Revisiting Residue Codes for Modern Memories

Evgeny Manzhosov

Adam Hastings, Meghna Pancholi, Ryan Piersma, Mohamed Tarek Ibn Ziad, and Simha Sethumadhavan

Department of Computer Science
Columbia University

CS@CU COMPUTER SCIENCE

A New Way to Store Metadata

PERFORMANCE

A New Way to Store Metadata

PERFORMANCE

SECURITY
RELIABILITY

A New Way to Store Metadata

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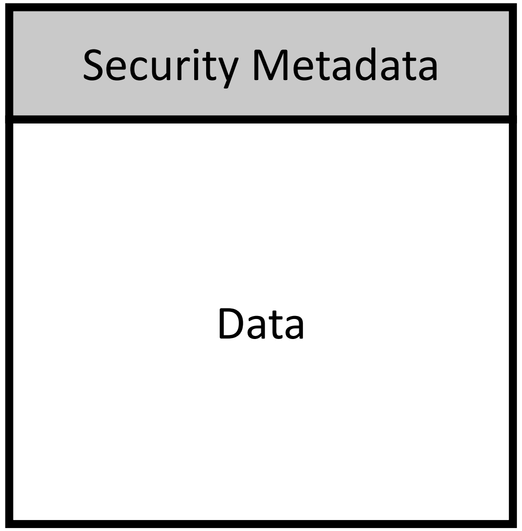

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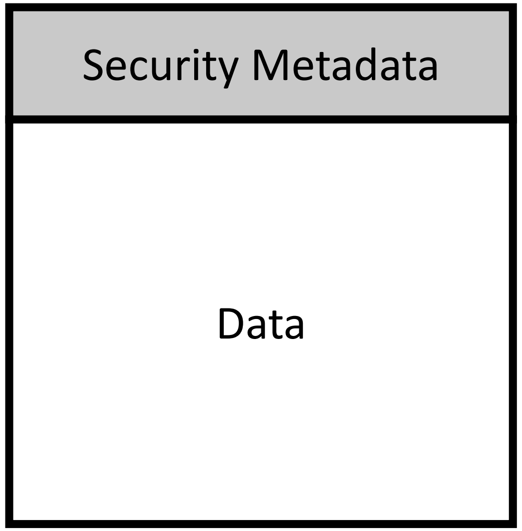

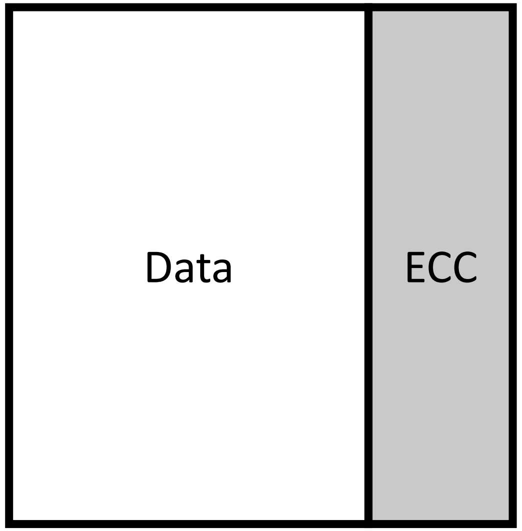

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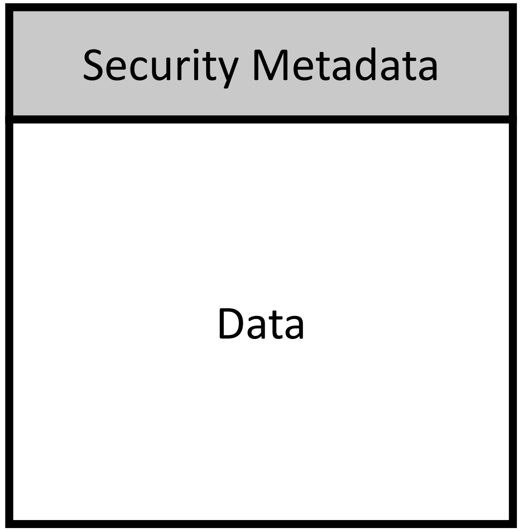

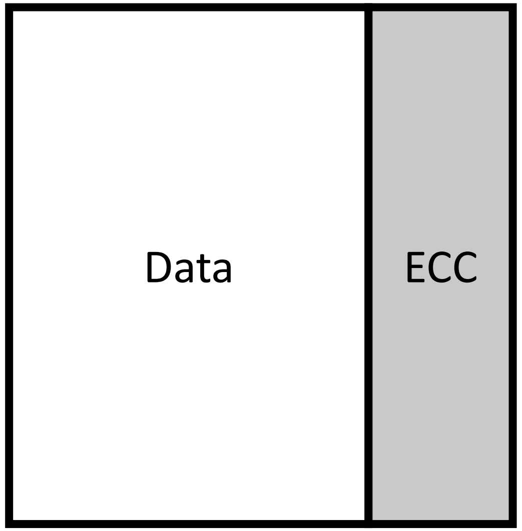

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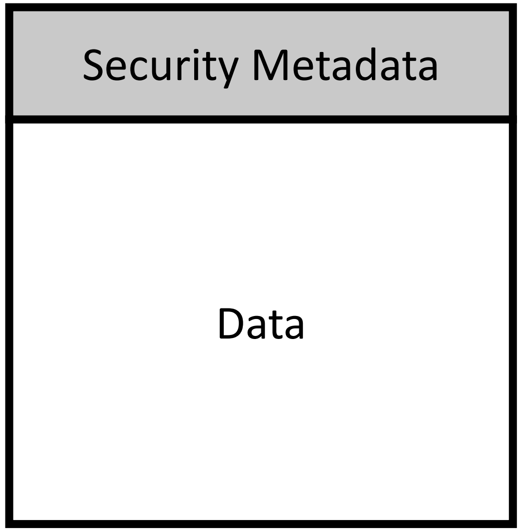

