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ReliaFHE: Resilient Design for Fully Homomorphic Encryption Accelerators

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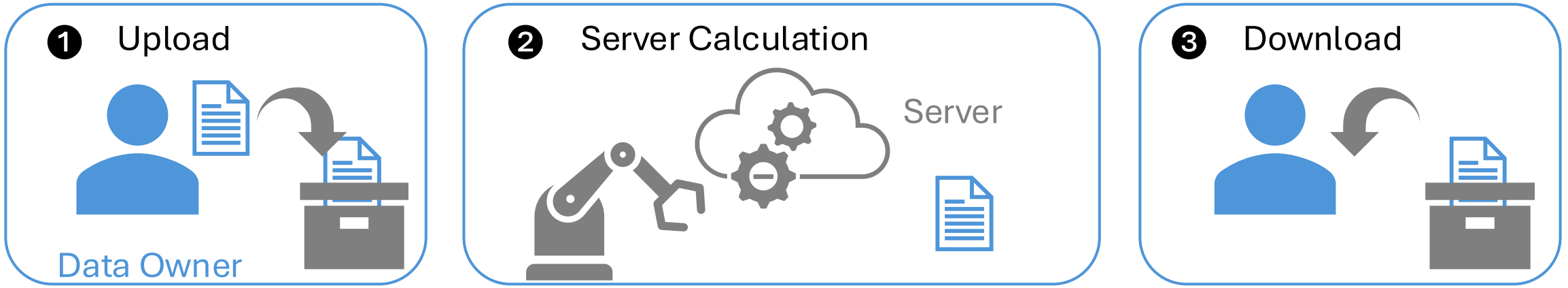
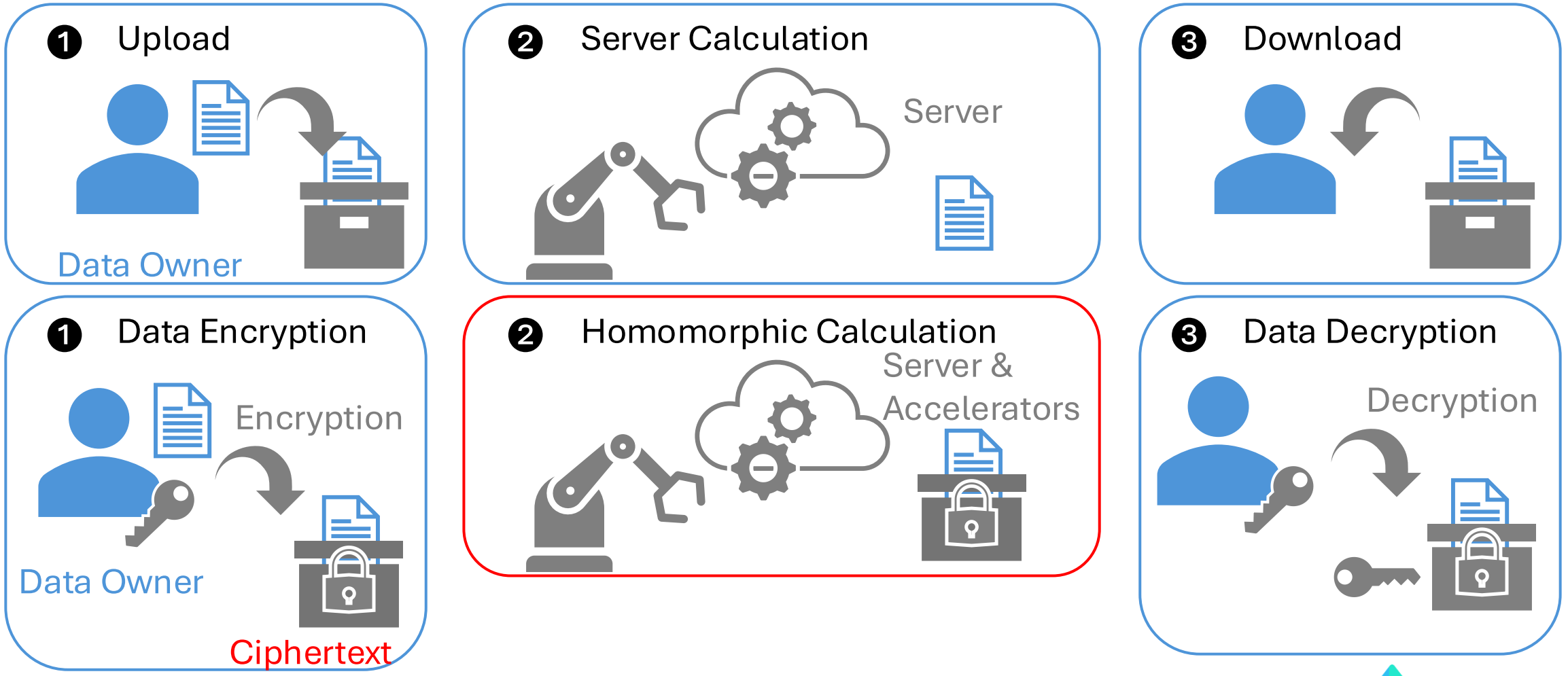
International Conference on Architectural Support for Programming Languages and Operating Systems

Fully Homomorphic Encryption (FHE)

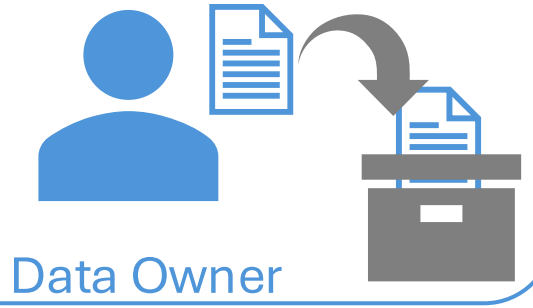


Fully Homomorphic Encryption (FHE)

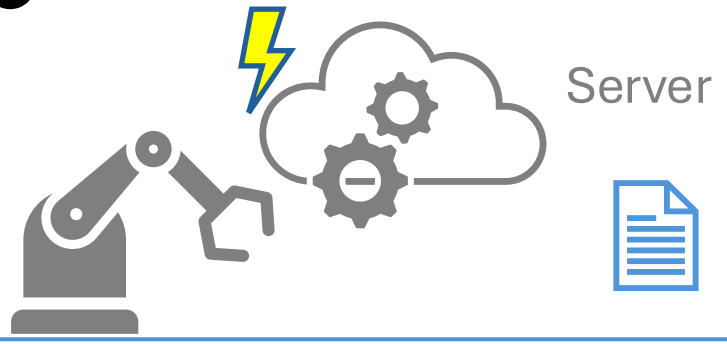


Fully Homomorphic Encryption (FHE)

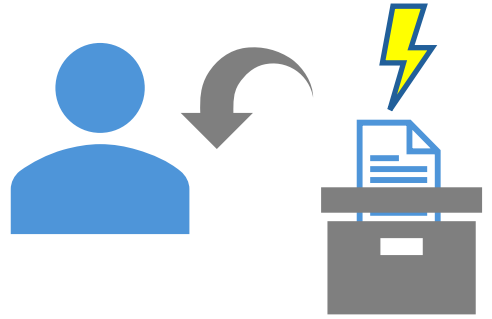
❶ Upload



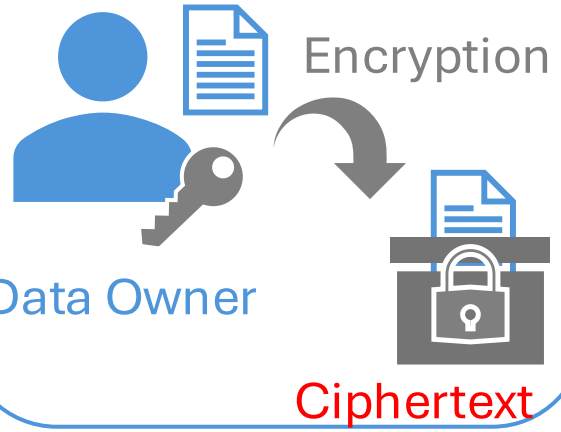
❷ Server Calculation



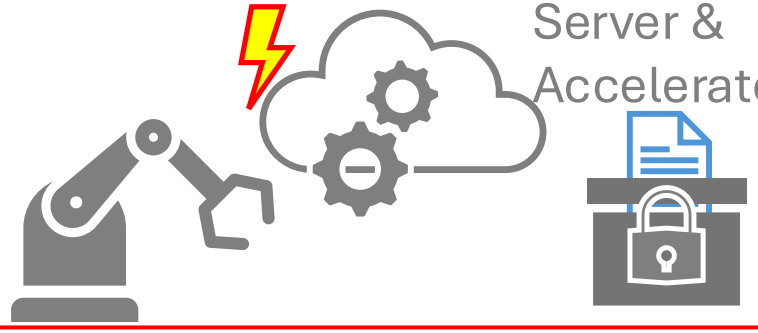
❸ Download



❶ Data Encryption

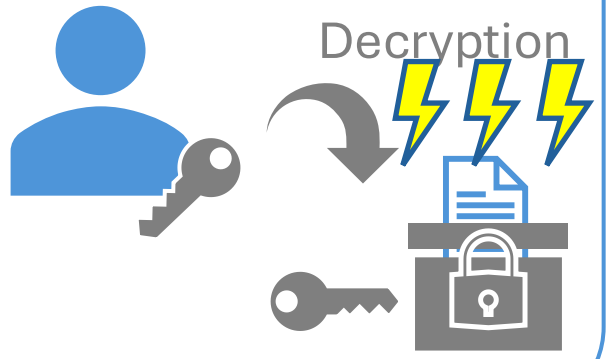


❷ Homomorphic Calculation



FHE is more error sensitive

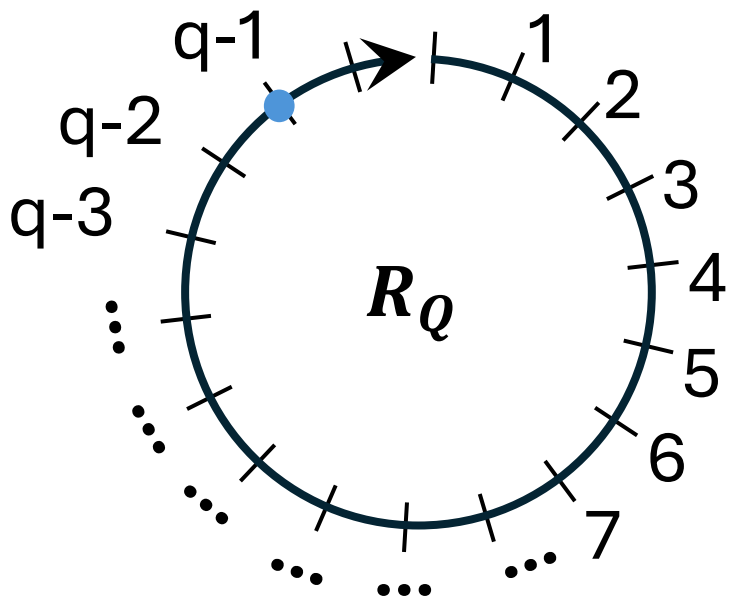
❸ Data Decryption



Error-Sensitivity Analysis

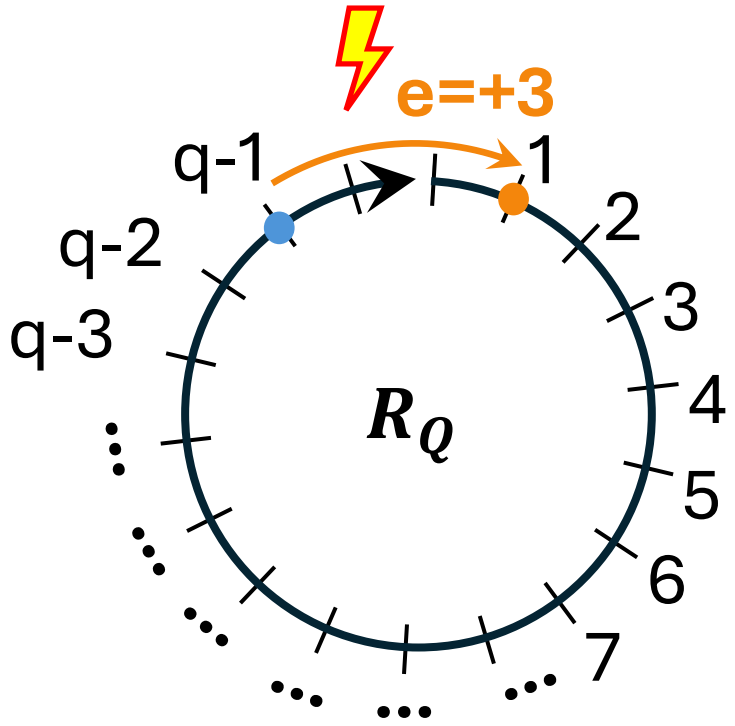
- Modulus Operations
- NTT Representation
- Packing Algorithm

Error-Sensitivity Analysis



- **Modulus Operations**
- NTT Representation
- Packing Algorithm

Error-Sensitivity Analysis



- **Modulus Operations**
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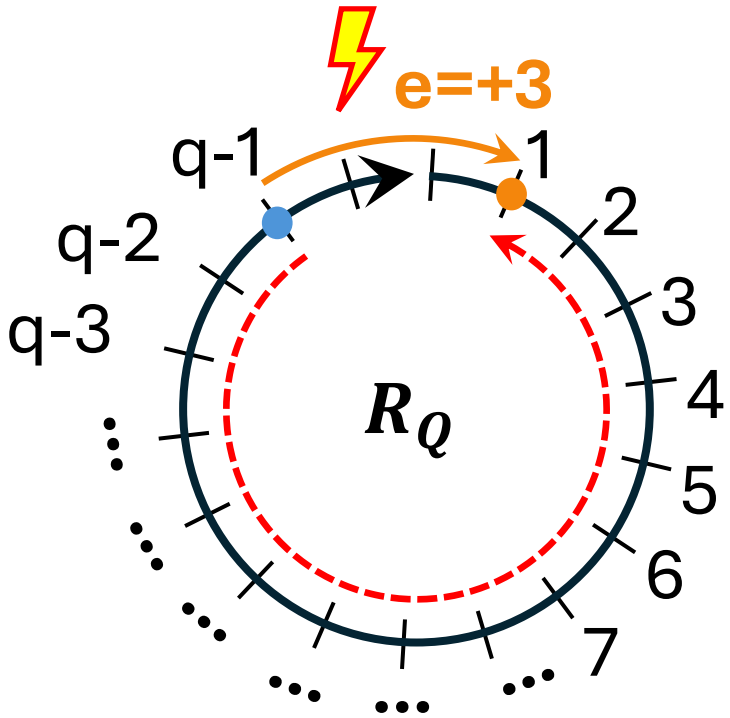
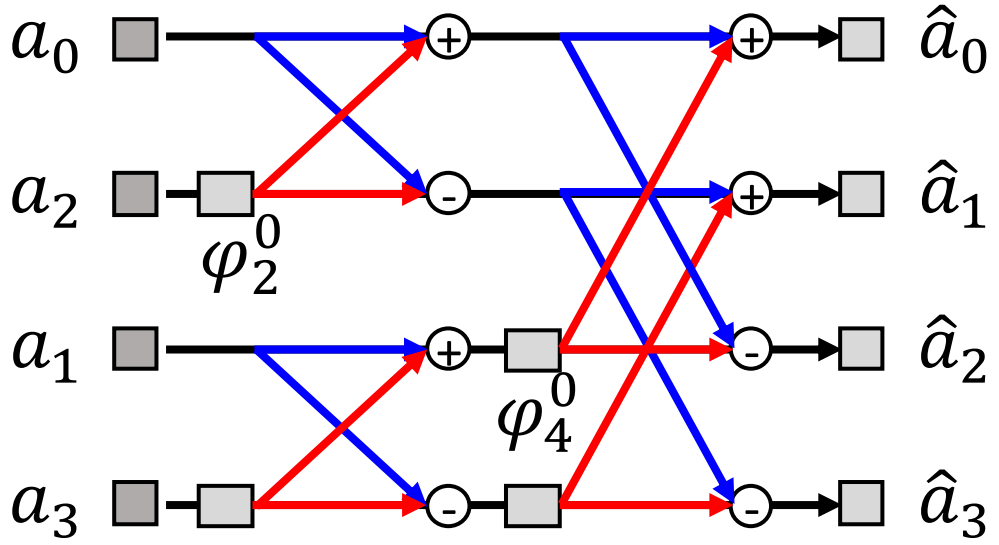
Error-Sensitivity Analysis



Error amplification

- **Modulus Operations**
- NTT Representation
- Packing Algorithm

Error-Sensitivity Analysis



- Modulus Operations
- **NTT Representation**
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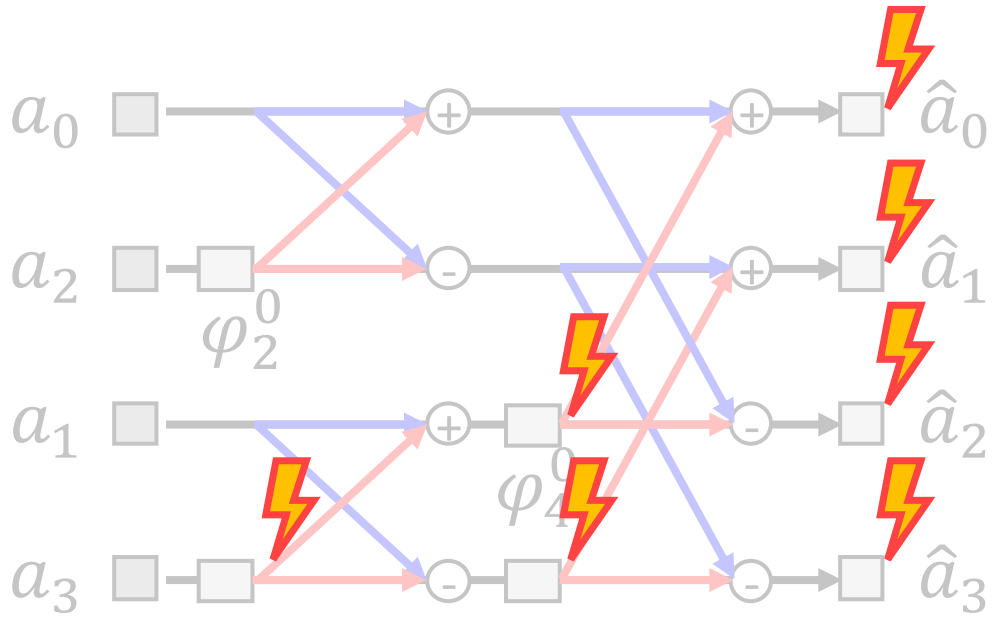
Error-Sensitivity Analysis



- Modulus Operations
- **NTT Representation**
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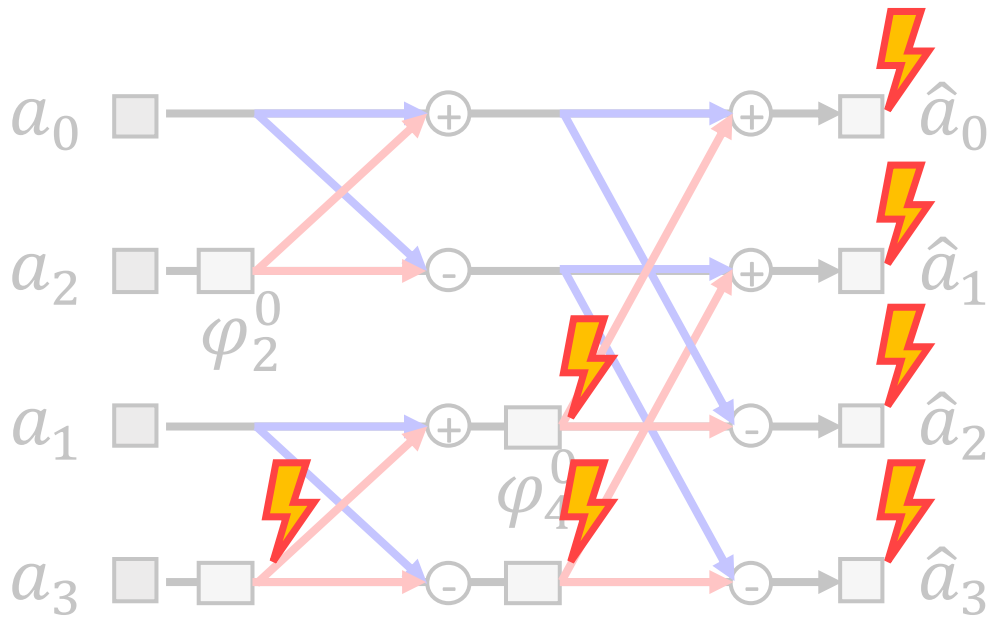
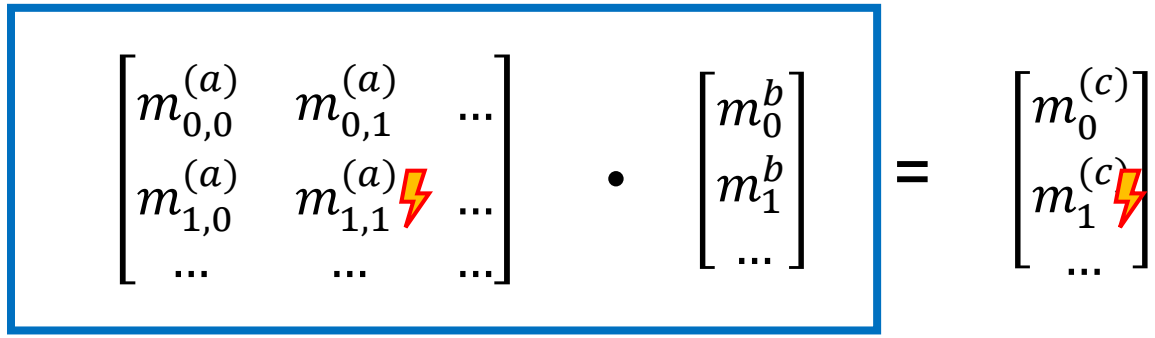


