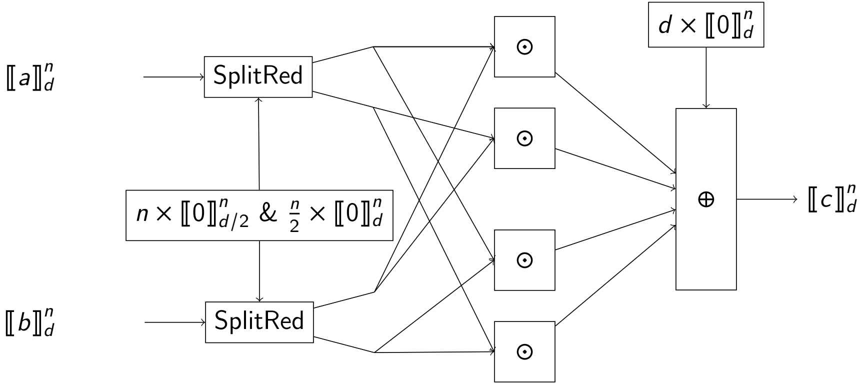
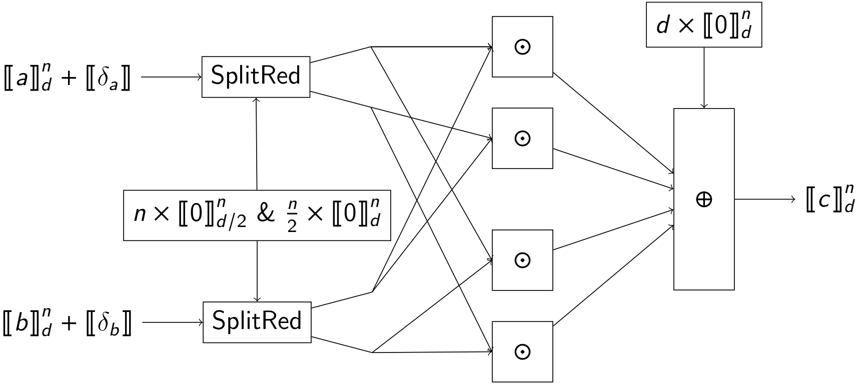
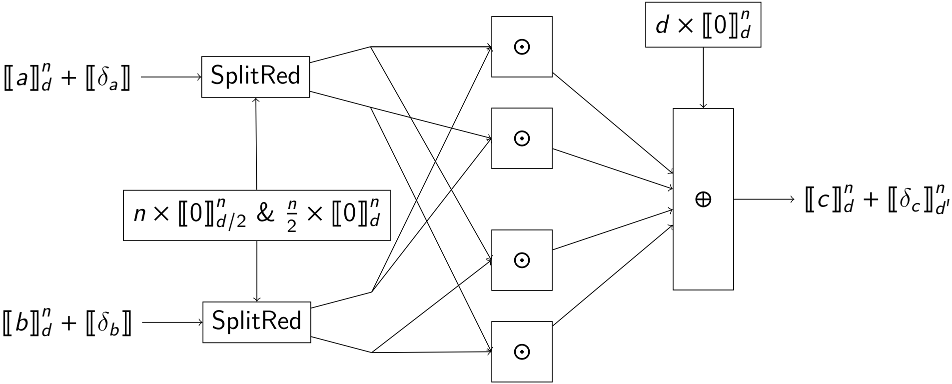