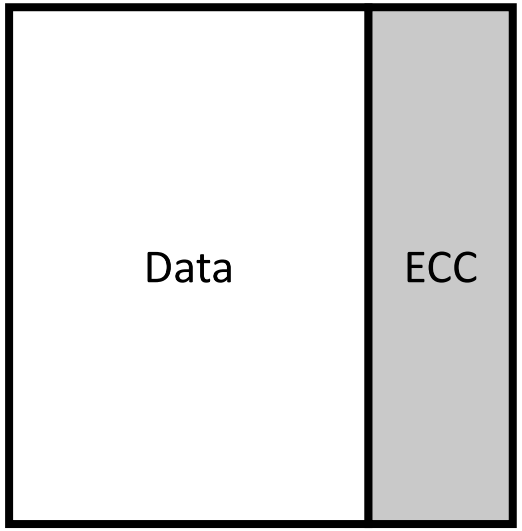

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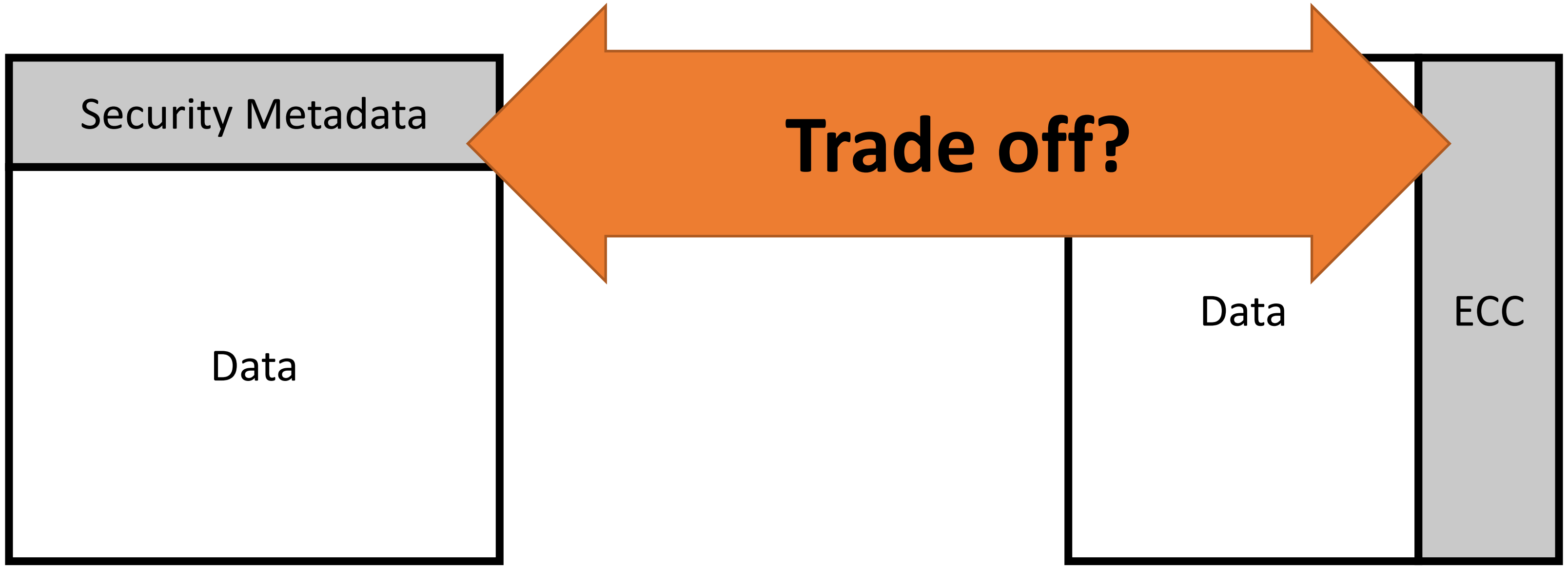

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  - Rowhammer defense w/ 40b hash w/o giving up on reliability

Talk Outline

- ChipKill with MUSE ECC

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- Use Cases:
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MUSE ECC

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$data$

MUSE ECC

$$codeword = data \times m$$

MUSE ECC

$$codeword = data \times m$$

Store To Memory

MUSE ECC

$$codeword = data\times m$$

Store To Memory

Read From Memory

MUSE ECC

$$codeword = data \times m$$

Store To Memory

$$remainder = codeword \bmod m$$

Read From Memory

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$$data = \begin{cases} codeword/m & remainder = 0 \\ & \end{cases}$$

Read From Memory

MUSE ECC

$$codeword = data \times m$$

Store To Memory

$$remainder = codeword \bmod m$$

$$data = \begin{cases} codeword/m & remainder = 0 \\ error & else \end{cases}$$

Read From Memory

MUSE ECC

$$\#(unique\ remainders) \equiv \#(all\ errors)$$

$$Single\ Error\ Correction$$

What is ChipKill?

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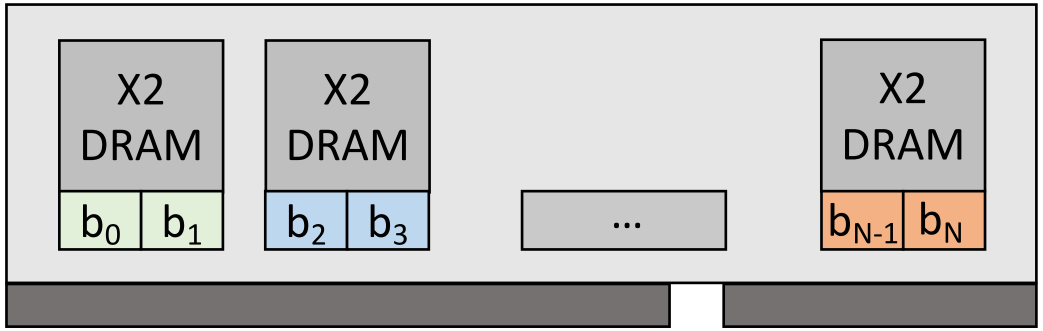