Error broadcast

- Modulus Operations
- **NTT Representation**
- Packing Algorithm

Error-Sensitivity Analysis

Plaintext



- Modulus Operations
- NTT Representation
- **Packing Algorithm**

Error-Sensitivity Analysis

Plaintext

$$\begin{bmatrix} m_{0,0}^{(a)} & m_{0,1}^{(a)} & \cdots \\ m_{1,0}^{(a)} & m_{1,1}^{(a)} & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix} \cdot \begin{bmatrix} m_0^b \\ m_1^b \\ \cdots \end{bmatrix} = \begin{bmatrix} m_0^{(c)} \\ m_1^{(c)} \\ \cdots \end{bmatrix}$$

Ciphertext

$$\left(\begin{bmatrix} ct_0^{(a)} \\ ct_1^{(a)} \\ \cdots \end{bmatrix} + \begin{bmatrix} ct_0^{(a)} \\ ct_1^{(a)} \\ \cdots \end{bmatrix} + \cdots \right) \cdot \begin{bmatrix} ct_0^{(b)} \\ ct_1^{(b)} \\ \cdots \end{bmatrix} \xrightarrow{Dec} \begin{bmatrix} m_0^{(c)} \\ m_1^{(c)} \\ \cdots \end{bmatrix}$$

- Modulus Operations
- NTT Representation
- **Packing Algorithm**

Error-Sensitivity Analysis

Plaintext

$$\begin{bmatrix} m_{0,0}^{(a)} & m_{0,1}^{(a)} & \cdots \\ m_{1,0}^{(a)} & m_{1,1}^{(a)} & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix} \cdot \begin{bmatrix} m_0^b \\ m_1^b \\ \cdots \end{bmatrix} = \begin{bmatrix} m_0^{(c)} \\ m_1^{(c)} \\ \cdots \end{bmatrix}$$

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Error-Sensitivity Analysis

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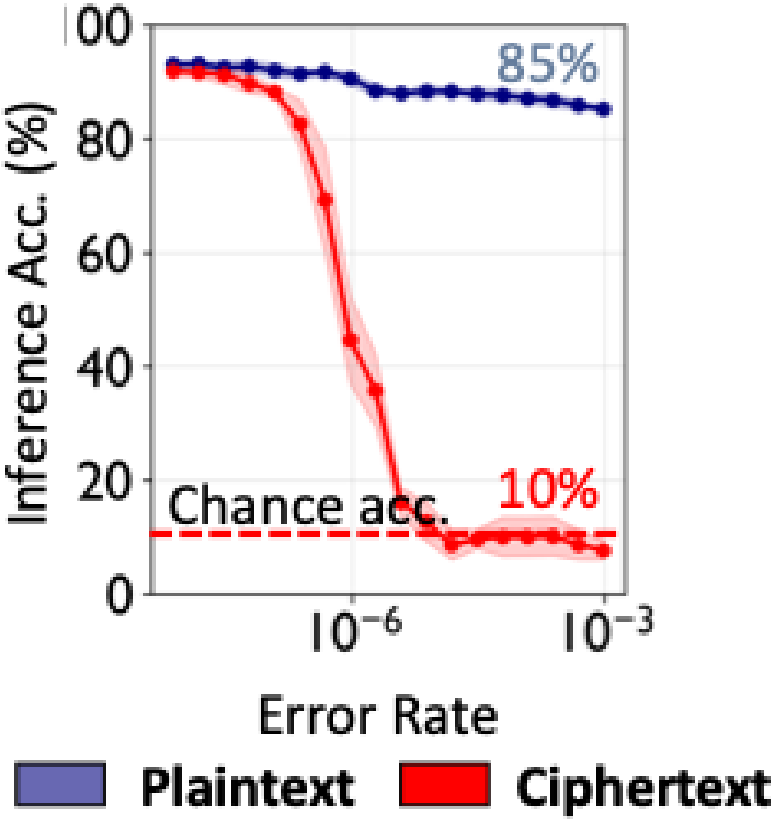
Error broadcast

- Modulus Operations
- NTT Representation
- **Packing Algorithm**

Error-Sensitivity Analysis

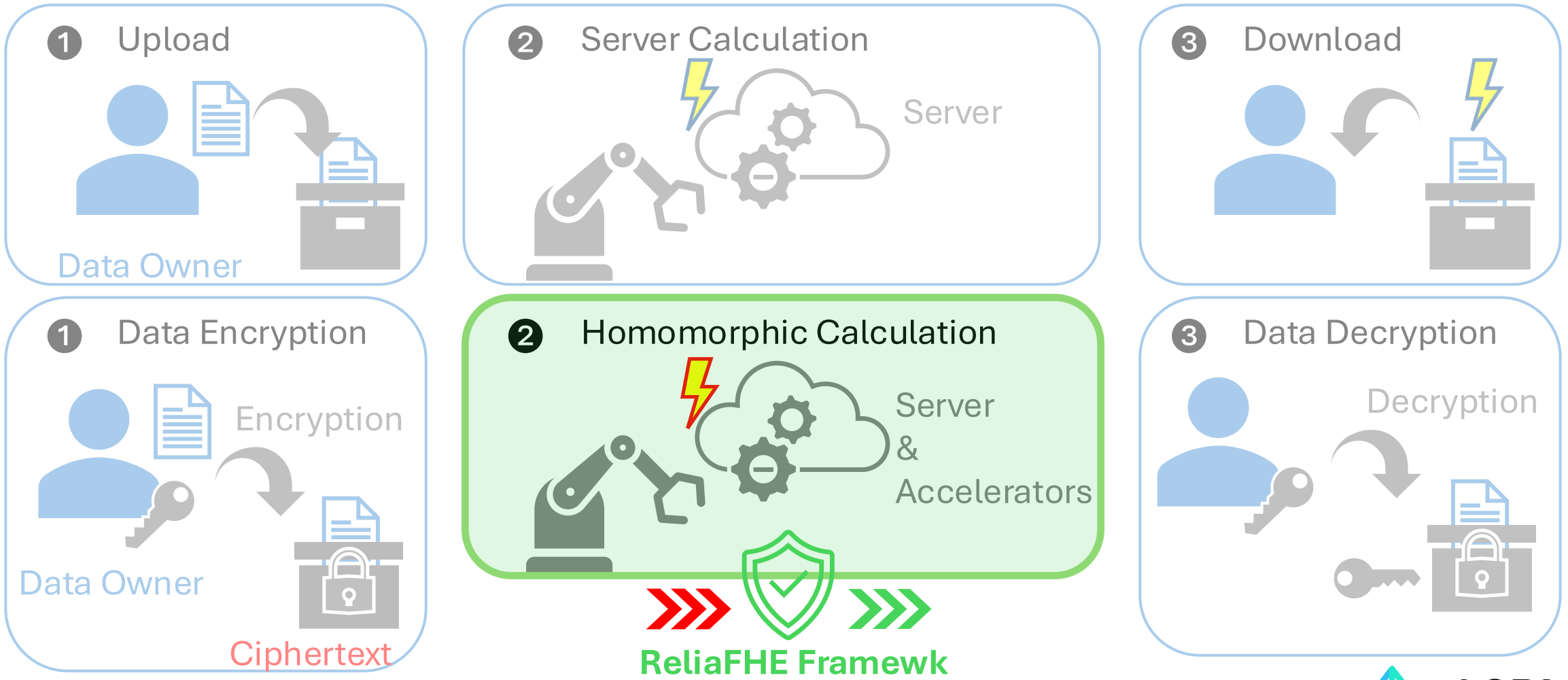
MNIST classification



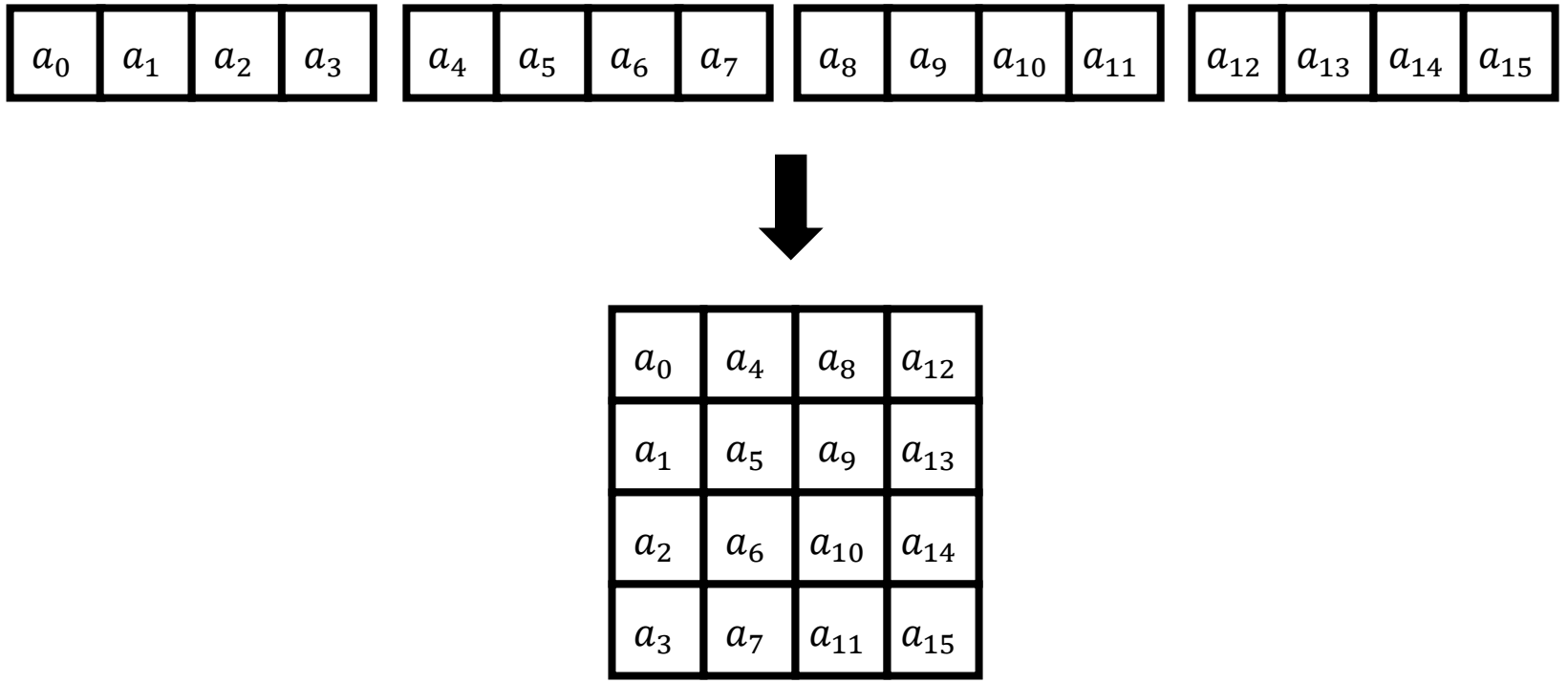
FHE-based model is more error sensitive

- Modulus Operations
- NTT Representation
- Packing Algorithm

ReliaFHE Framework



Storage Protection(e.g. coefficient storage)



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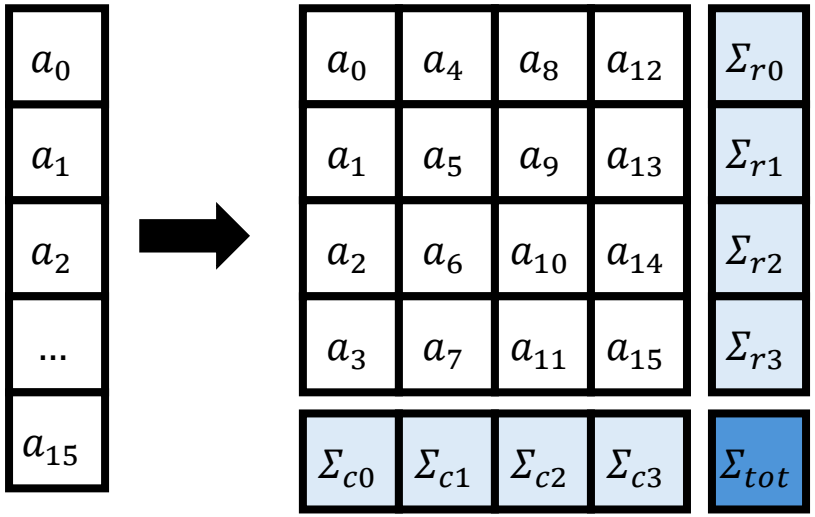
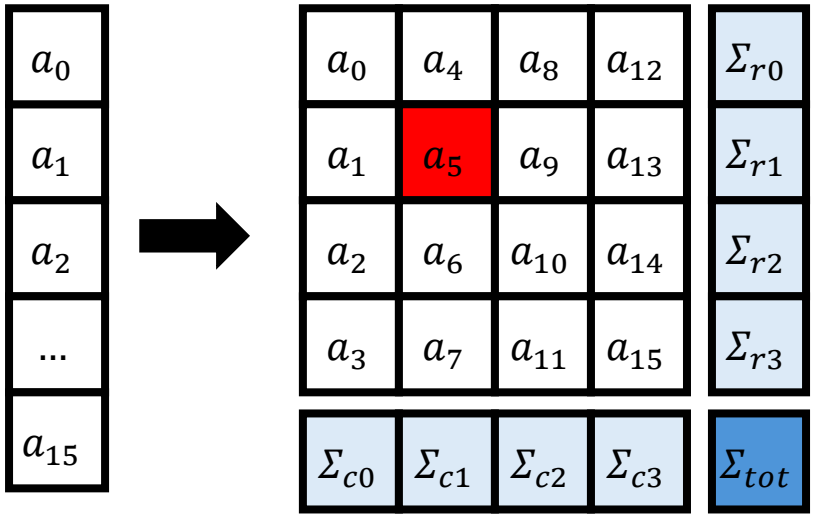


Σ_r, Σ_c : row and col-wise Checksum

Σ_{tot}: total Checksum

Storage Protection(e.g. coefficient storage)



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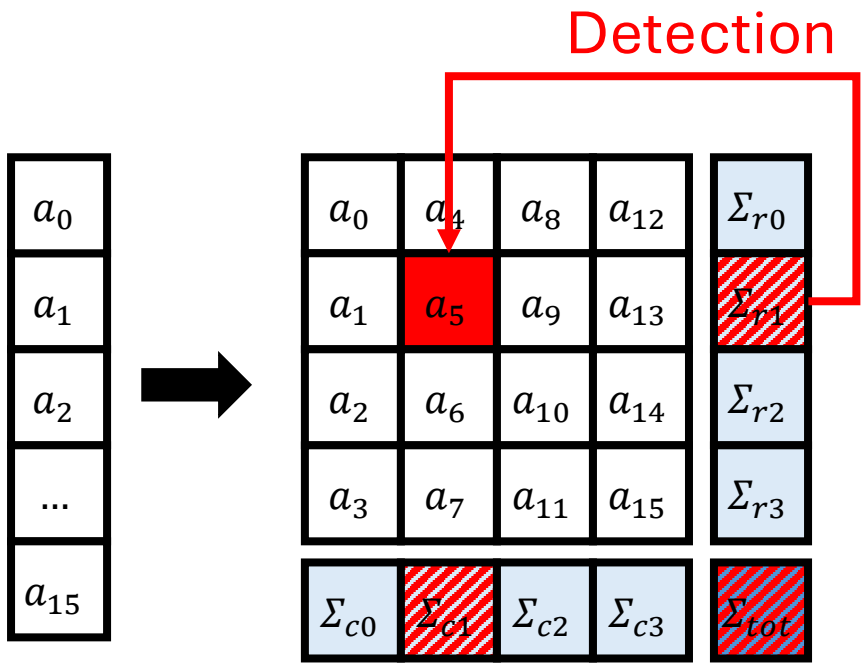

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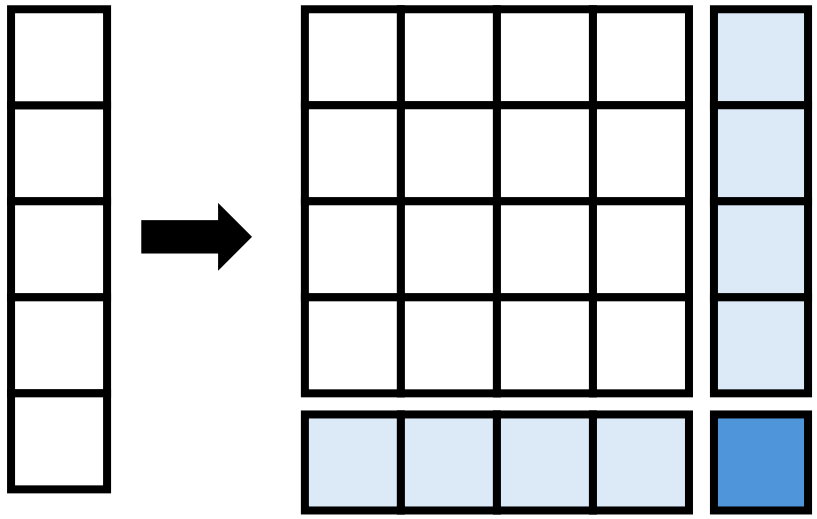
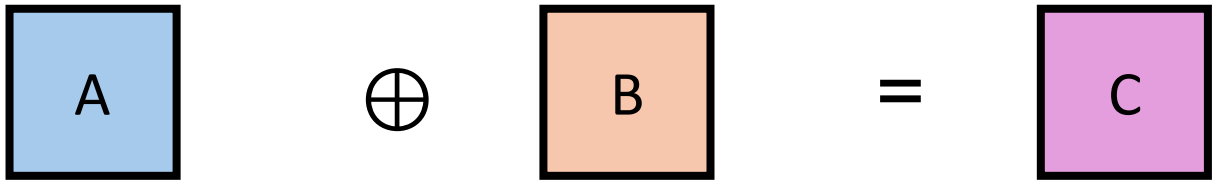