Security: Fault-Robustness



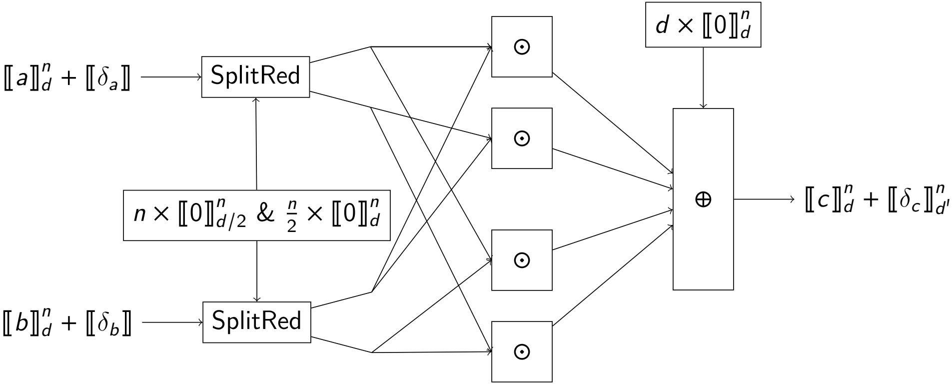
e faults

Security: Fault-Robustness



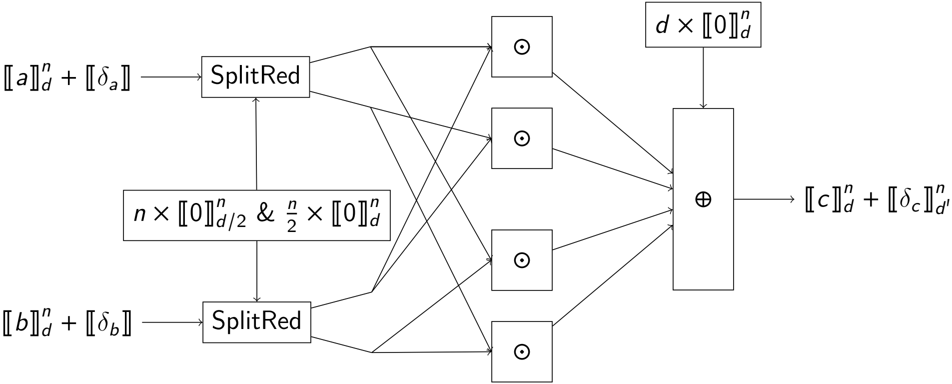
e faults result in $[\![\delta_c]\!]_{d'}^n$

Security: Fault-Robustness



e faults result in $[\![\delta_c]\!]^n_{d'}$ with $d' > d$

Security: Fault-Robustness



e faults result in $[\![\delta_c]\!]_{d'}^n$ with $d' > d$ or $[\![\delta_c]\!]_{d'}^n = (0, \ldots, 0)$

Security: Combined Resilience

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(a) *e*-Fault Robustness

Security: Combined Resilience

(a) e-Fault Robustness
(b) d-Probing Security (or $d/2$ probes in each gadget)

Security: Combined Resilience

(a) e-Fault Robustness
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(c) Fault Invariance

Security: Combined Resilience

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(c) Fault Invariance

- Each intermediate value can be written as a function $f(x_0, x_1, \dots)$ with input values $(x_0, x_1, \dots)$

Security: Combined Resilience

(a) e-Fault Robustness

(b) d-Probing Security (or $d/2$ probes in each gadget)

(c) Fault Invariance

- Each intermediate value can be written as a function $f(x_0, x_1, \dots)$ with input values $(x_0, x_1, \dots)$
- Let f' be the corresponding value in the faulted gadget

Security: Combined Resilience

(a) *e*-Fault Robustness

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- Each intermediate value can be written as a function $f(x_0, x_1, \dots)$ with input values $(x_0, x_1, \dots)$
- Let f' be the corresponding value in the faulted gadget
- There are functions χ, χ_0, χ_1 s.t. $f' = \chi(f(\chi_0(x_0), \chi_1(x_1), \dots))$

Security: Combined Resilience

(a) e-Fault Robustness

(b) d-Probing Security (or $d/2$ probes in each gadget)

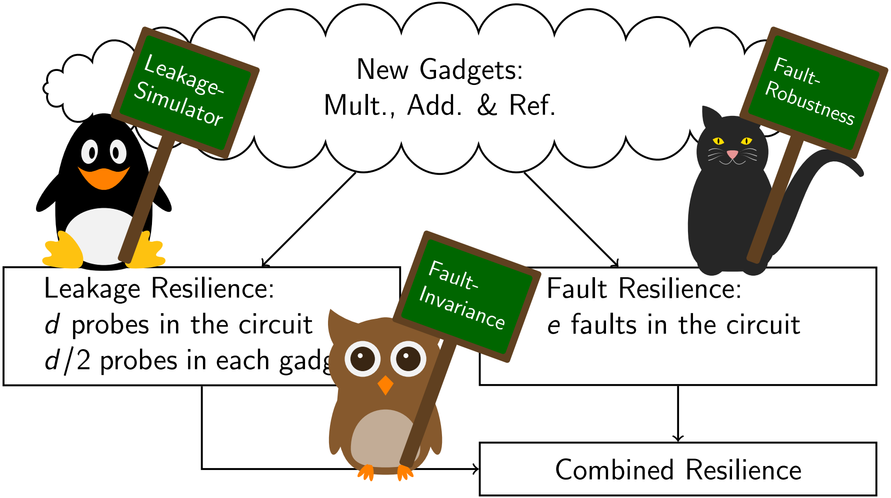
(c) Fault Invariance

- Each intermediate value can be written as a function $f(x_0, x_1, \dots)$ with input values $(x_0, x_1, \dots)$
- Let f' be the corresponding value in the faulted gadget
- There are functions χ, χ_0, χ_1 s.t. $f' = \chi(f(\chi_0(x_0), \chi_1(x_1), \dots))$