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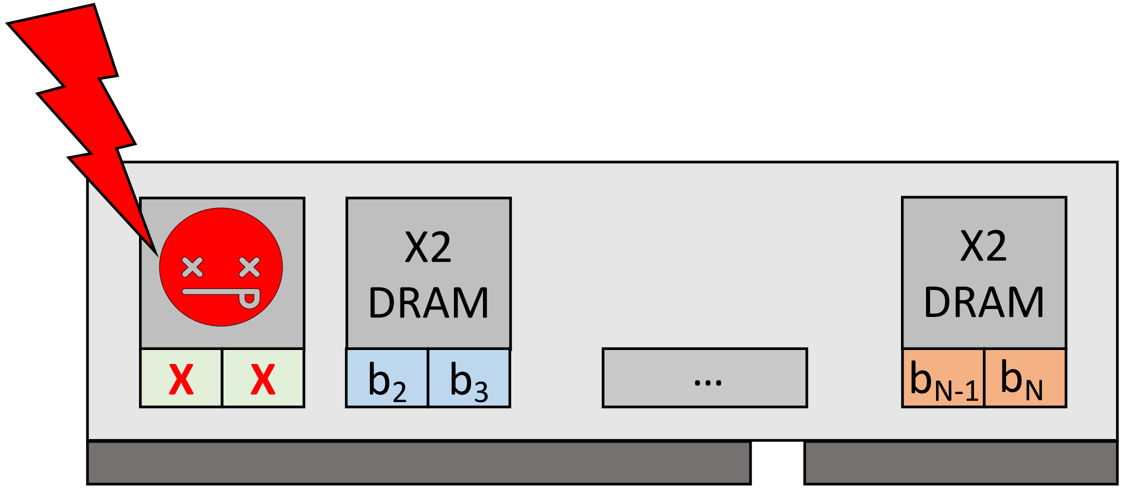

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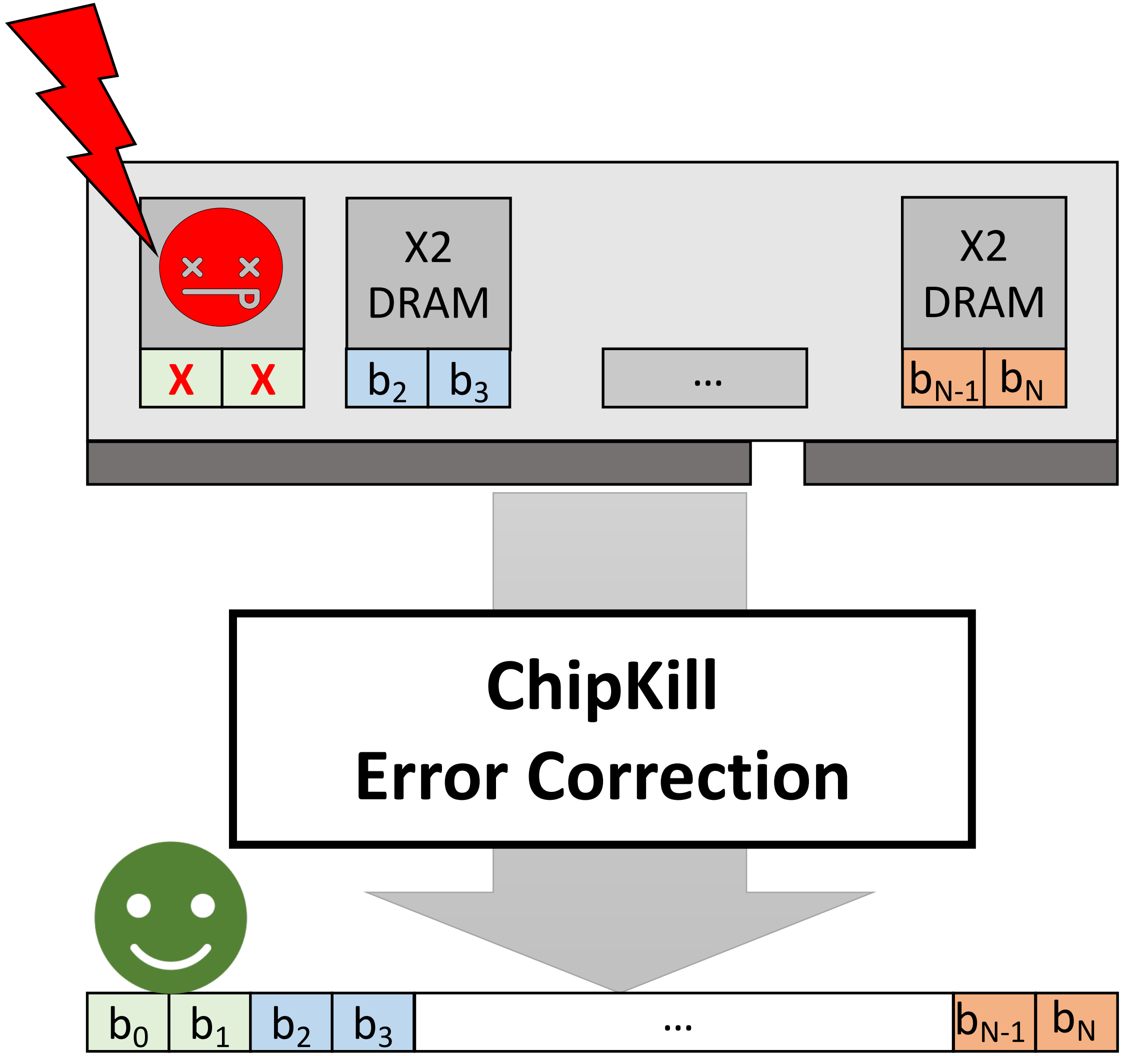
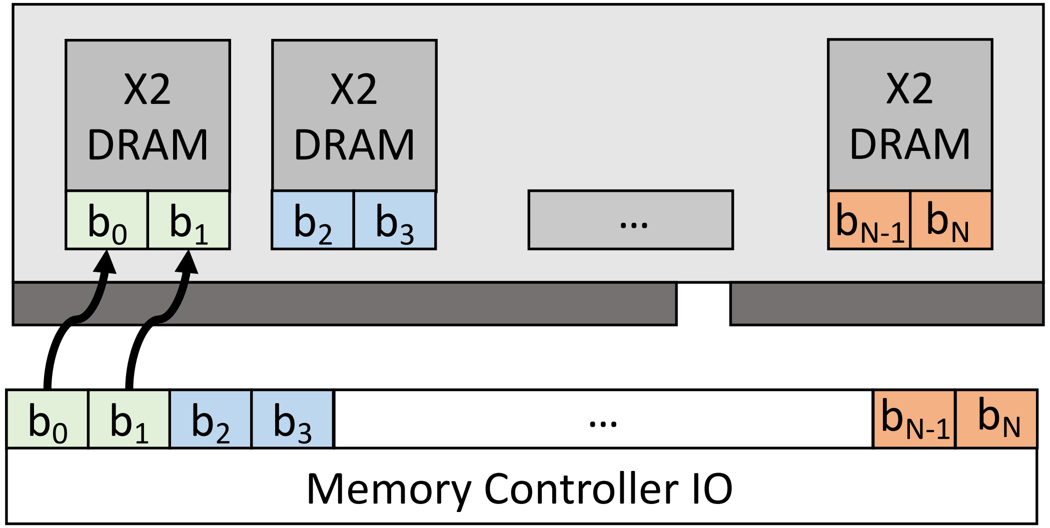