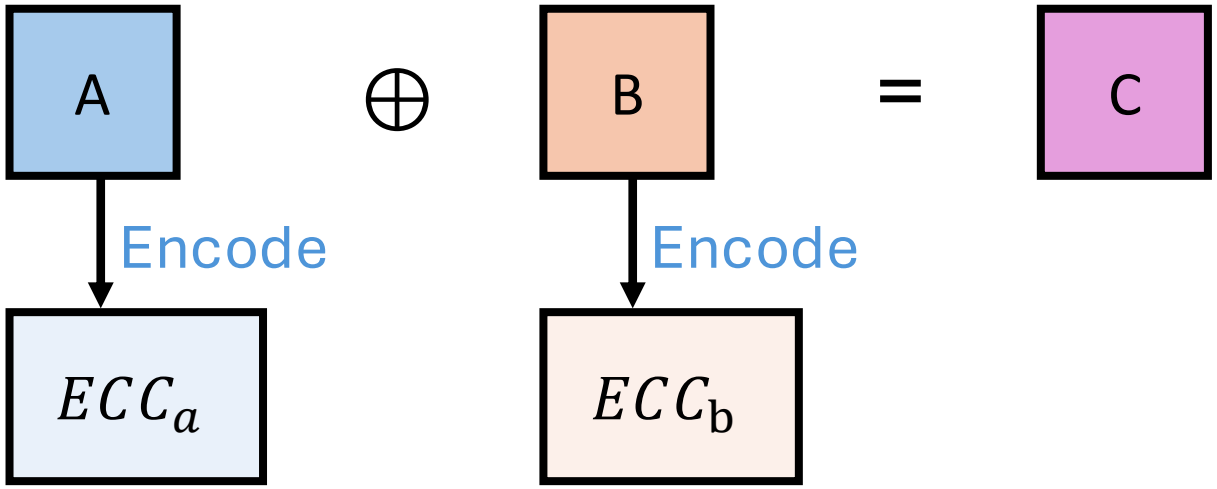
Redundancy: $O(\sqrt{n})$

e.g.
|v|=65536
|R|= 256
0.3% Redundancy

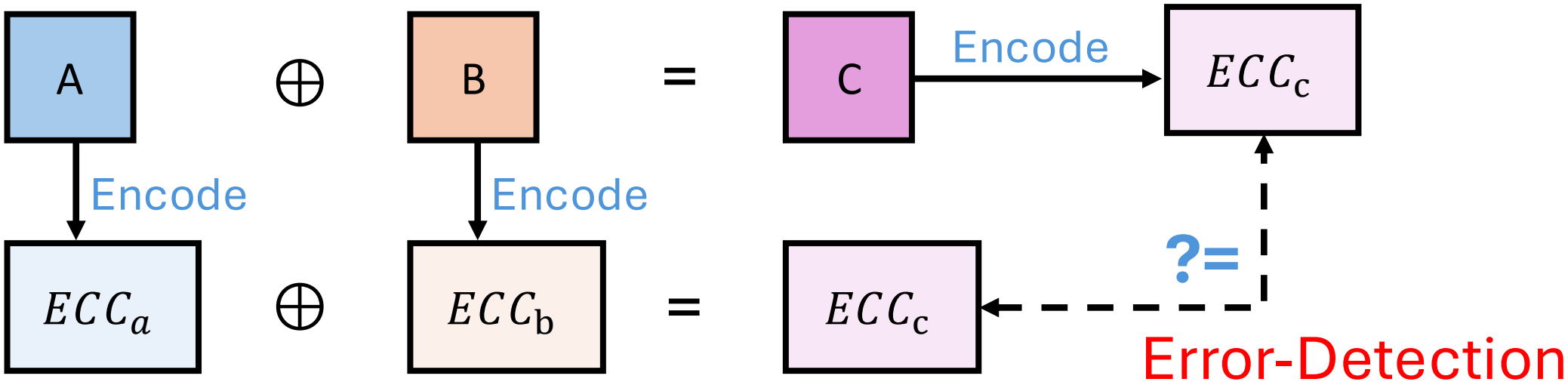
Computation Protection



Computation Protection



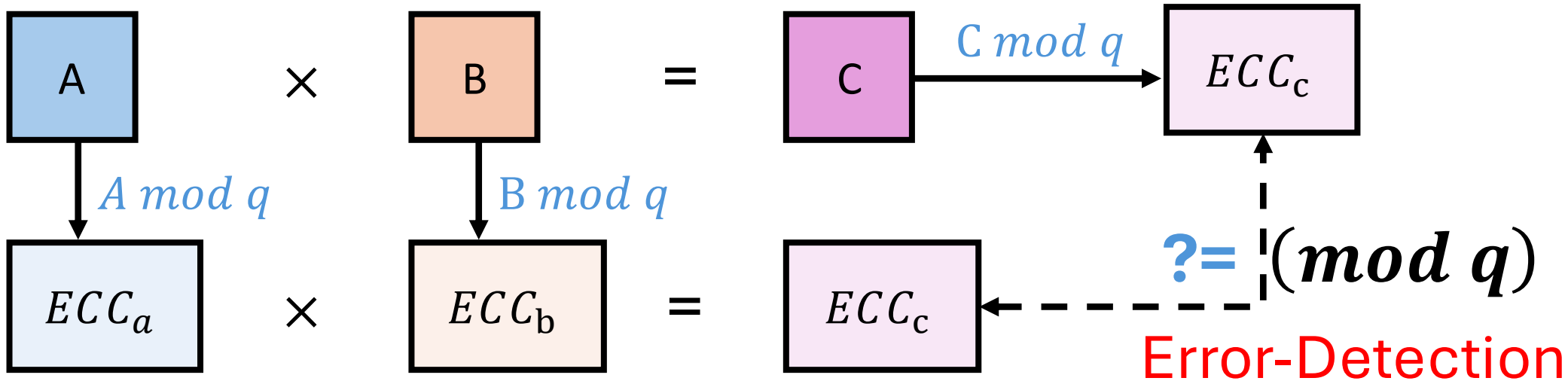
Computation Protection



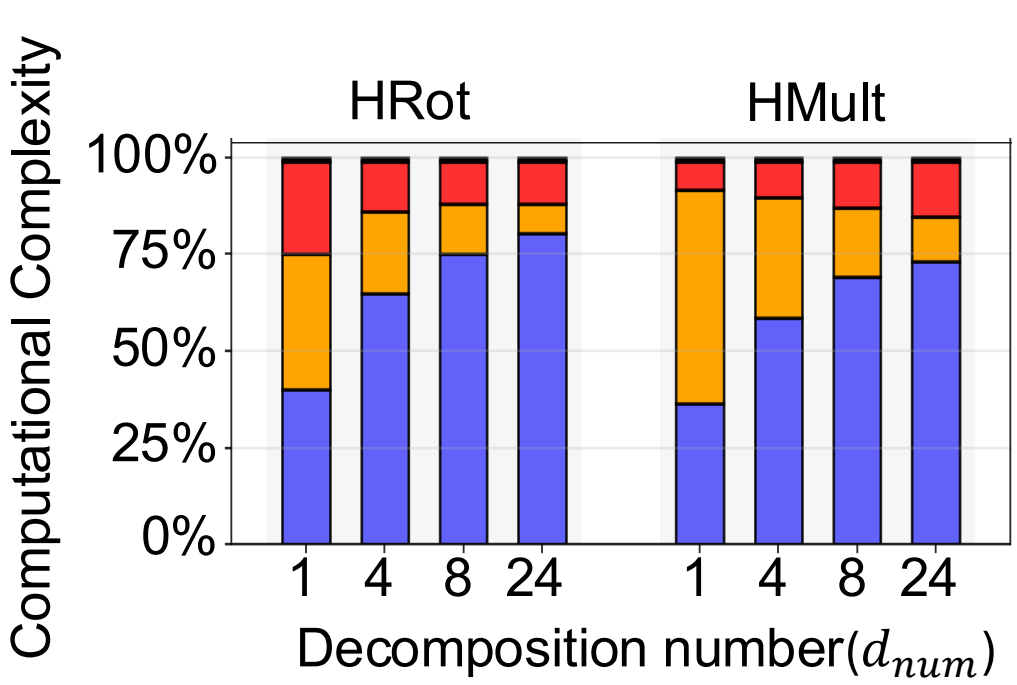
Construct computational compatible ECC

Computation Protection

e.g.



FHE Computation Kernels



Computational Protection

NTT

Elementwise Operation

Scale Operation

> 98%

Others

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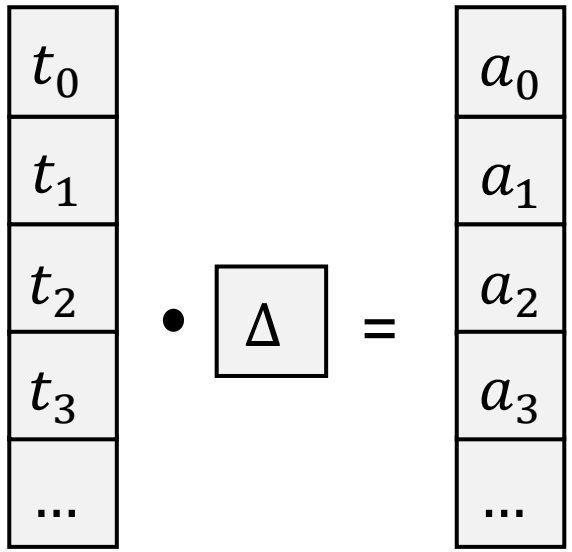
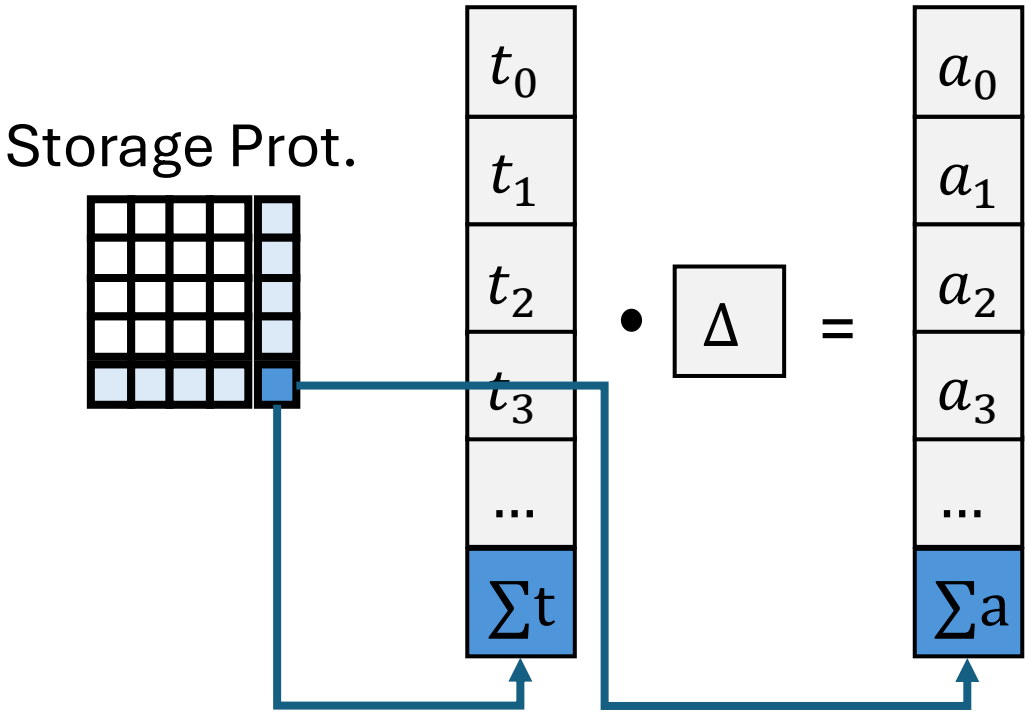
Scaling Operation (e.g., BConv)

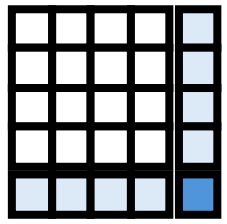


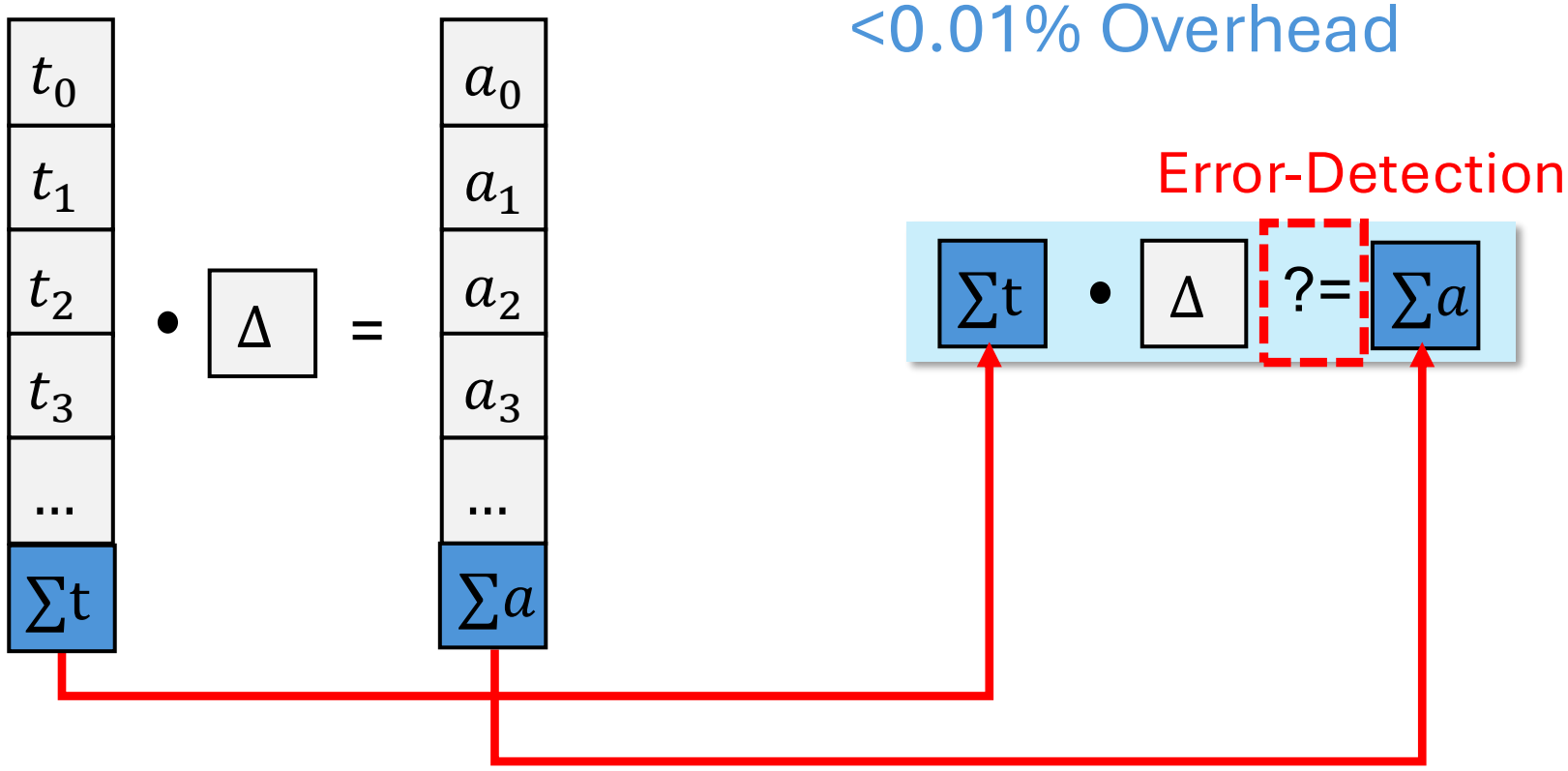
Scaling Operation (e.g., BConv)



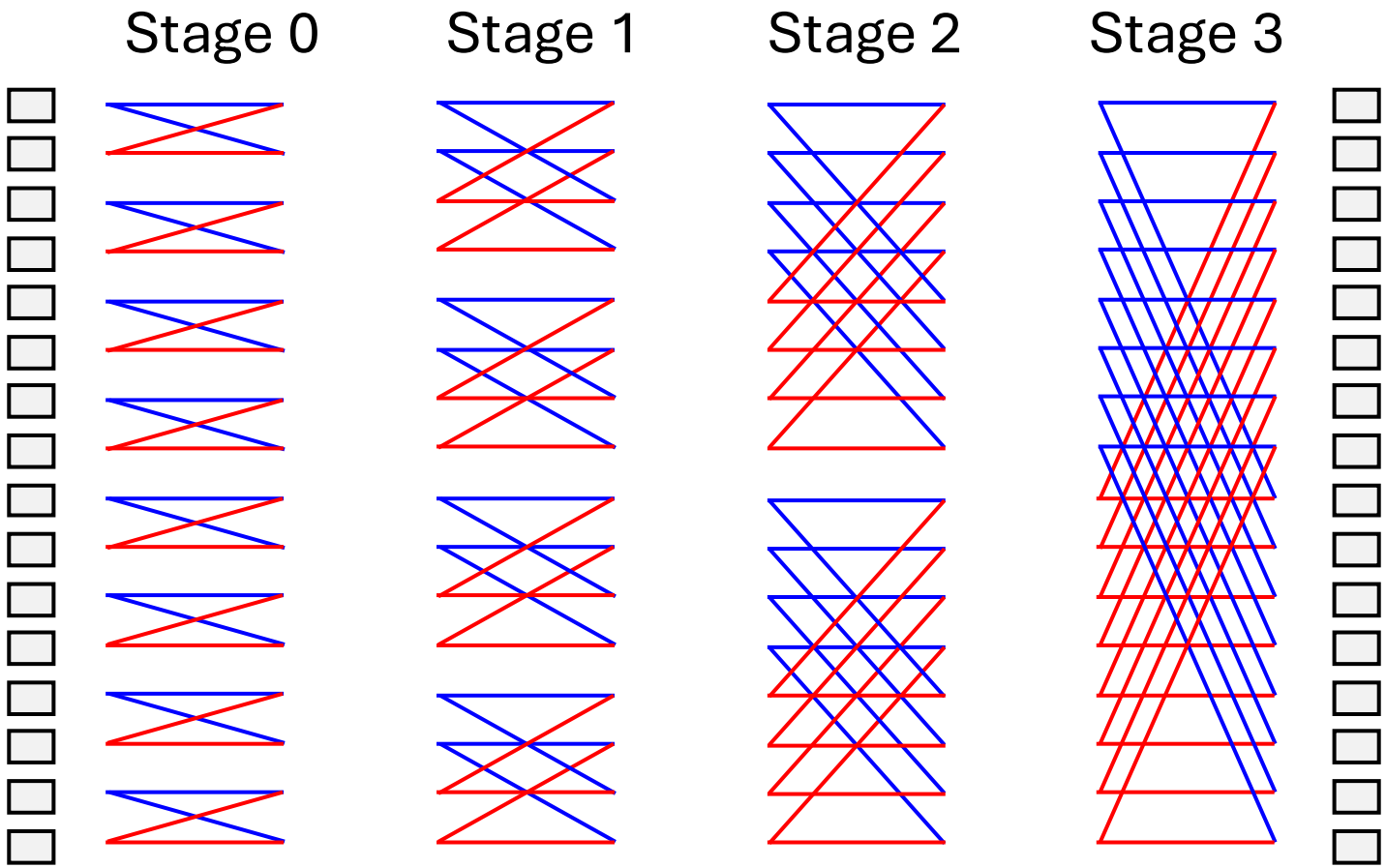
Scaling Operation (e.g., BConv)

Storage Prot.