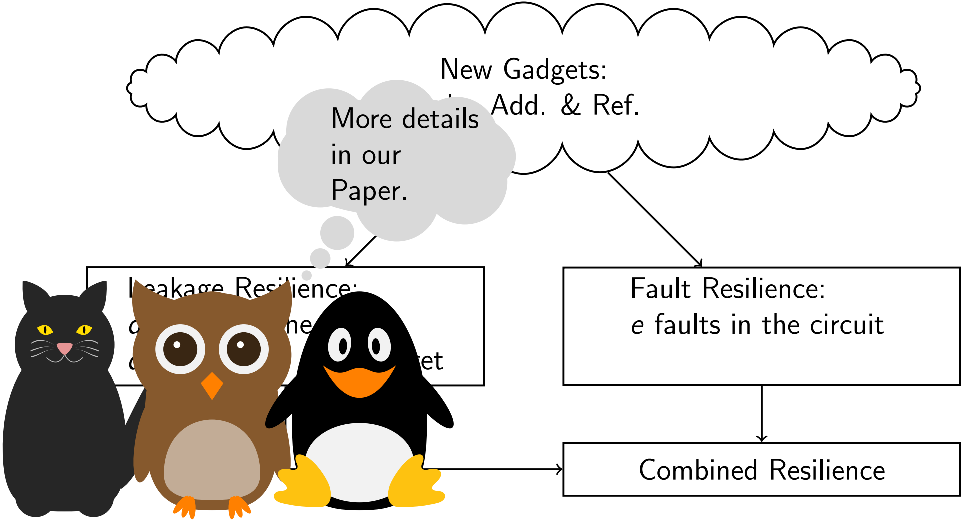
(a)+(b)+(c)= Combined Resilience

Conclusion

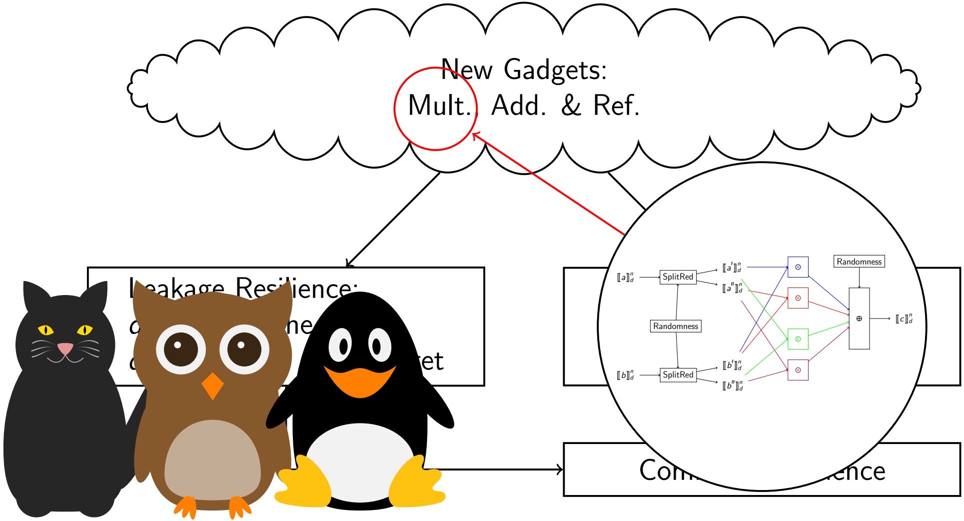
Conclusion


New Gadgets:
Mult., Add. & Ref.
Leakage-Simulator
Fault-Robustness
Fault-Invariance
Leakage Resilience:
d probes in the circuit
$d/2$ probes in each gadg
Fault Resilience:
e faults in the circuit
Combined Resilience

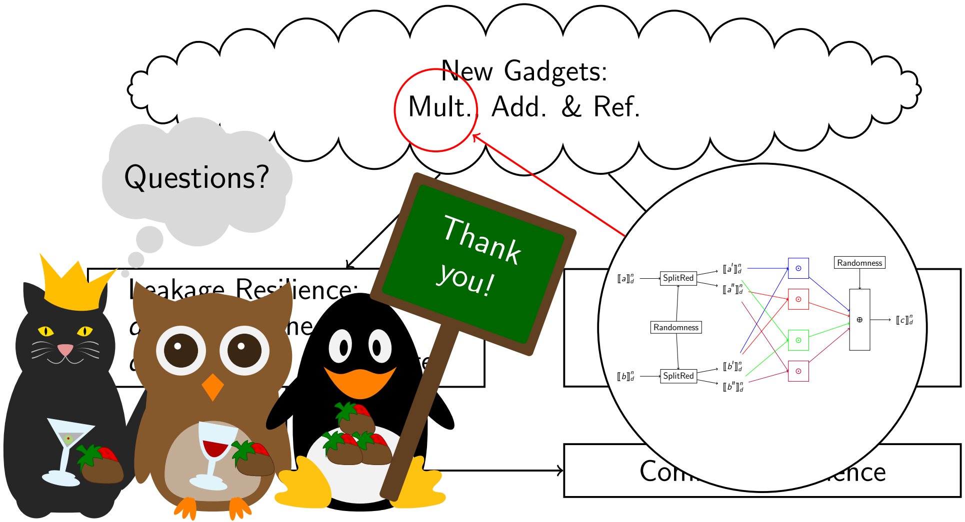
Conclusion


New Gadgets:
Add. & Ref.
More details in our Paper.
Fault Resilience:
e faults in the circuit
Combined Resilience

Conclusion


New Gadgets:
Mult. Add. & Ref.
Leakage Resilience:
Randomness
SplitRed
Randomness
SplitRed

Conclusion


New Gadgets:
Mult. Add. & Ref.
Questions?
Thank you!
SplitRed
Randomness
SplitRed
Randomness