ChipKill with MUSE ECC



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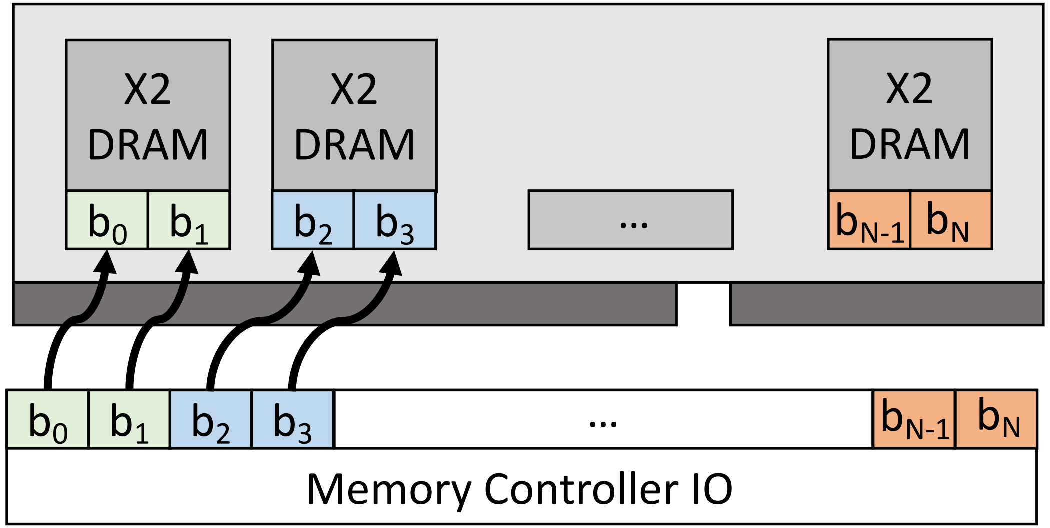

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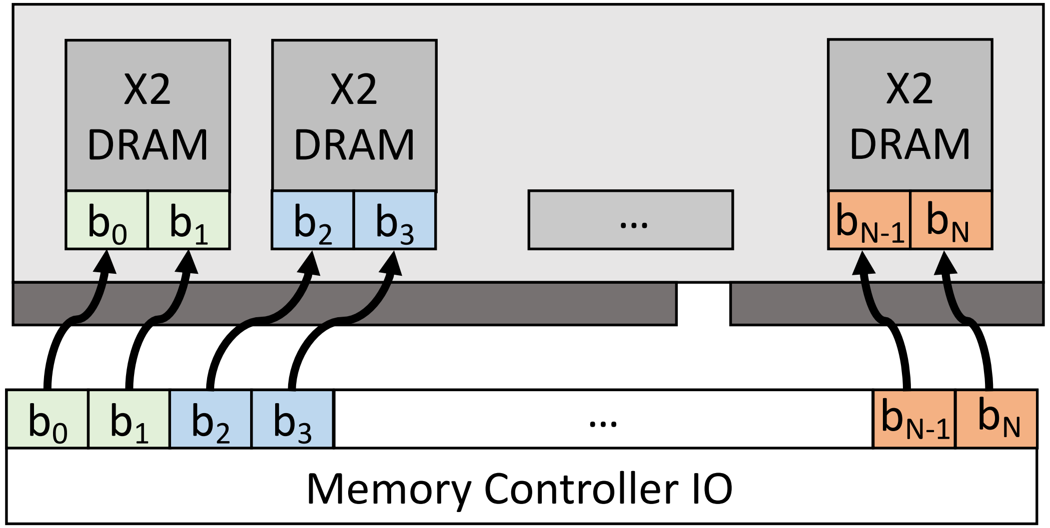