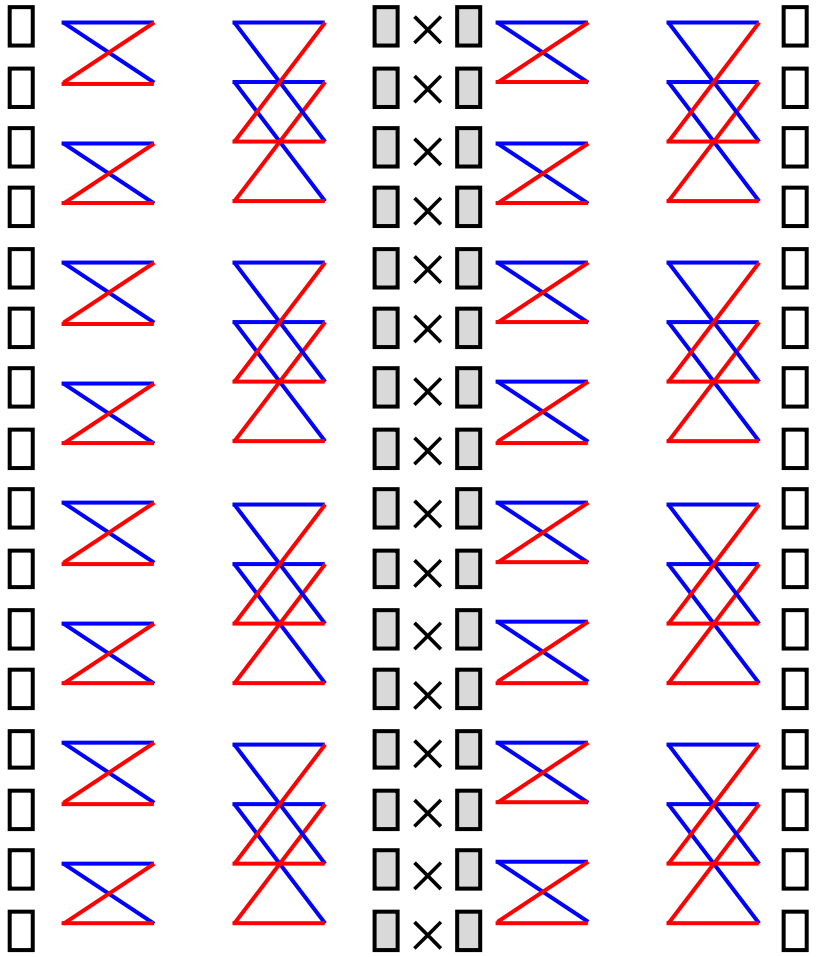




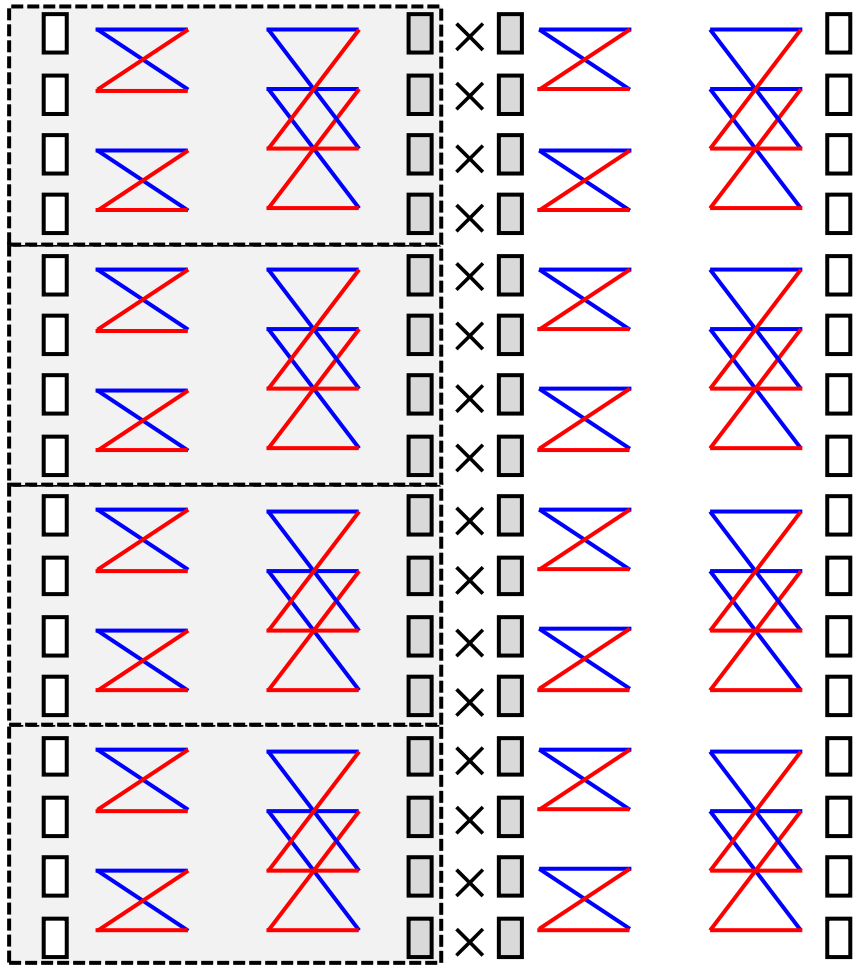
NTT Protection

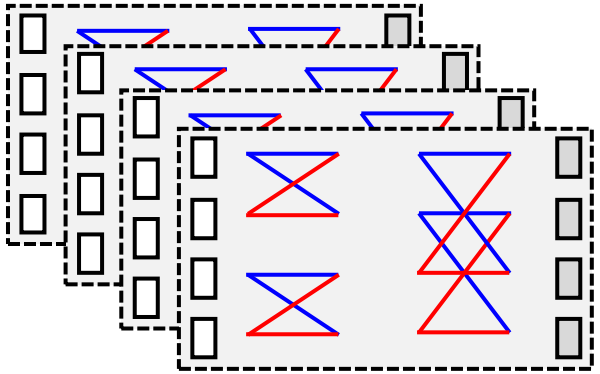


NTT Protection

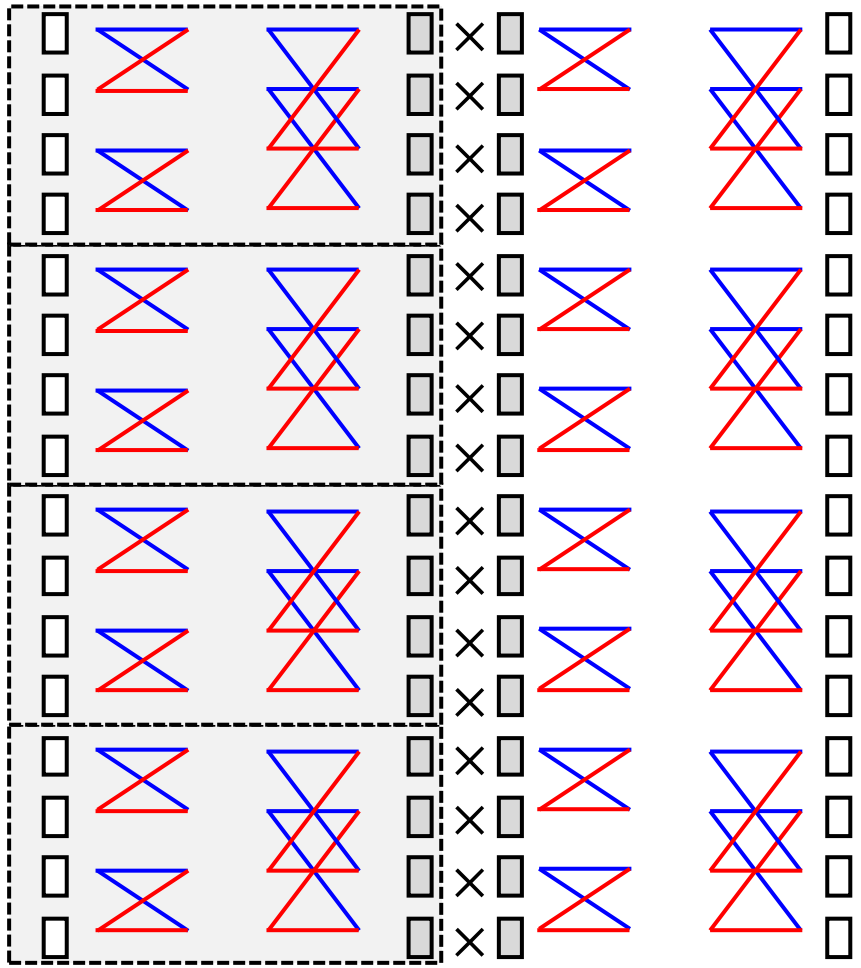


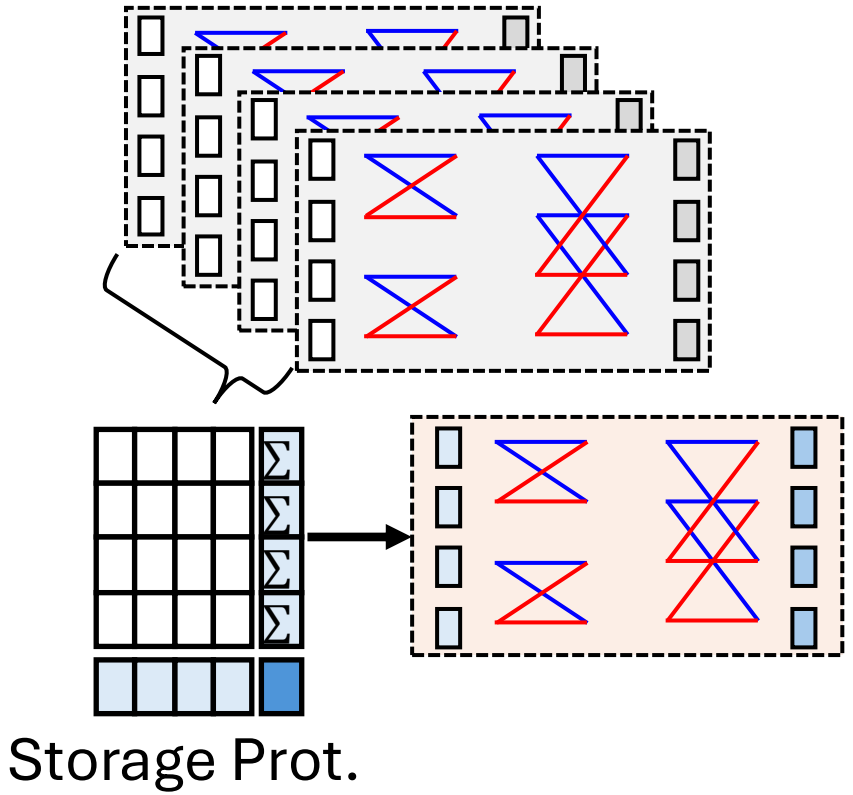
NTT Protection





NTT Protection





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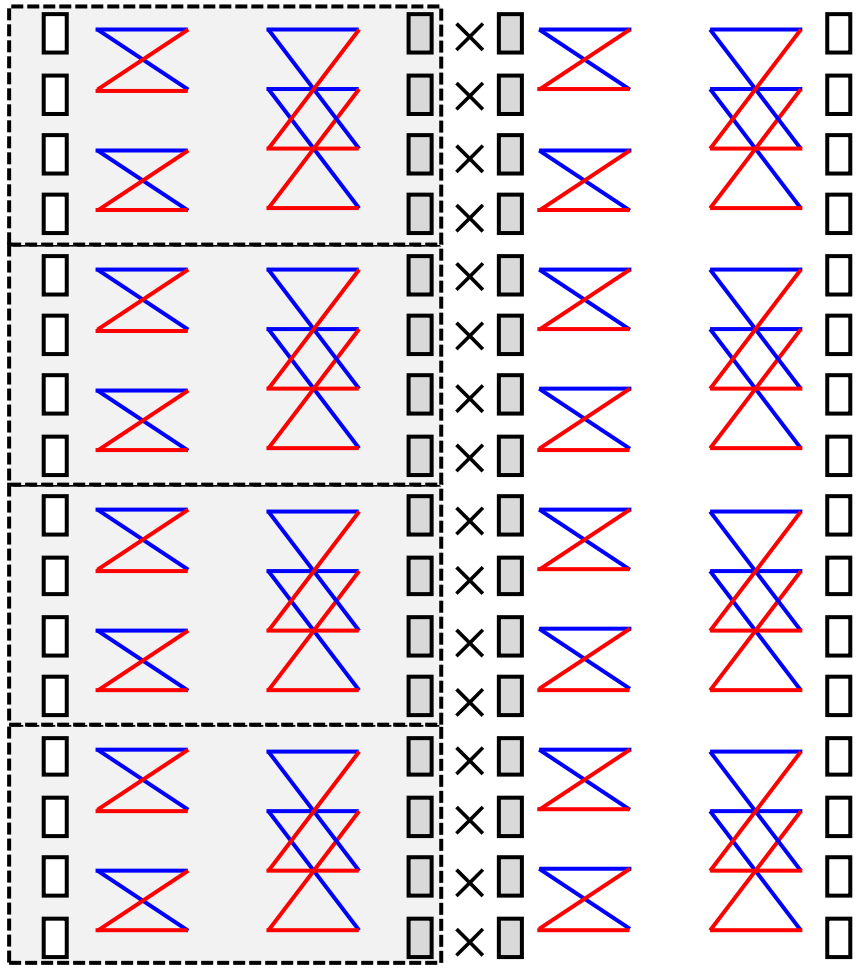
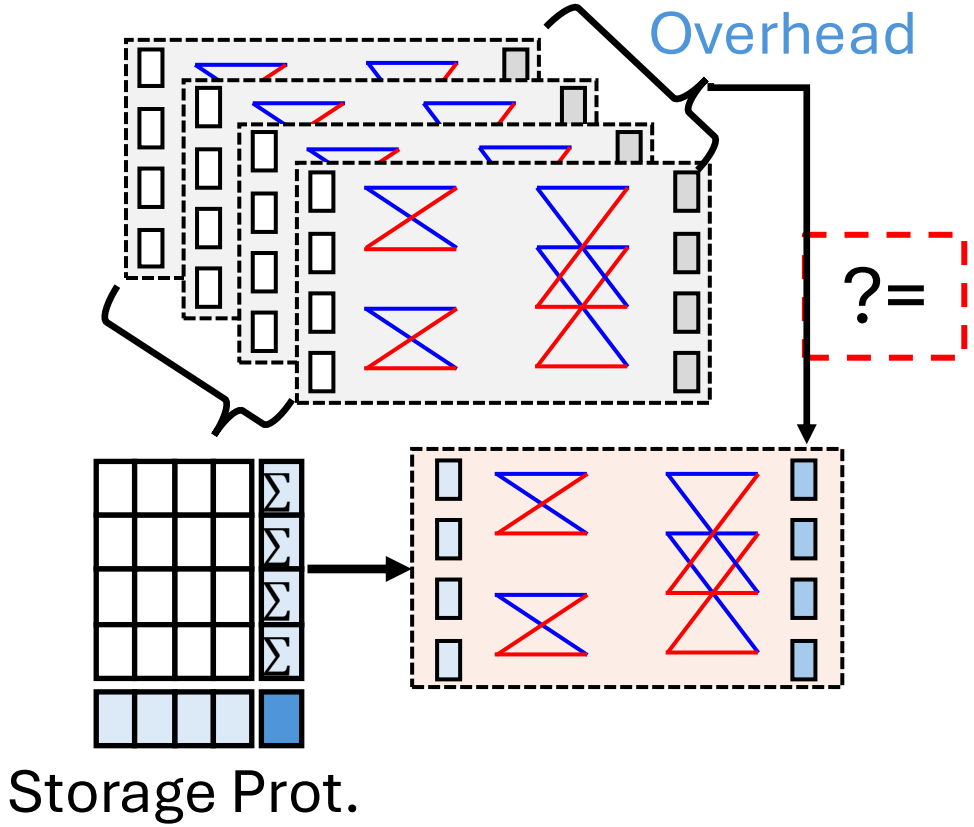
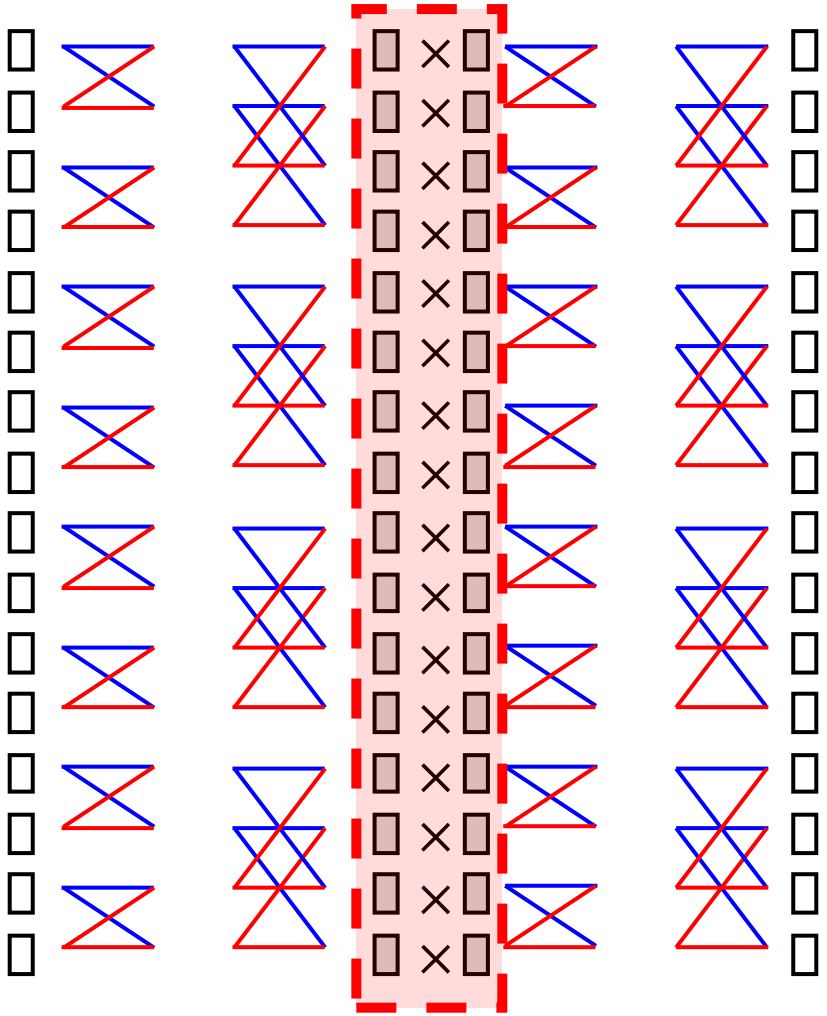
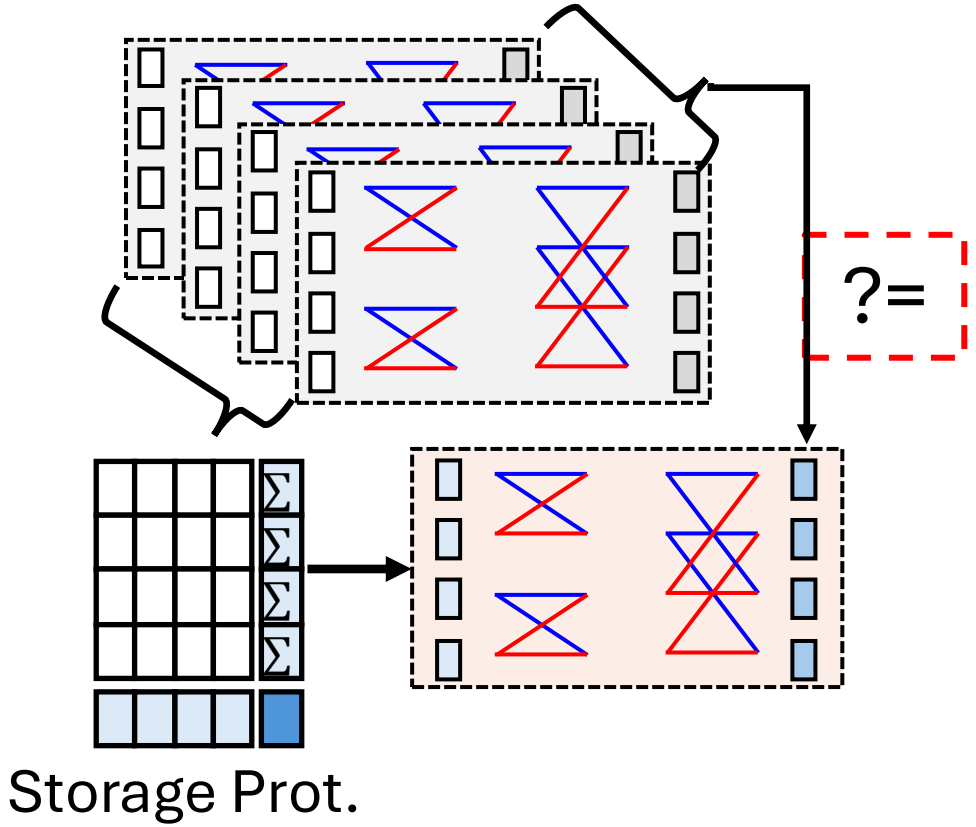


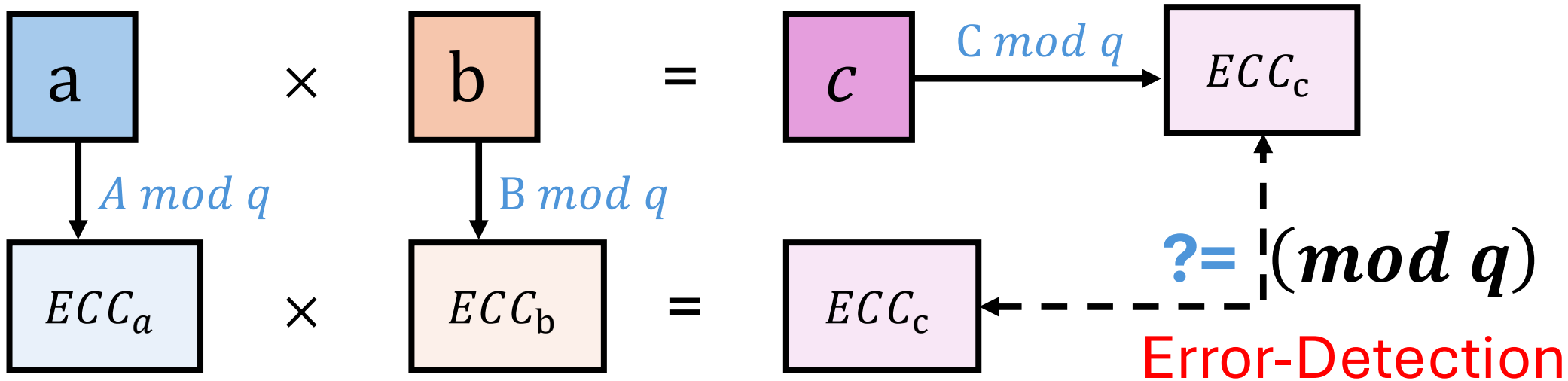


NTT Protection





Elementwise Protection (e.g. EvkMult)



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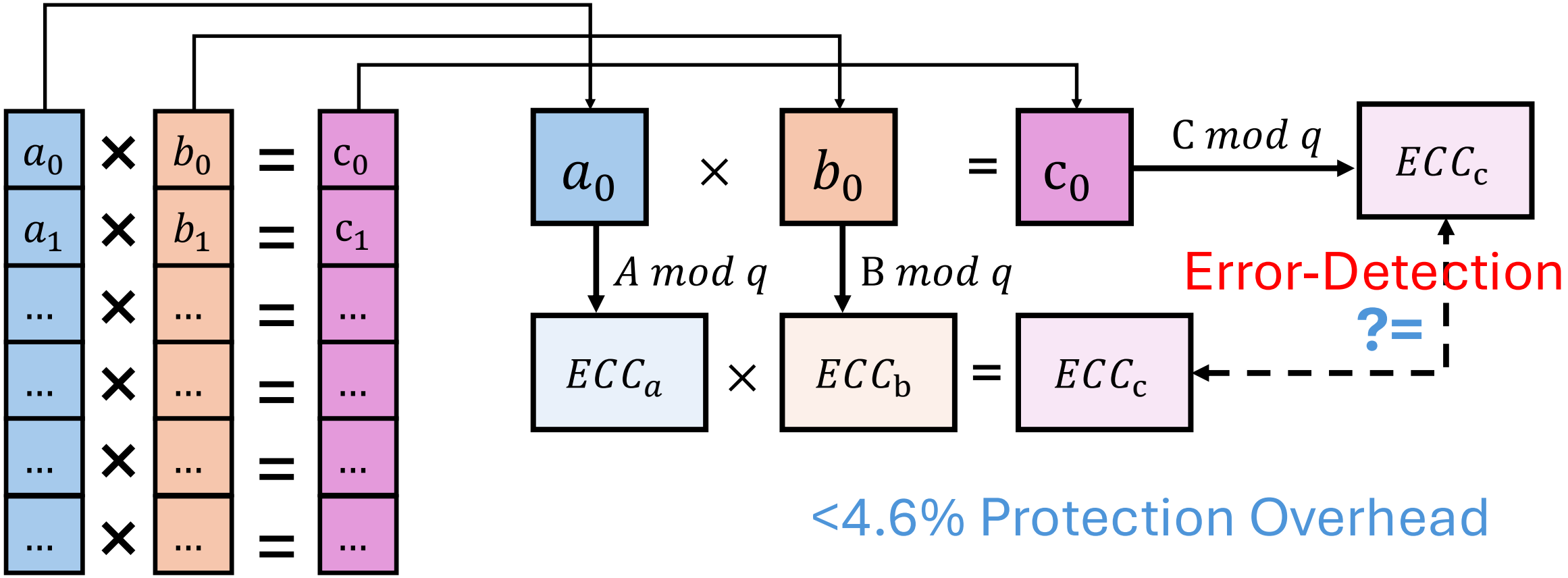
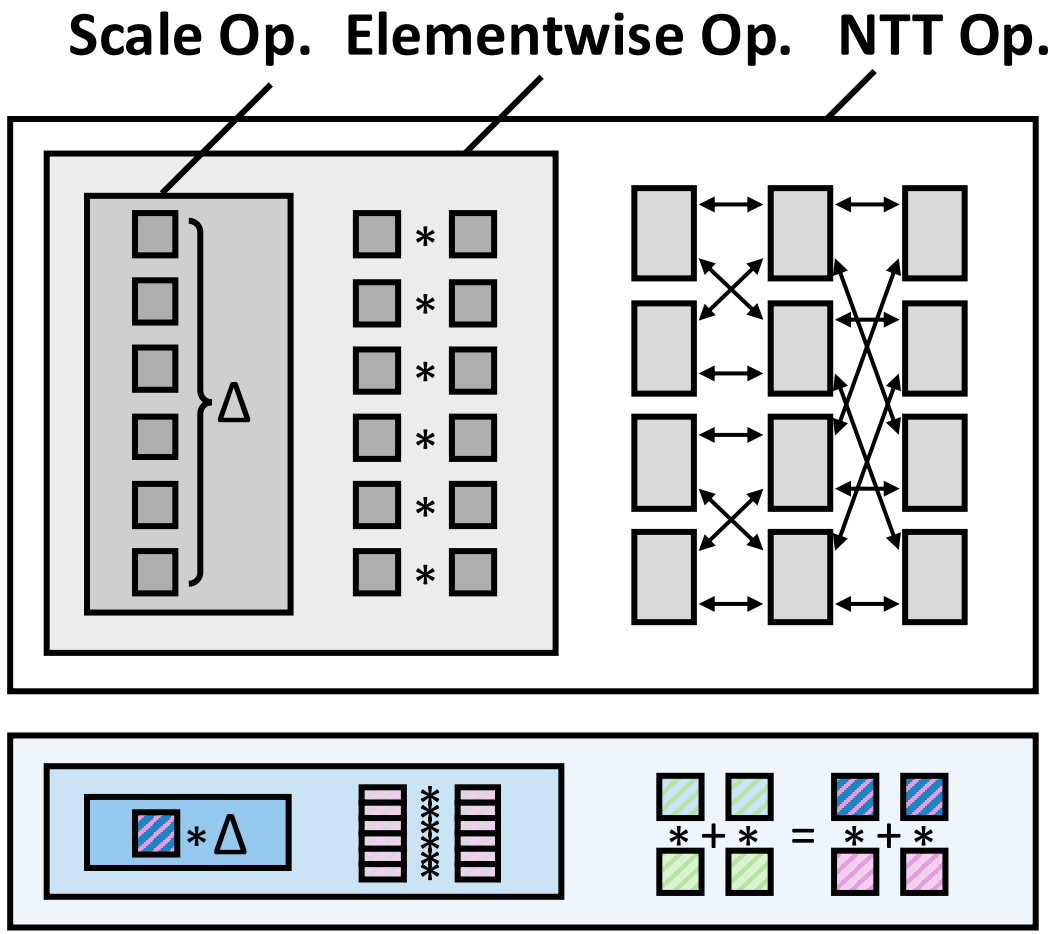