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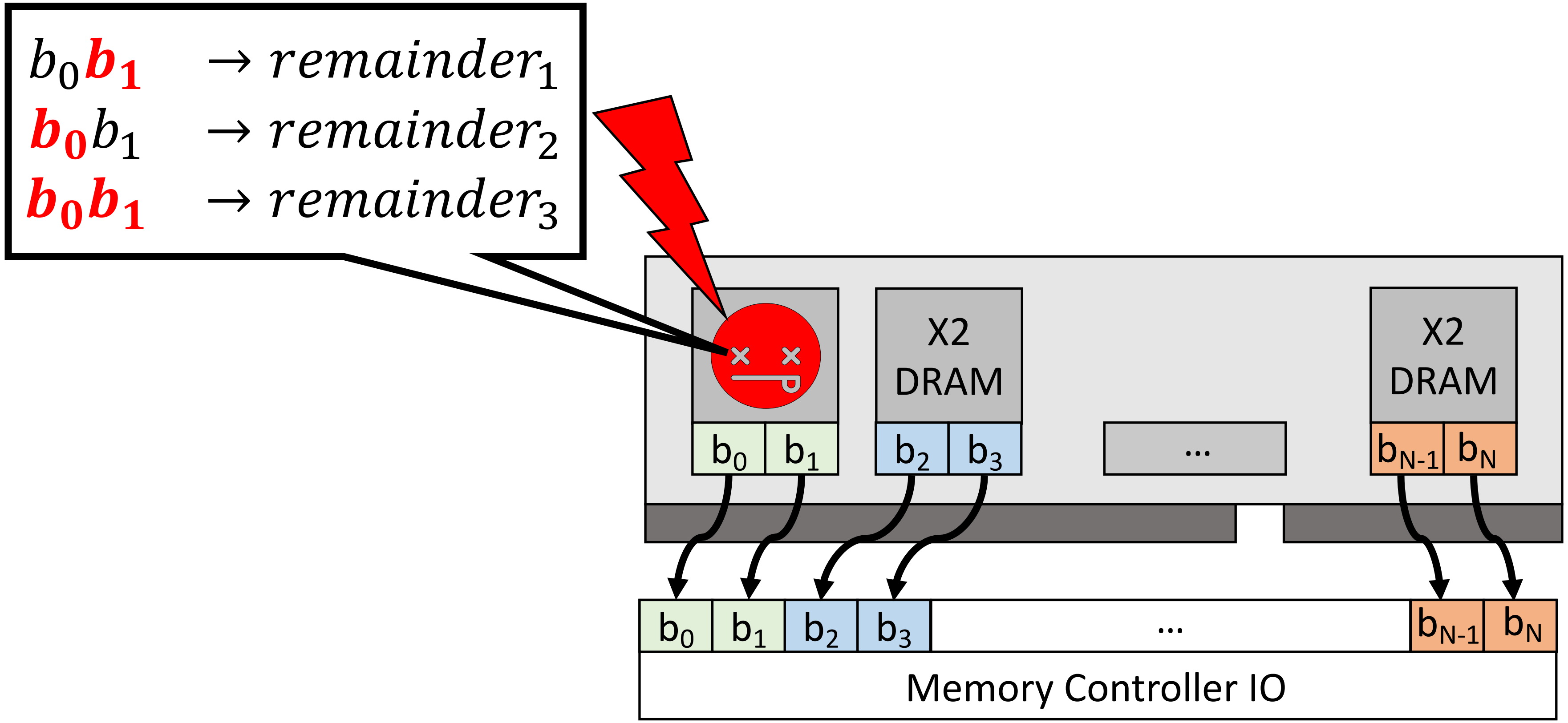

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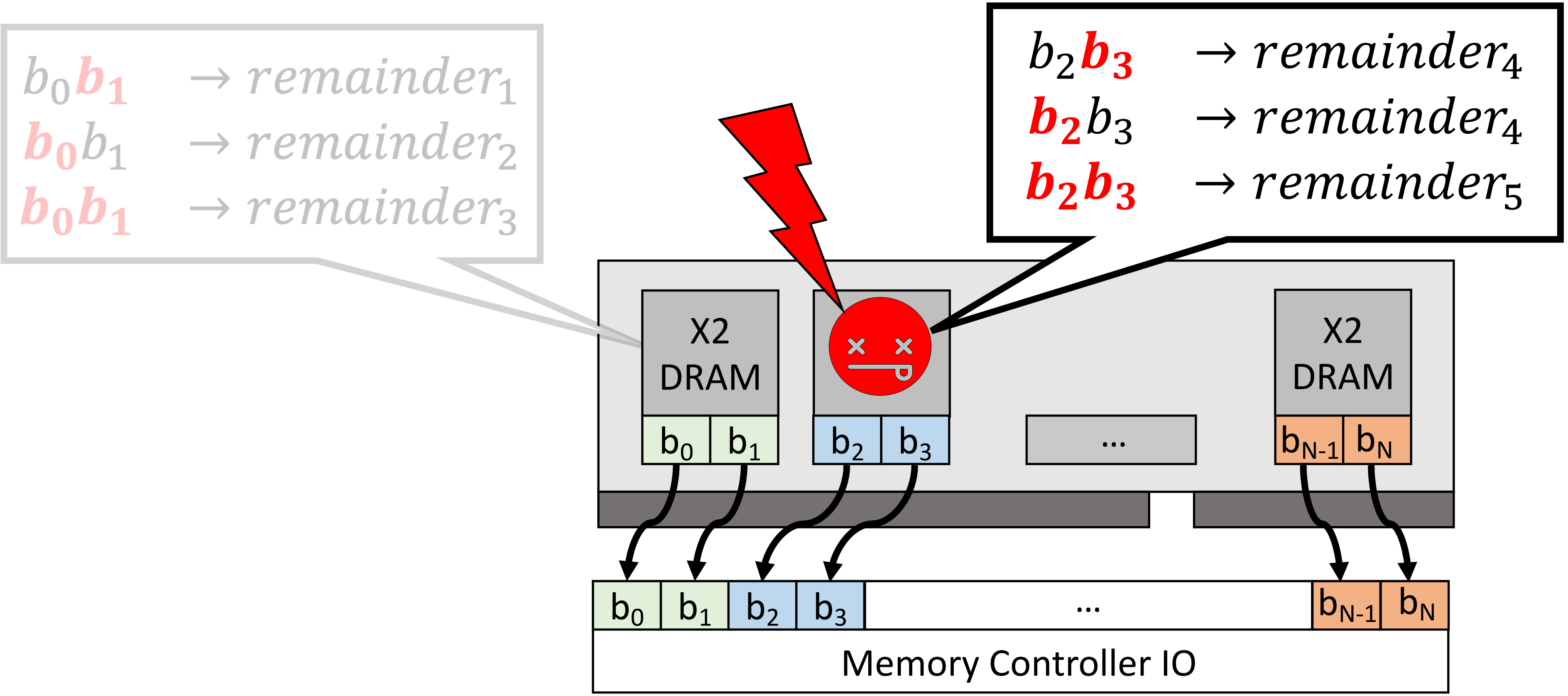