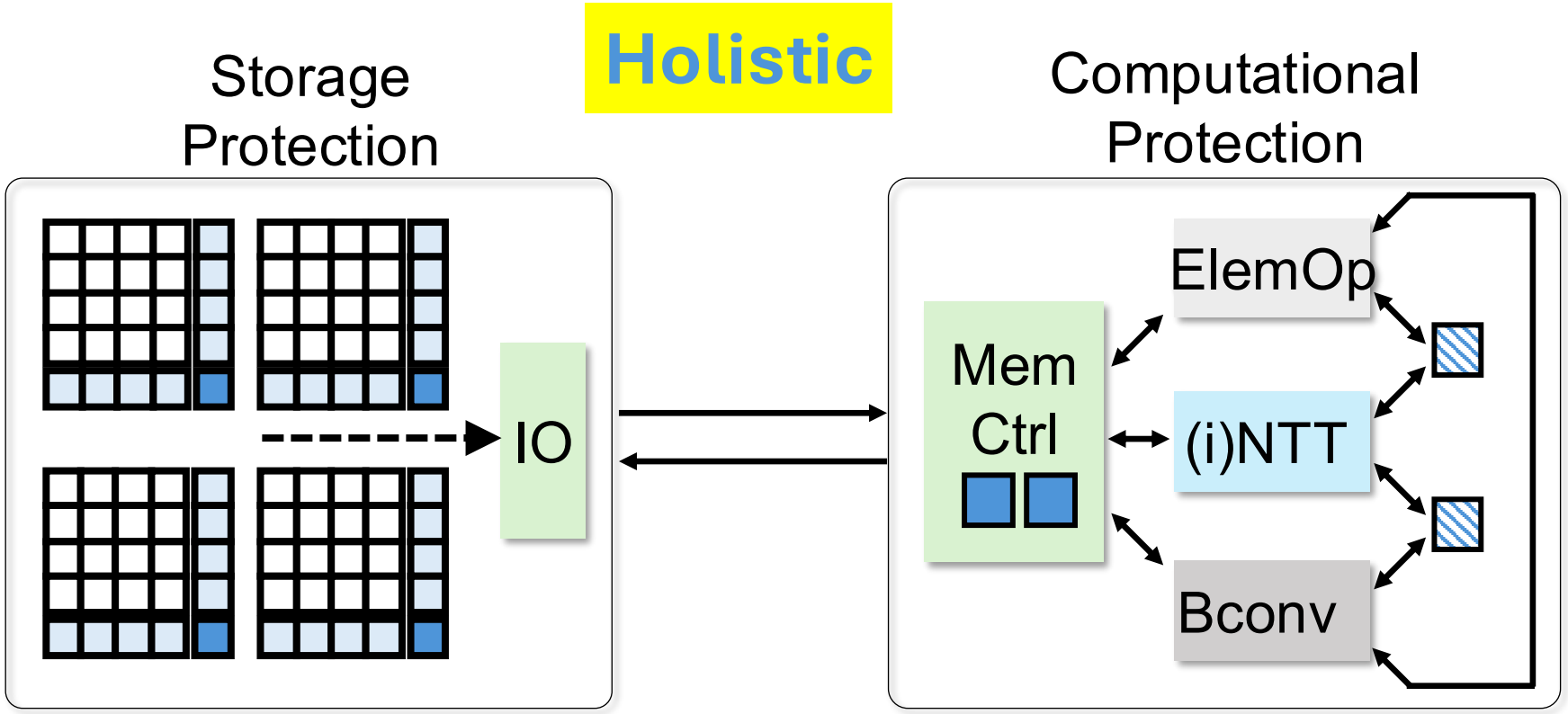
<4.6% Protection Overhead

Conclusion



Hierarchical

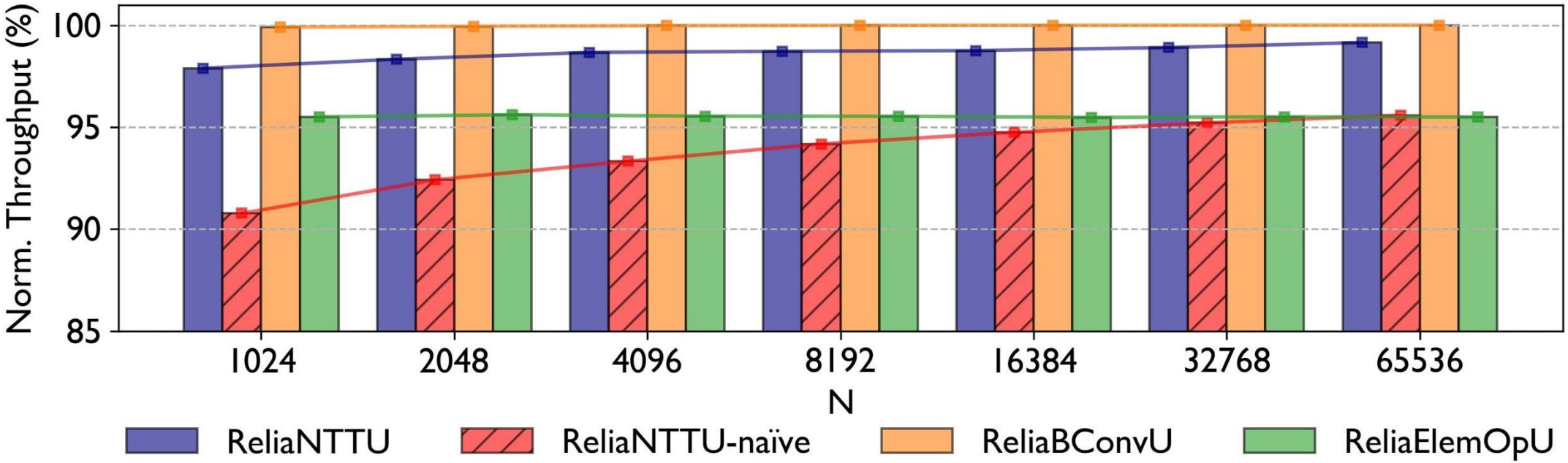
Conclusion


Holistic
Storage Protection
Computational Protection
IO
Mem Ctrl
ElemOp
(i)NTT
Bconv

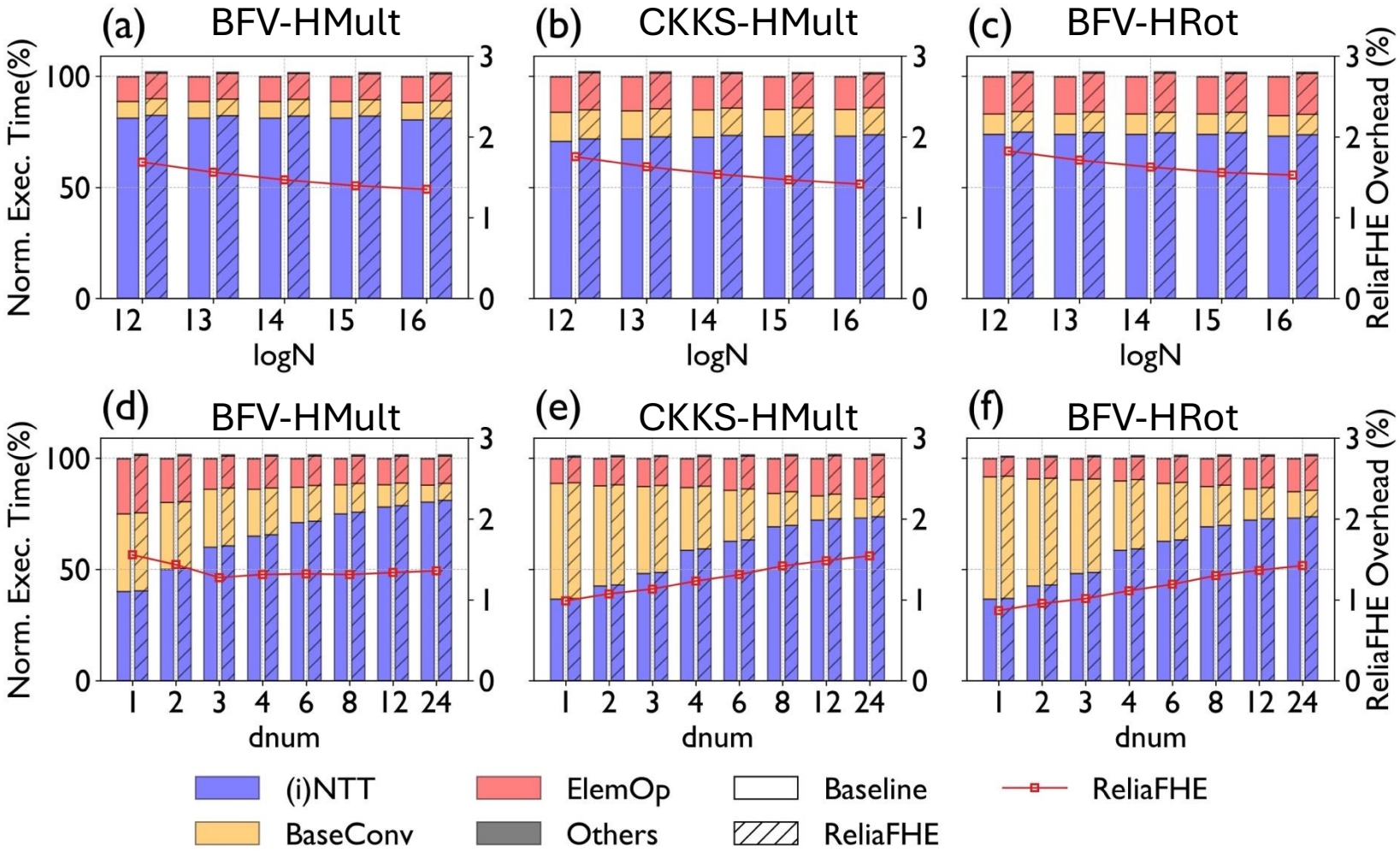
Conclusion

Holistic	Hierarchical	Lightweight
Complete Protection	**Multi-level Defense**	**Minimal Impact**
Integrated security for both **Memory** and **Computation**.	Layered granularity: **Scale operation** →**Elementwise Operation** → **NTT operation**.	Exceptional efficiency with only **1%~2%** overhead.

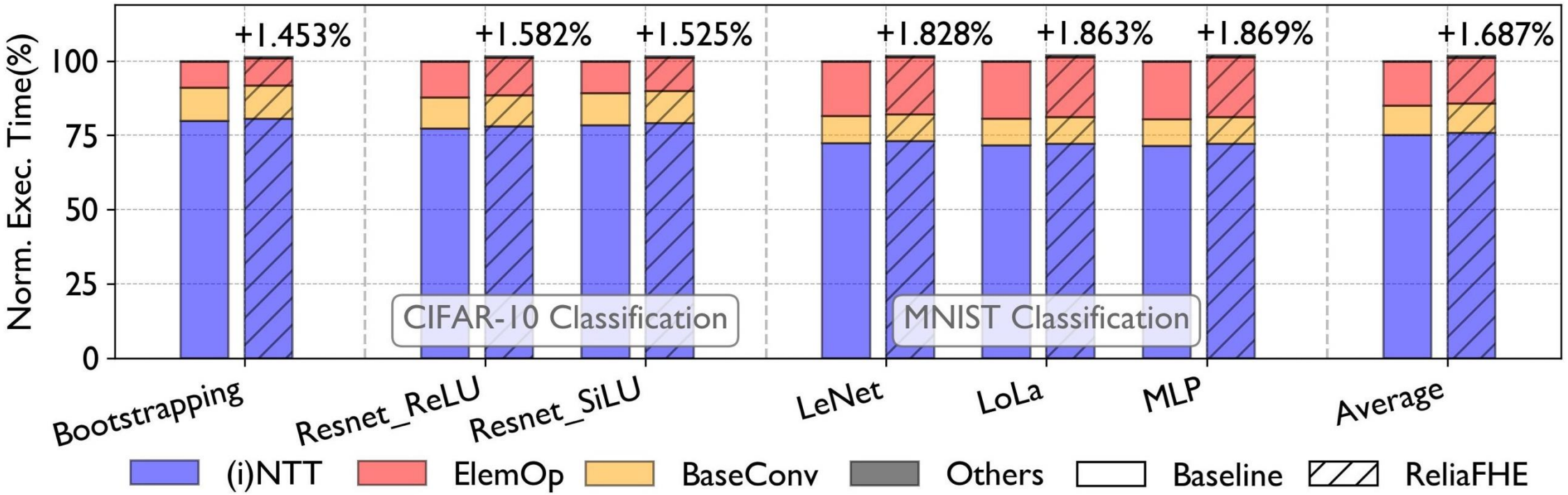
Performance-Operation Kernels



Performance-Primitive Operations

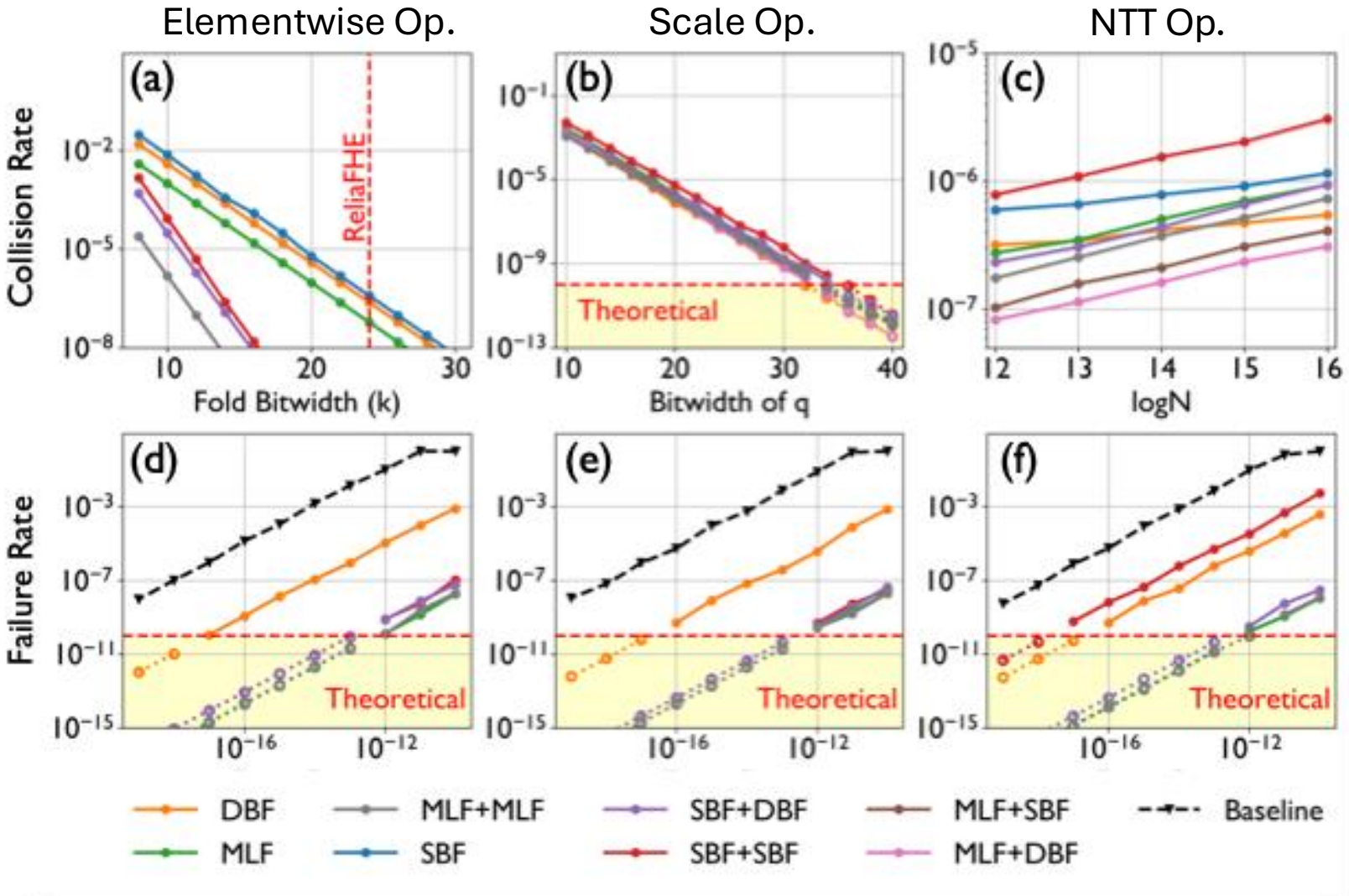


Performance-Application



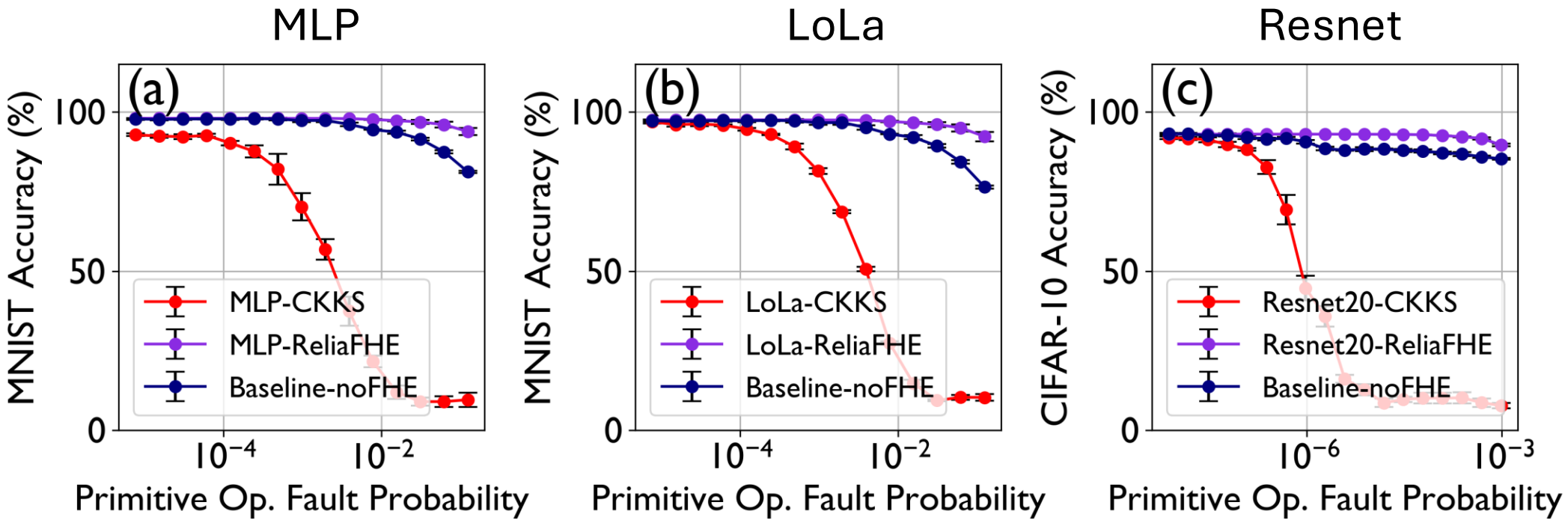
ASPLOS

Reliability



ASPLOS

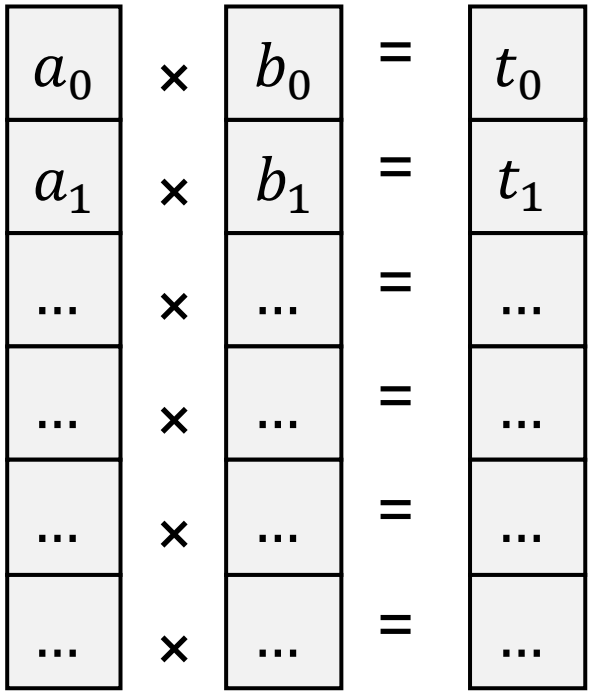
Error-tolerance Ability



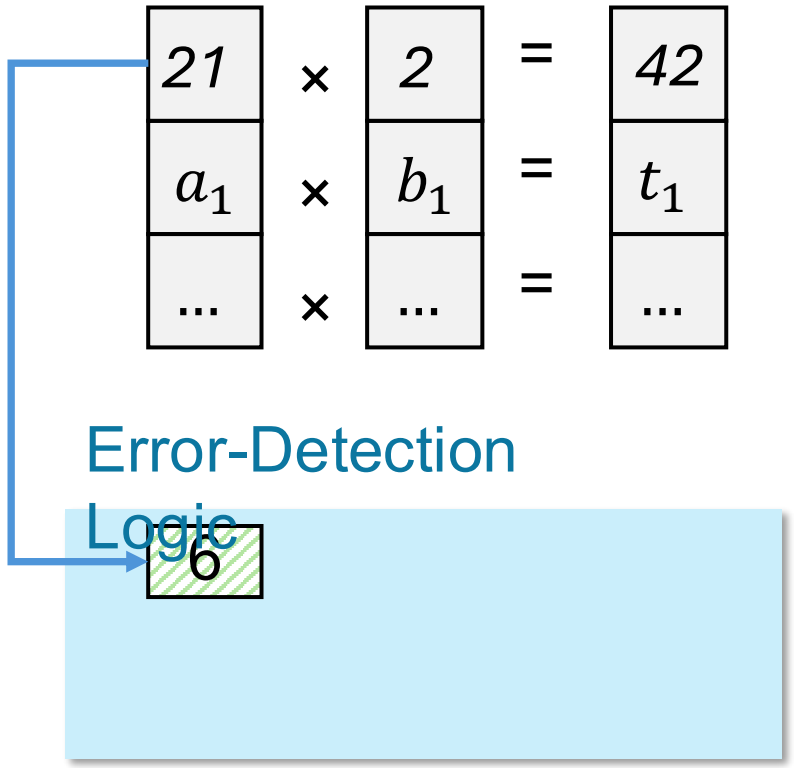
Thank you for listening
Q&A

Fan Li

Elementwise Operation (e.g. EvkMult)