ChipKill with MUSE ECC

$$\#(unique\ remainders) \equiv \#(all\ symbol\ errors)$$

$$ChipKill$$

ChipKill with MUSE ECC

$$\#(unique\ remainders) \equiv \#(all\ symbol\ errors)$$

12b instead of 16b

DDR4 MUSE: 25% fewer ECC bits

MUSE ECC: Shuffling

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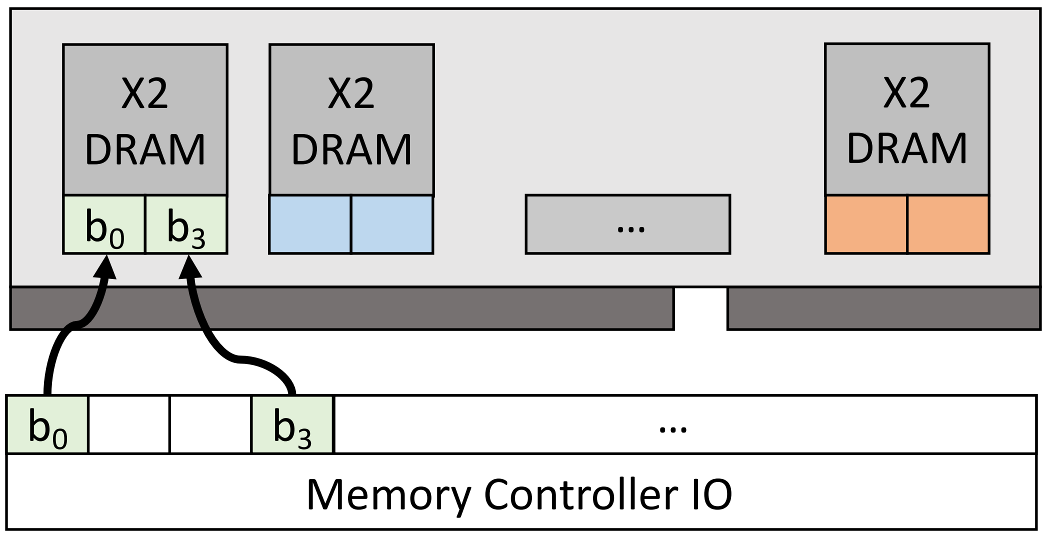
$$remainder(\boldsymbol{error_1}) = remainder(\boldsymbol{error_2})$$

$$\Downarrow$$

$$\cancel{ChipKill}$$

MUSE ECC: Shuffling



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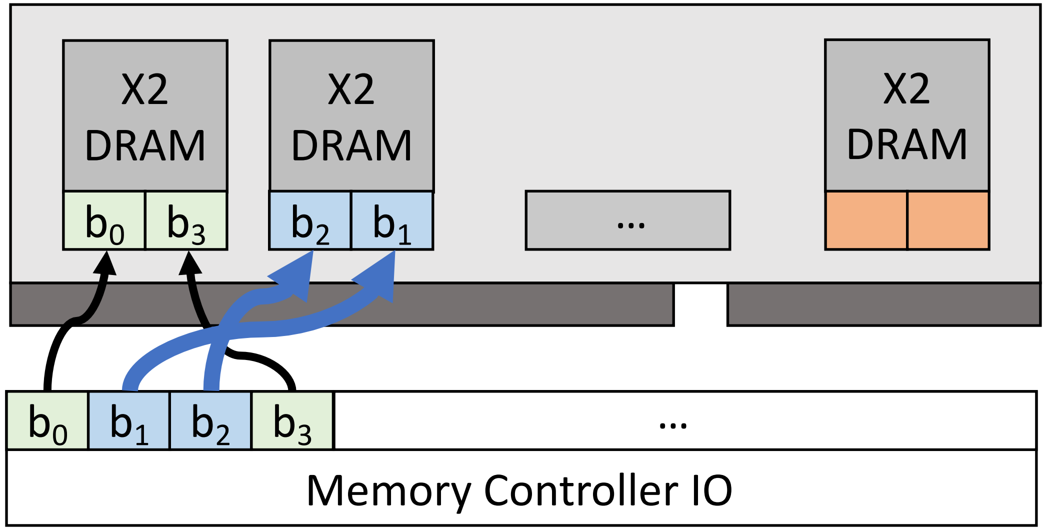

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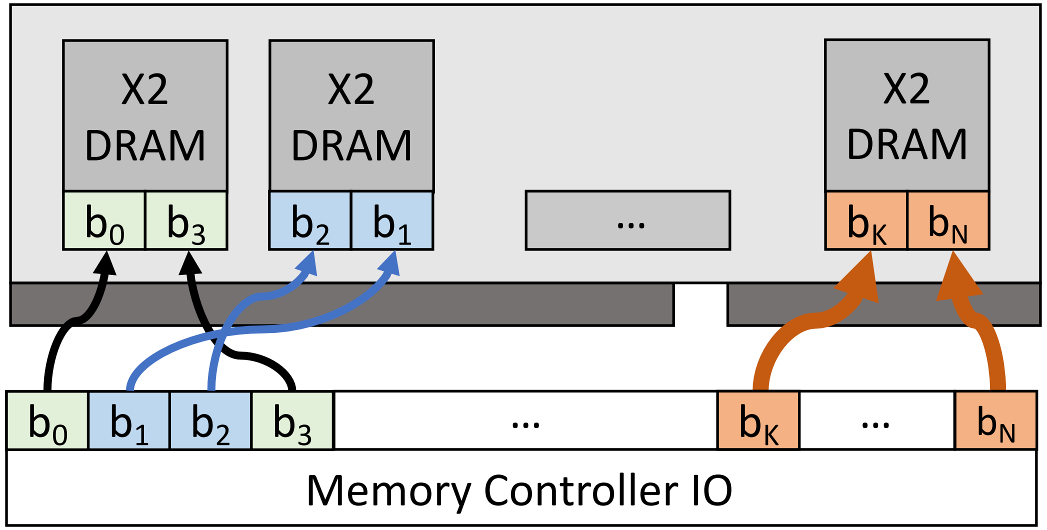

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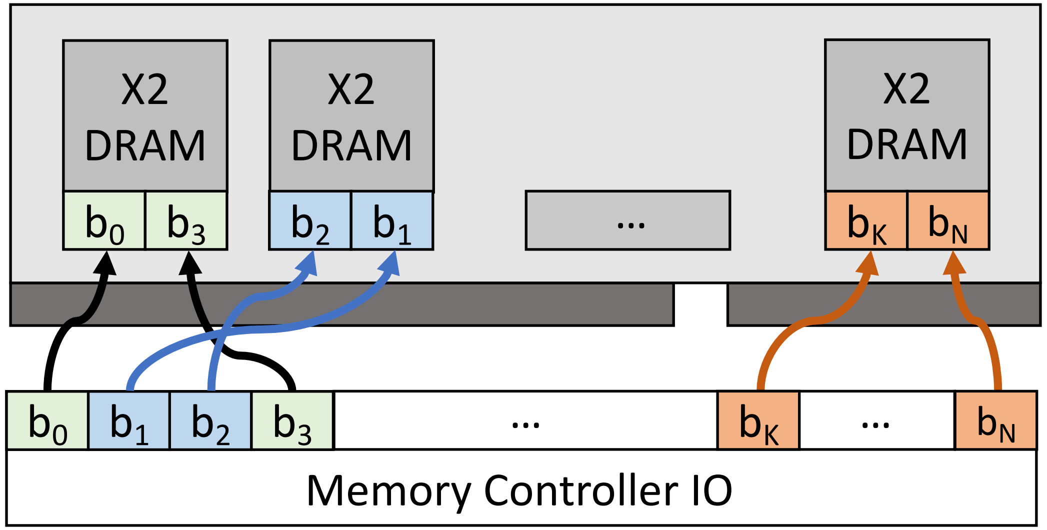

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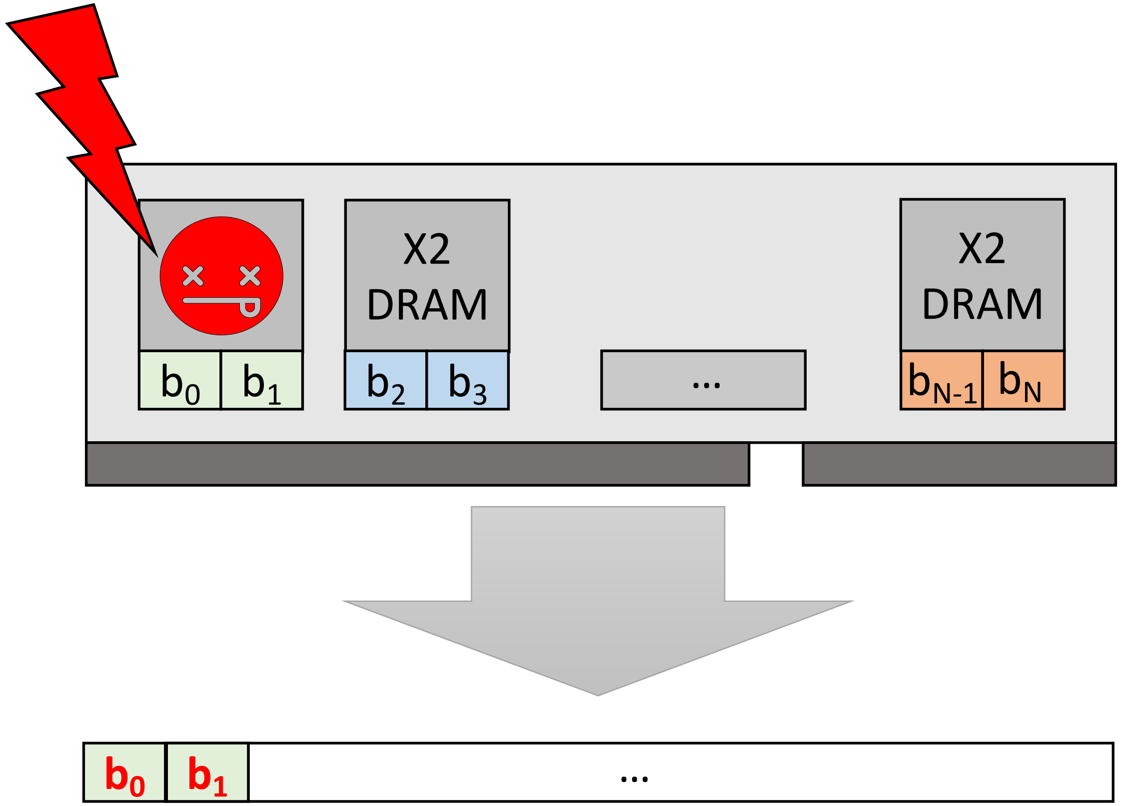
MUSE Chip Kill