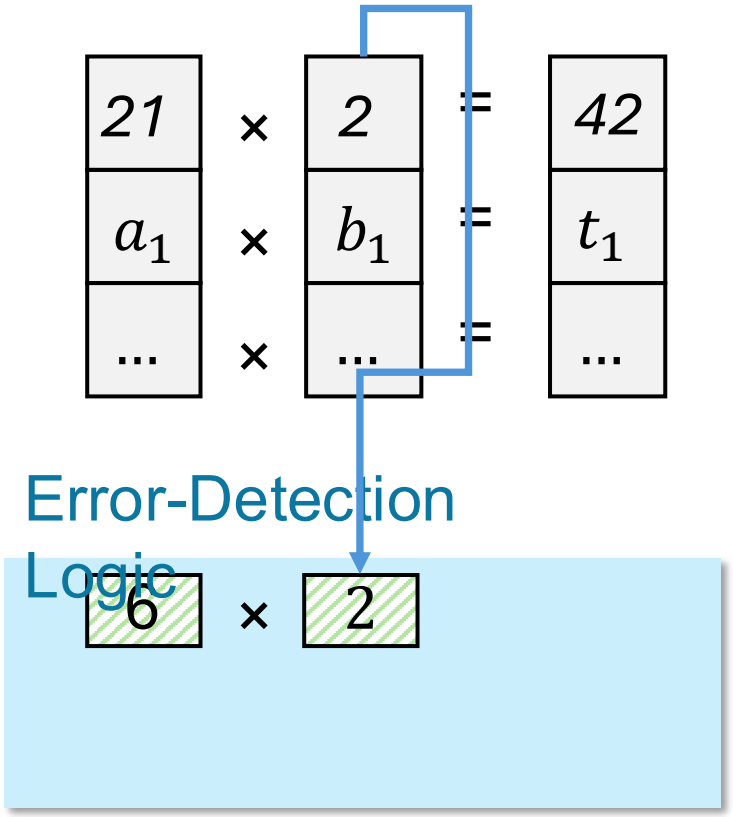
Elementwise Operation (e.g. EvkMult)



21=b0000 0000 0001 0101

21_{Σ}=b(0000 + 0000 + 0001 + 0101)
=b0110
=6

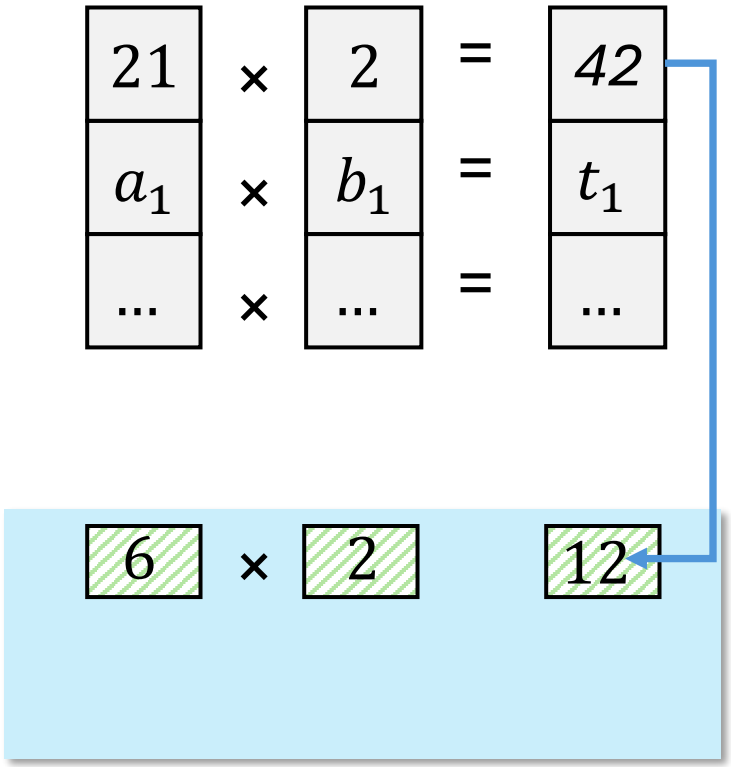
Elementwise Operation (e.g. EvkMult)



2 =b0000 0000 0000 0010

2_Σ=b(0000 + 0000 + 0000 + 0010)
=b0010
=2

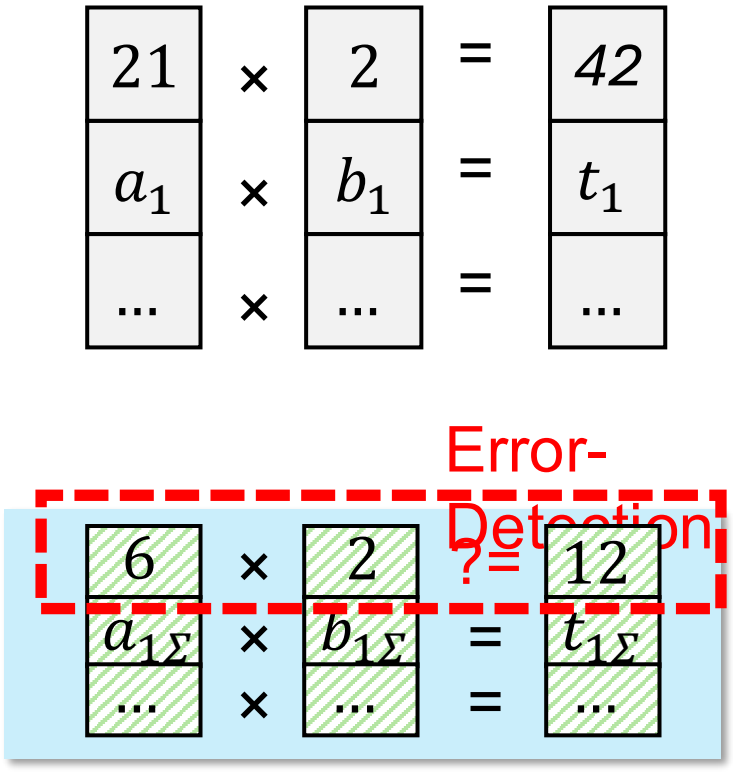
Elementwise Operation (e.g. EvkMult)



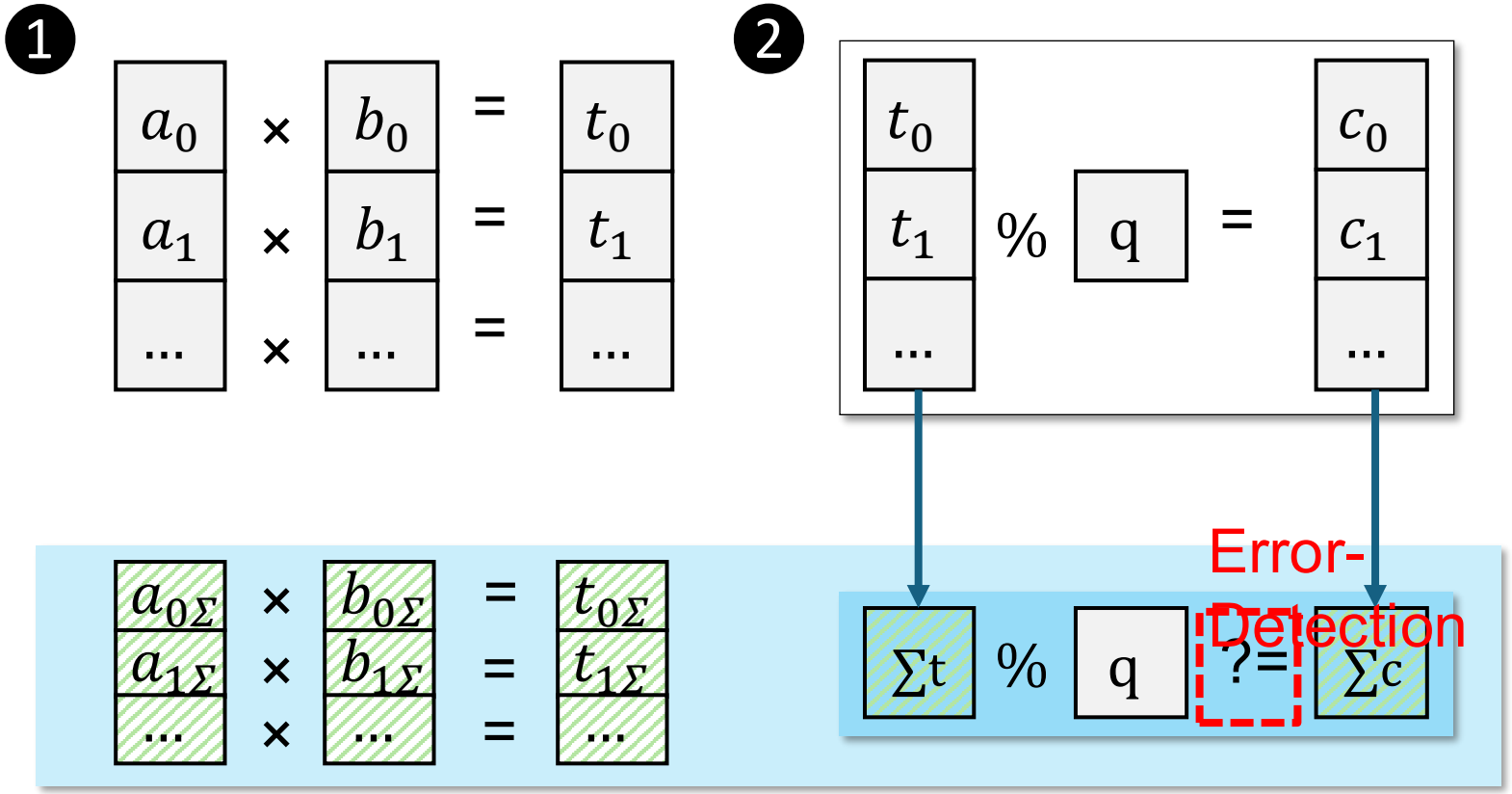
42=b0000 0000 0010 1010

42_{Σ}=b(0000 + 0000 + 0010 + 1010)
=b1100
=12

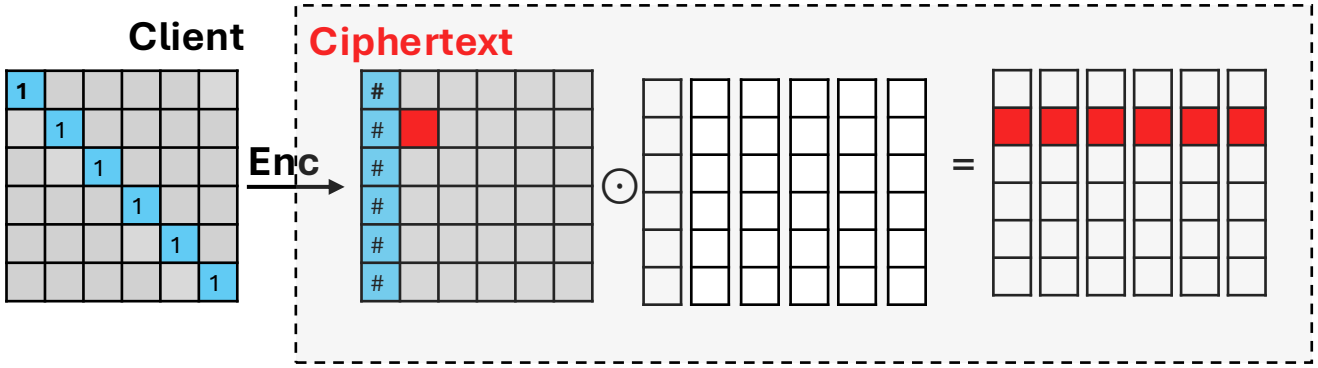
Elementwise Operation (e.g. EvkMult)



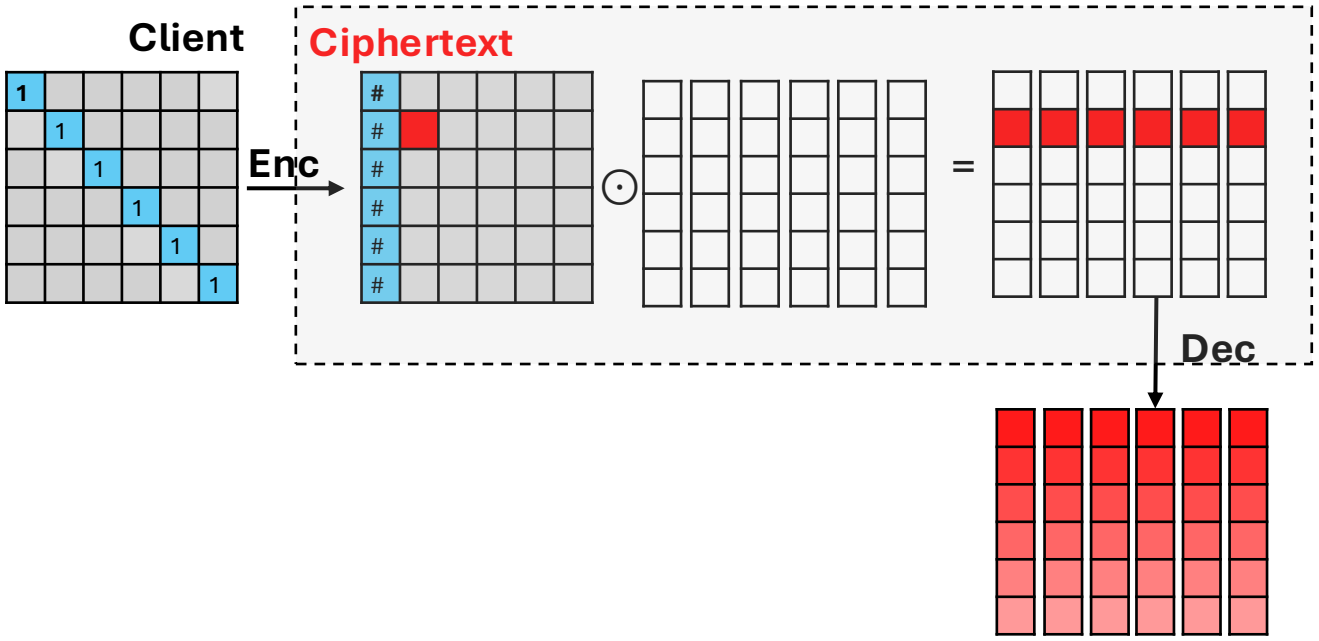
Elementwise Operation (e.g. EvkMult)



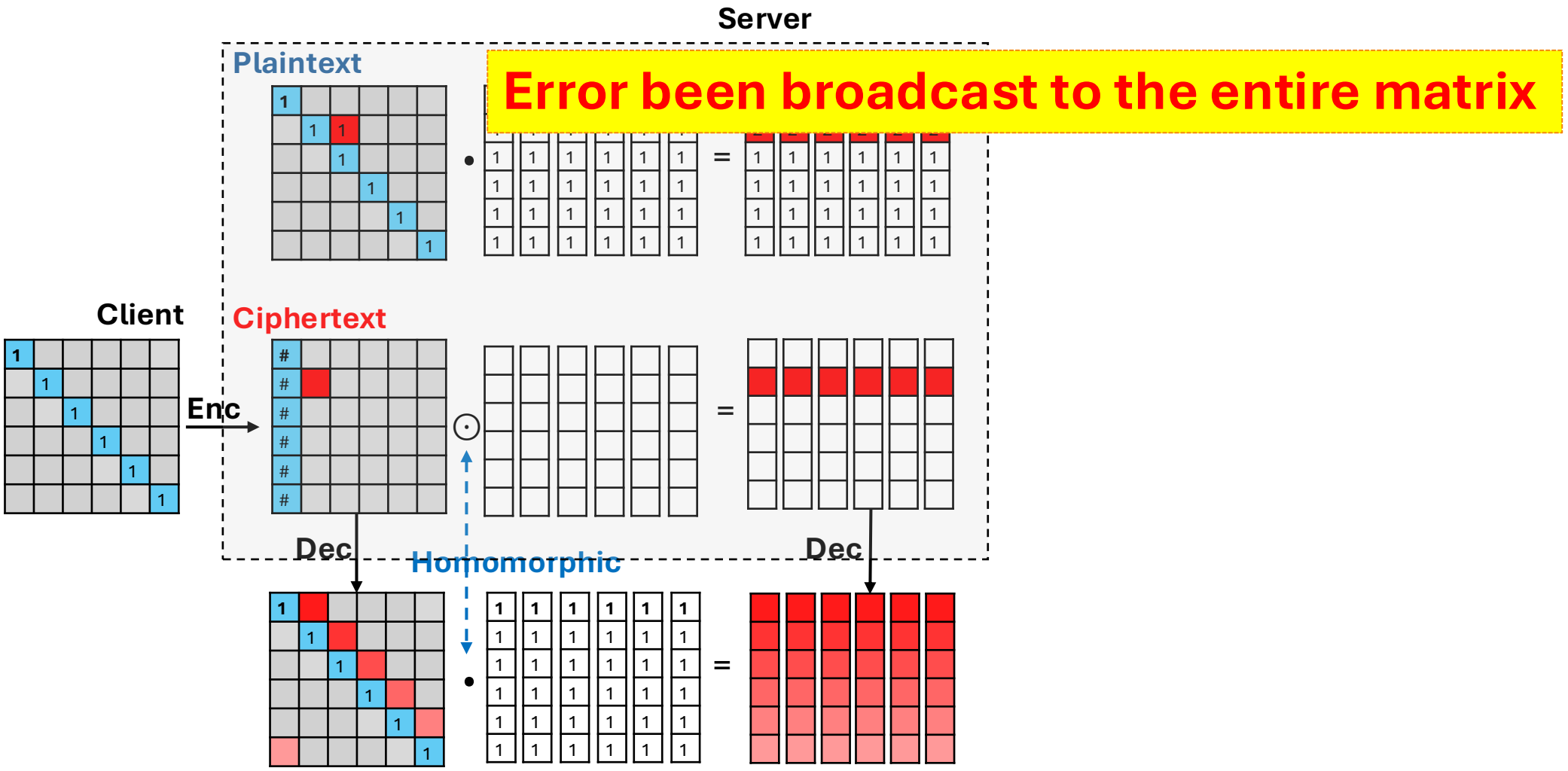
Algorithm-SIMD Packing



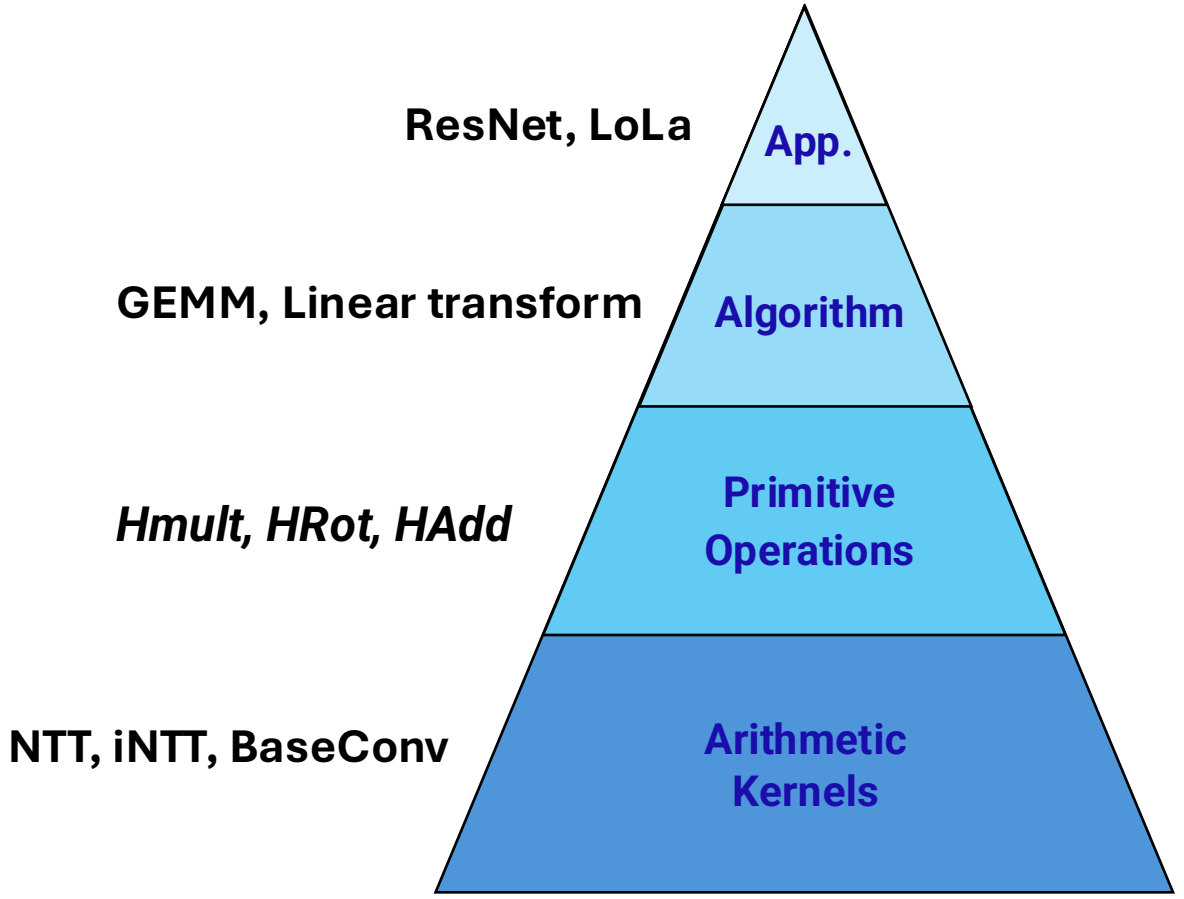
Algorithm-SIMD Packing



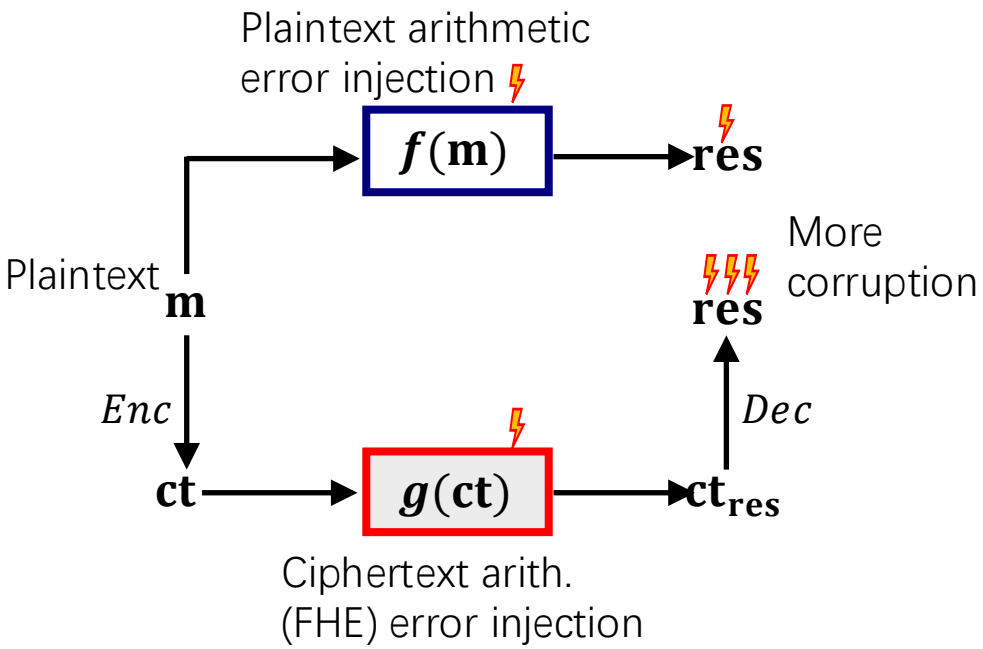
Algorithm-SIMD Packing

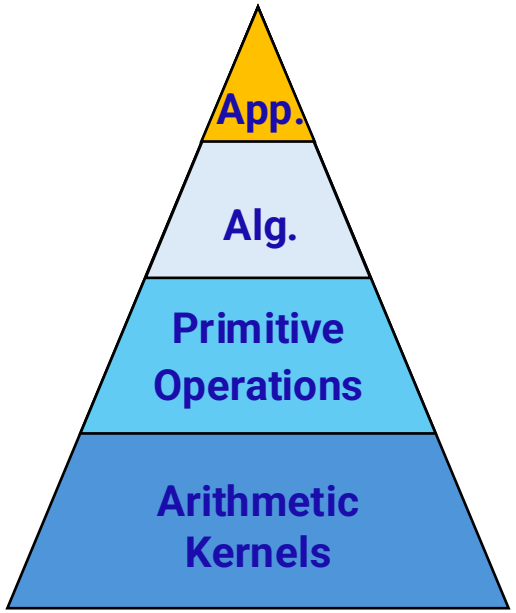


Operations

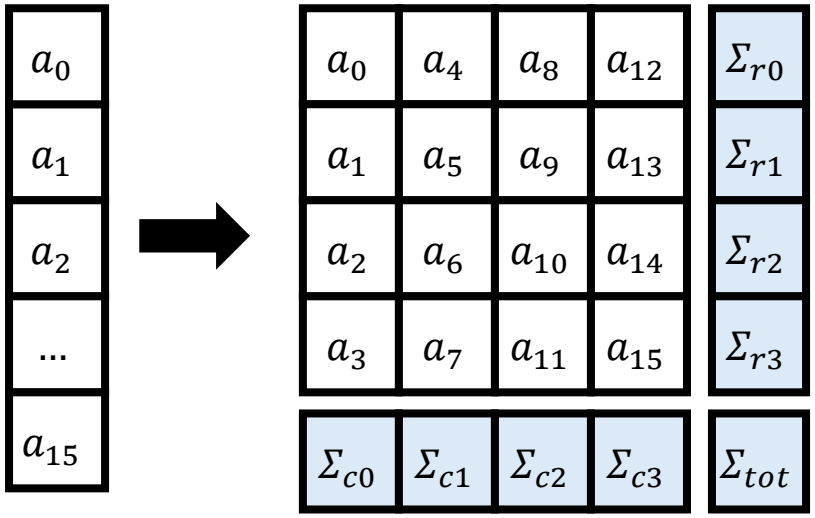

ResNet, LoLa
App.
GEMM, Linear transform
Algorithm
Hmult, HRot, HAdd
Primitive Operations
NTT, iNTT, BaseConv
Arithmetic Kernels

Application



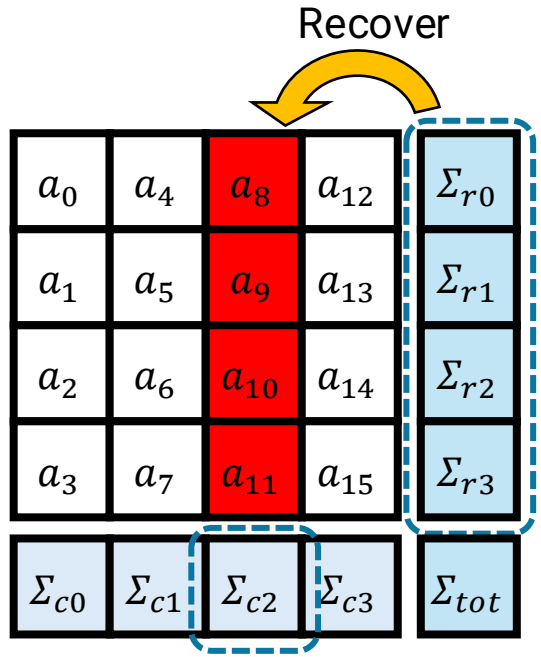


Storage Protection(e.g. coefficient)



Σ_{tot}: total Checksum

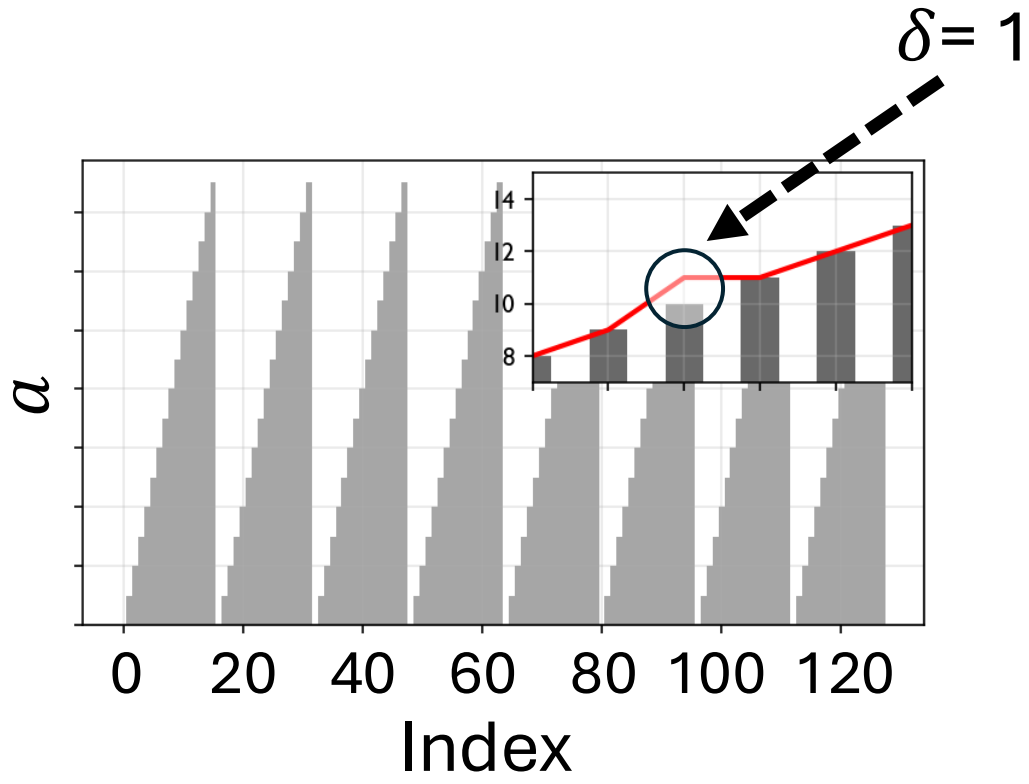
$\Sigma_{r,}\ \Sigma_c$: row and col-wise Checksum



Detect

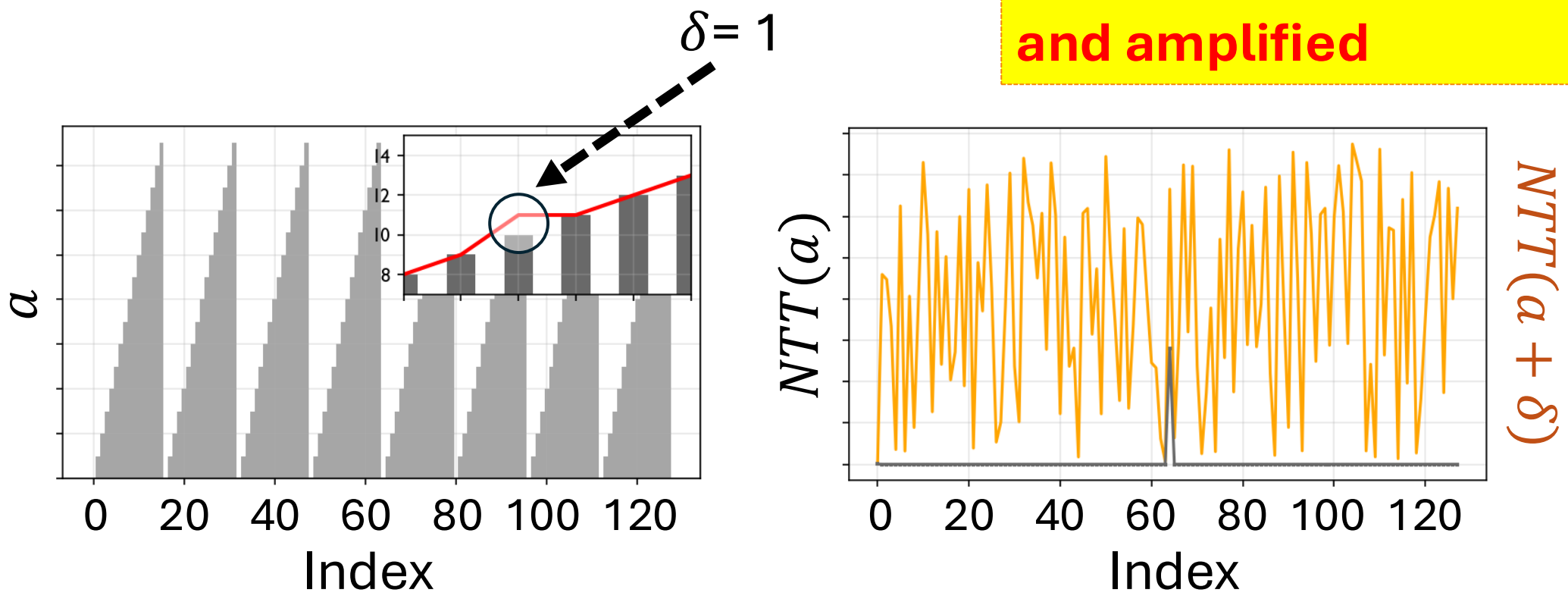
$\Sigma_{c2} \neq a_8 + a_9 + a_{10} + a_{11}$

Arithmetic Kernel-(i)NTT



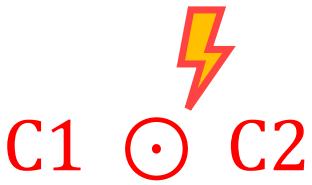
Arithmetic Kernel-(i)NTT

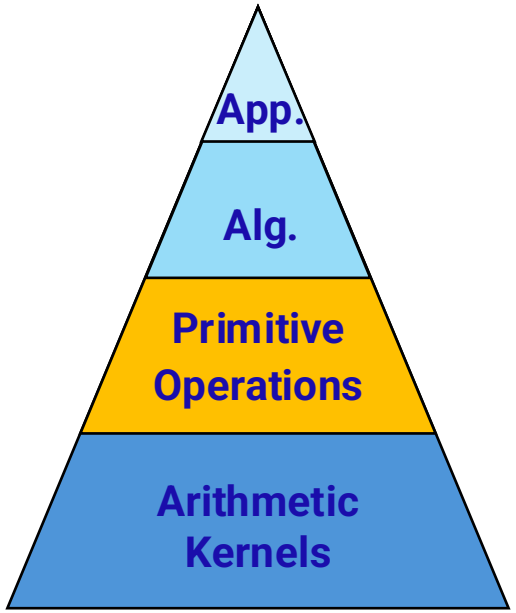
Error been broadcasted and amplified



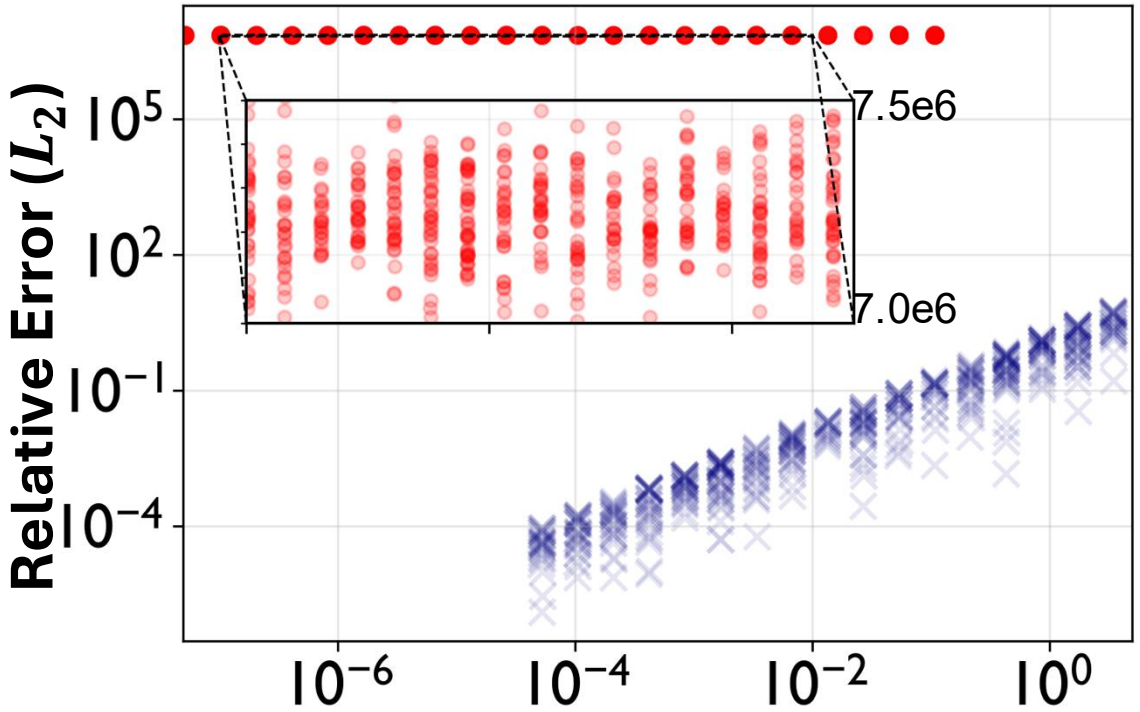
Primitive Operations-Hadamard Product

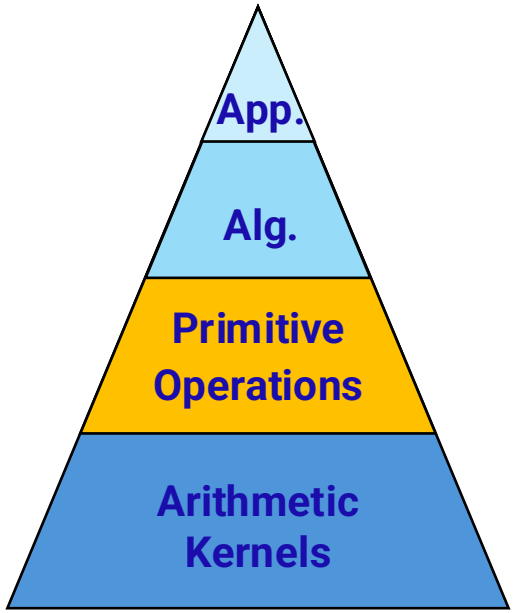
Versus



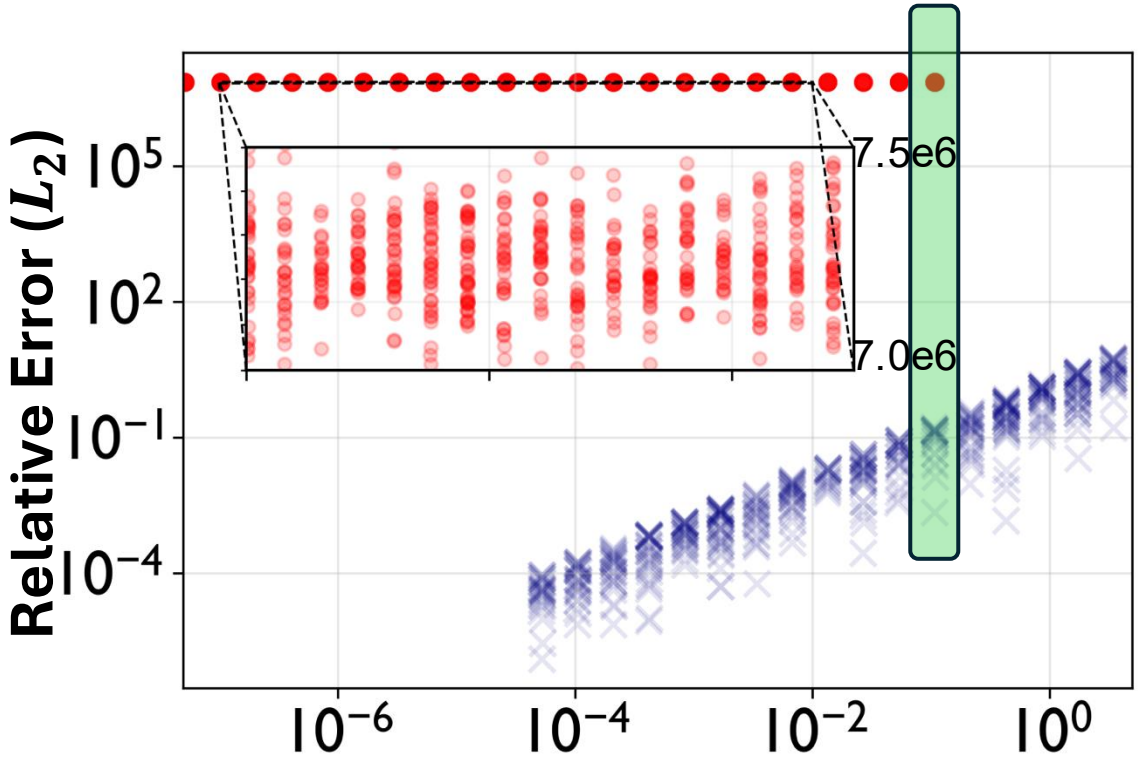


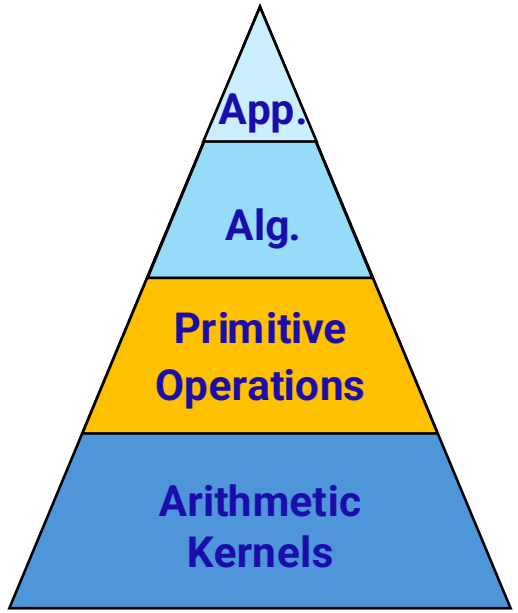
Primitive Operations-Hadamard Product



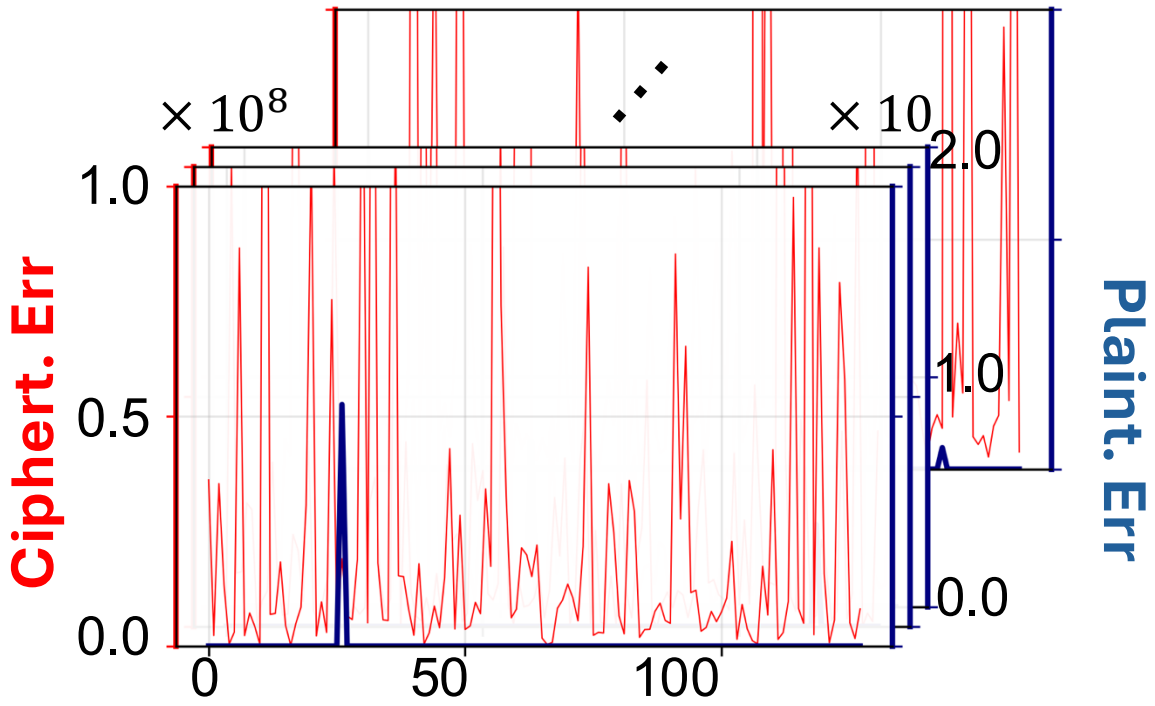


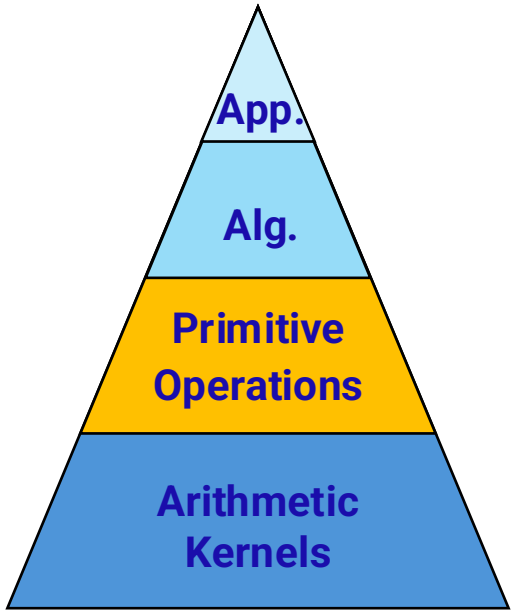
Primitive Operations-Hadamard Product



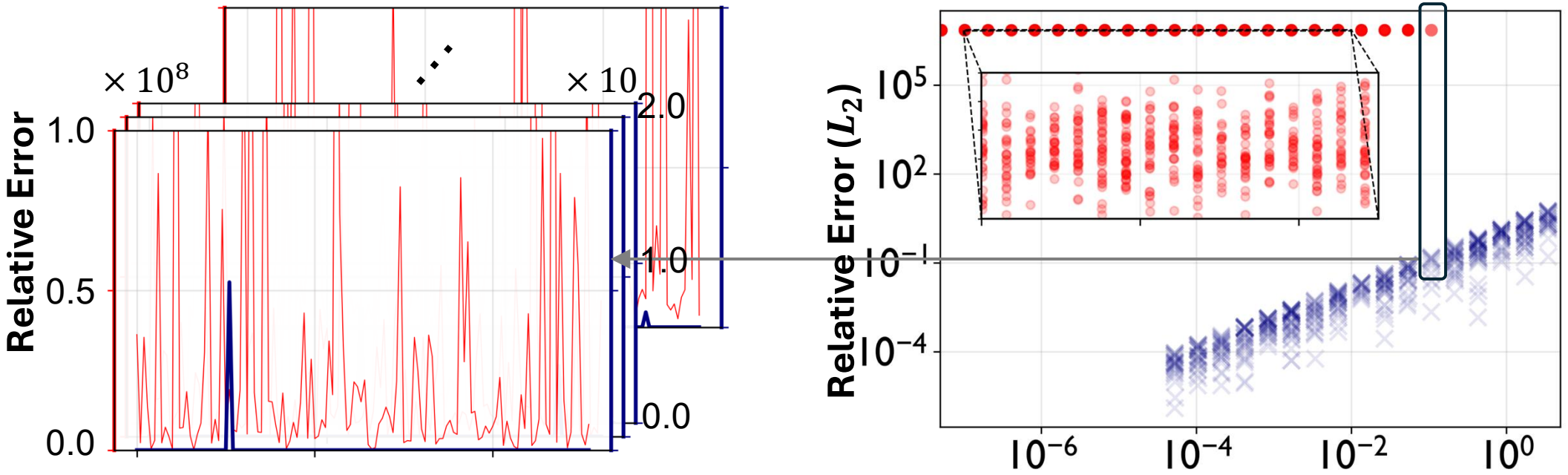


Primitive Operations-Hadamard Product





Primitive Operations-Hadamard Product



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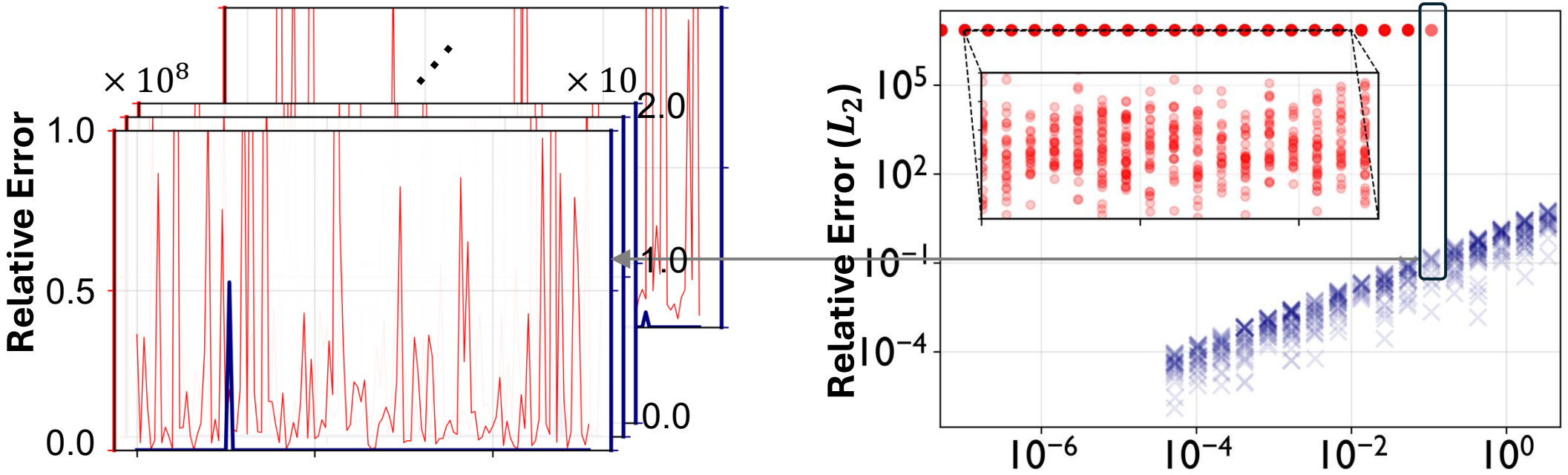
Primitive Operations-Hadamard Product

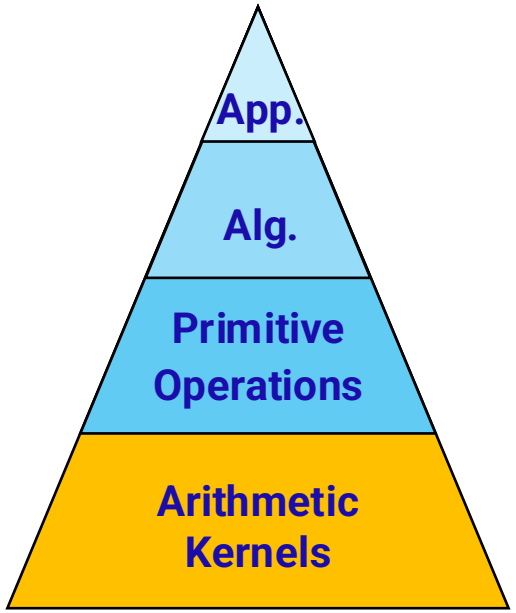


Error been broadcast to all elements

ASPLOS

Arithmetic Kernel-BaseConversion

$$[\mathbf{a}]_{\mathcal{B}} = FastBaseConv_{\{\mathcal{C}\to\mathcal{B}\}}([\mathbf{a}]_{\mathcal{C}}) = \sum_{i=0}^{L}\left([\mathbf{a}]_{q_i}\cdot\frac{q_i}{Q}mod q_i\right)\cdot\frac{Q}{q_i}mod p_j$$



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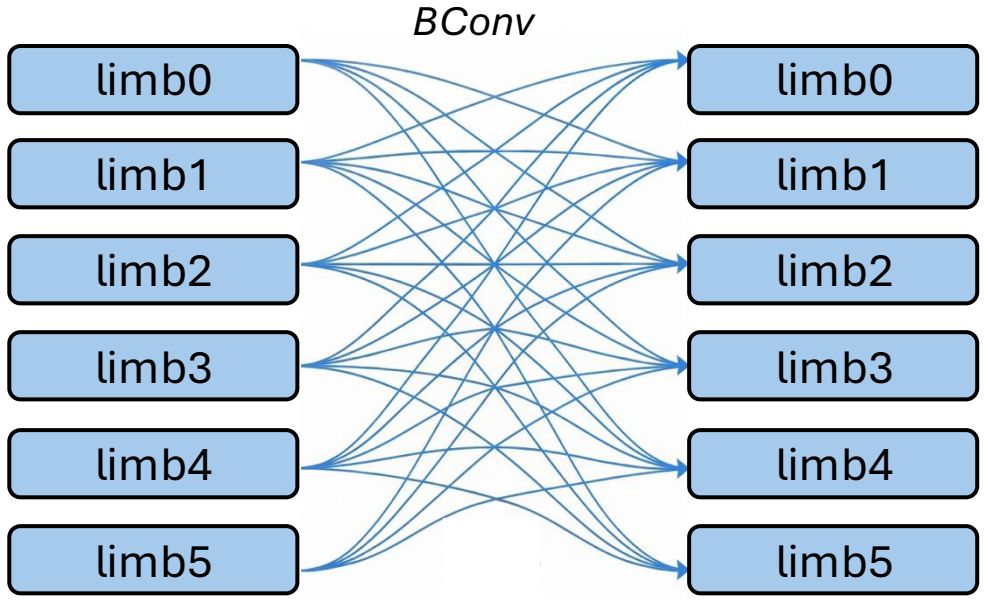

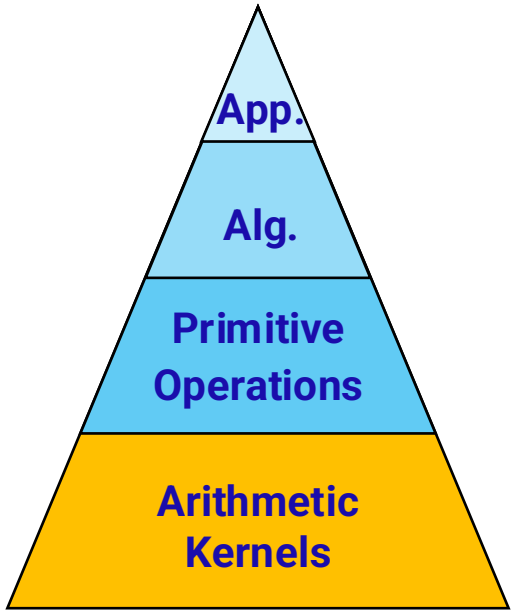

Arithmetic Kernel-BaseConversion

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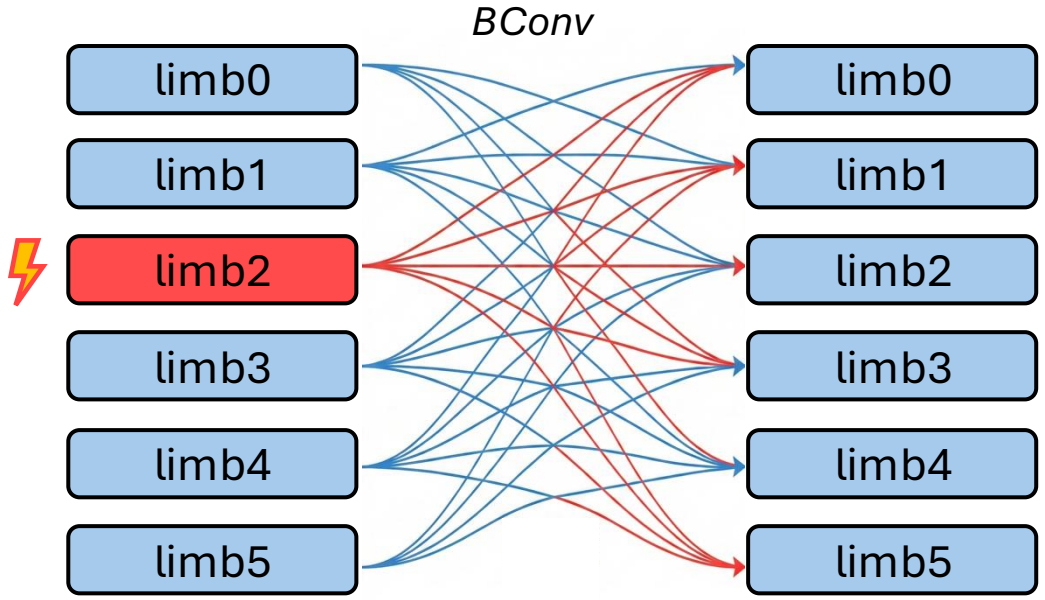

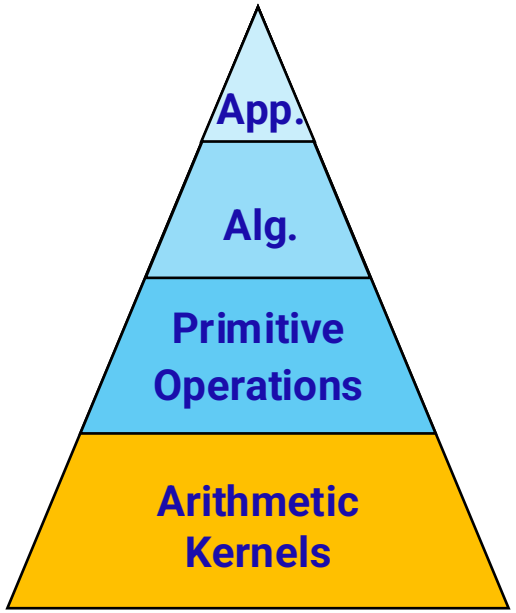

Arithmetic Kernel-BaseConversion

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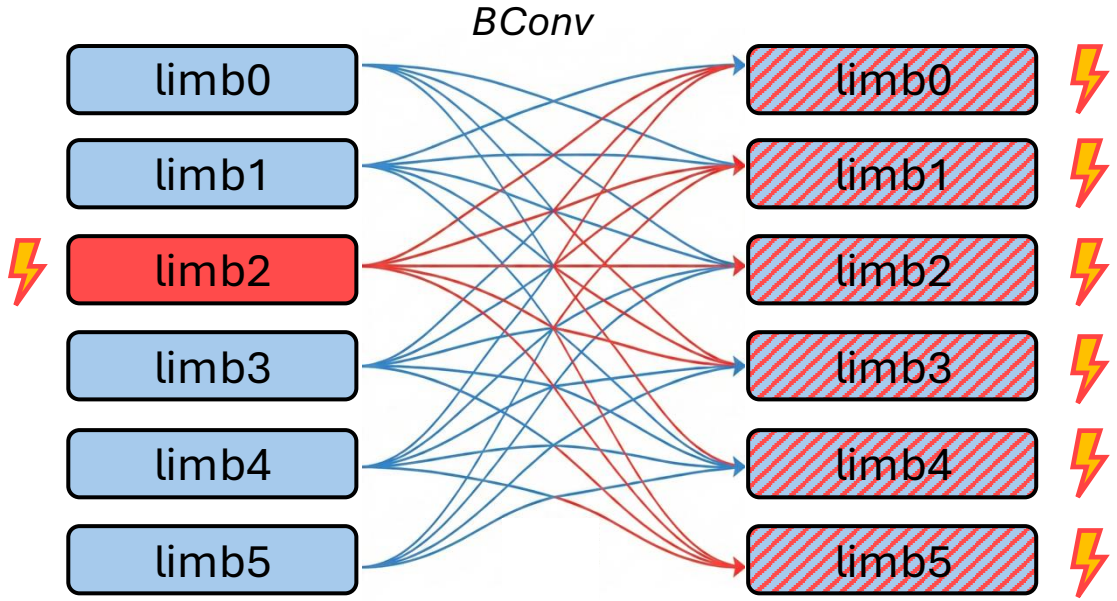

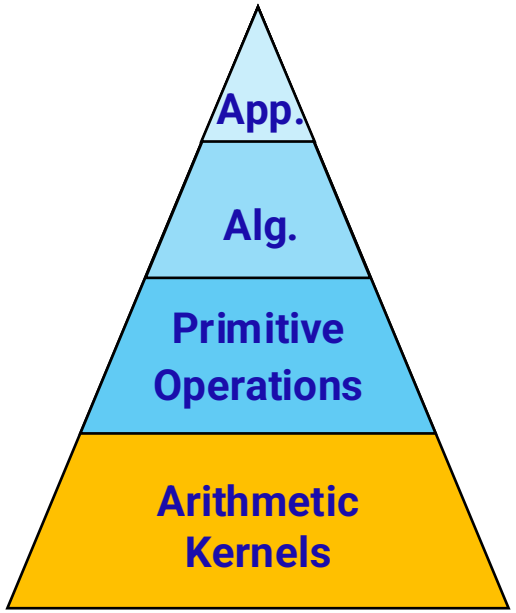

Error been broadcast to all limbs

Elementwise Operation -- Modulus

Algorithm 1 Resilient Barrett Reduction ($\mathbf{c} \equiv \mathbf{t} \bmod q$)

Notation: modulus q; $\mathbf{t} \in \mathbb{Z}_{2^{2K}}^{N}$

Precomputed: $K = \lceil \log_2 q \rceil$, $\mu = \lfloor 2^{2K}/q \rfloor$

Input: $\mathbf{t}$, t_{tot}; **Output:** $\mathbf{c}$, c_{tot},

1: **procedure** RELIA-BARRETT-REDUCE($\mathbf{t}, t_{tot}$)
2: **for** each t_i in $\mathbf{t}$ **do**
3: $s_i \leftarrow (t_i \times \mu) \gg 2K$
4: $c_i \leftarrow t_i - s_i \times q$
5: **if** $c_i \geq q$ **then** $c_i \leftarrow c_i - q$ **end if**
6: **assert** $0 \leq c_i < q$ //range check
7: **end for**
8: $c_{tot} \leftarrow t_{tot} \pmod q$
9: **assert** $c_{tot} == \sum \mathbf{c}$ //verify inter-elem sum
10: **return** $\mathbf{c}, c_{tot}$
11: **end procedure**