MUSE ECC: Shuffling

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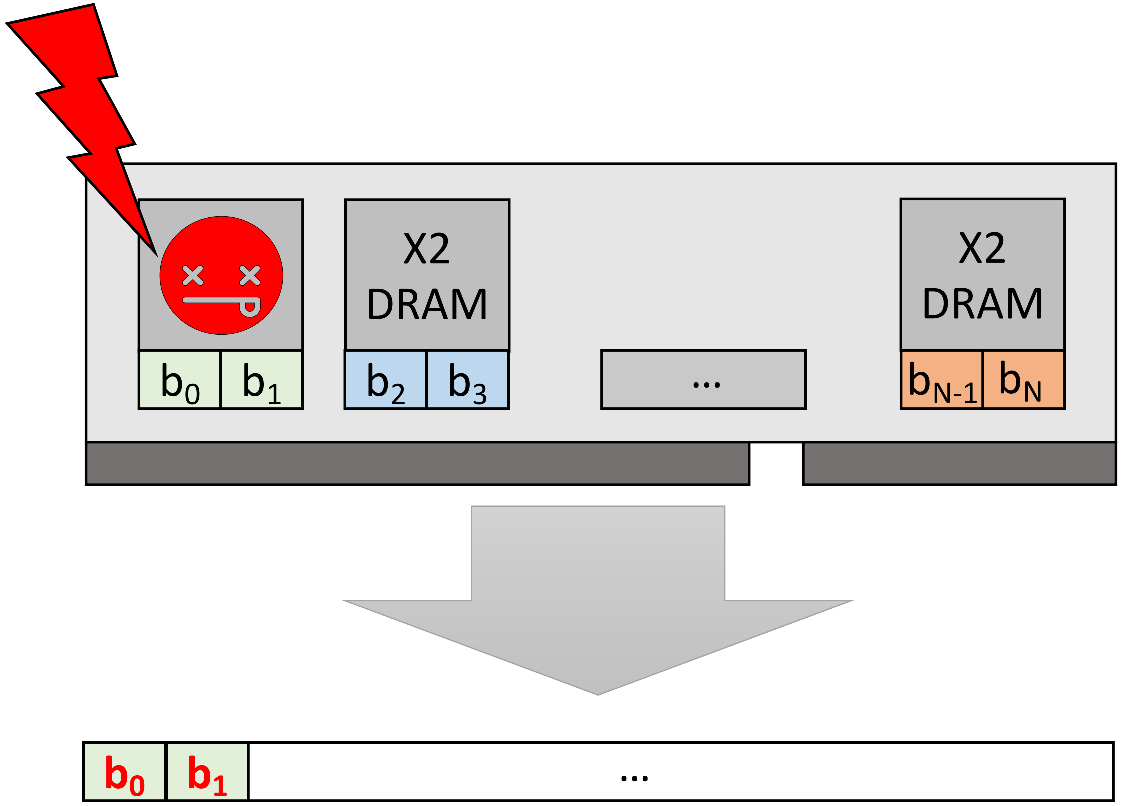
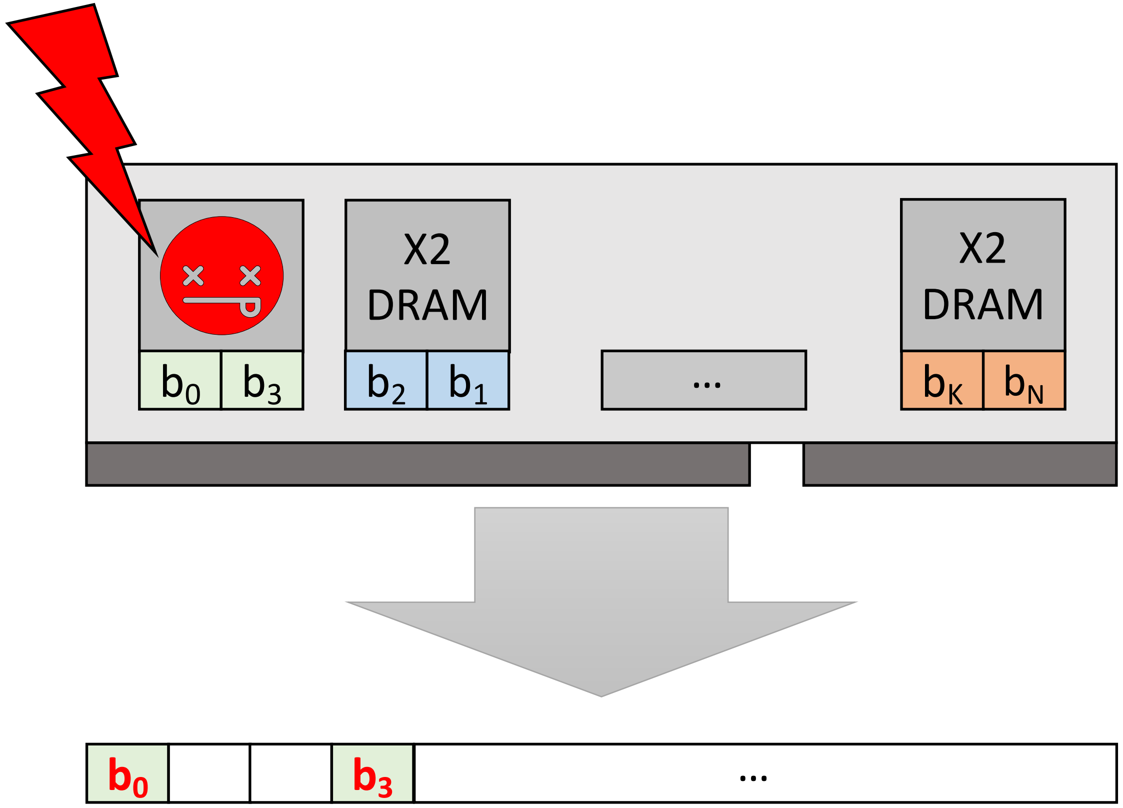


MUSE ChipKill w/ Shuffling



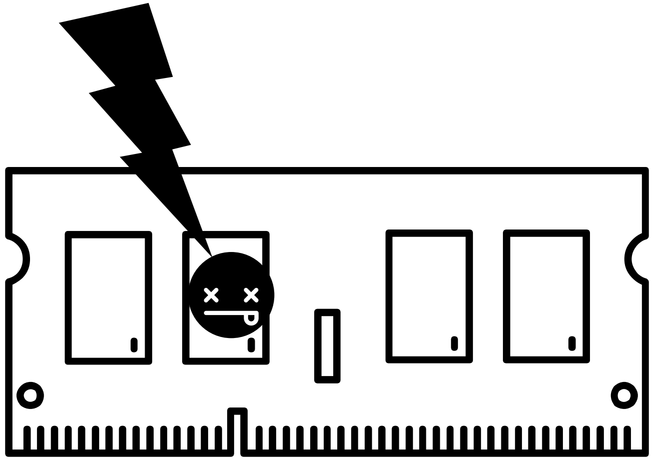
MUSE ECC: Shuffling

$$\#(unique\ remainders) \equiv \#(all\ symbol\ errors)$$

$$ChipKill$$

MUSE (Multi-Use) ECC

ChipKill Guarantees



Multi-Use (MUSE) ECC

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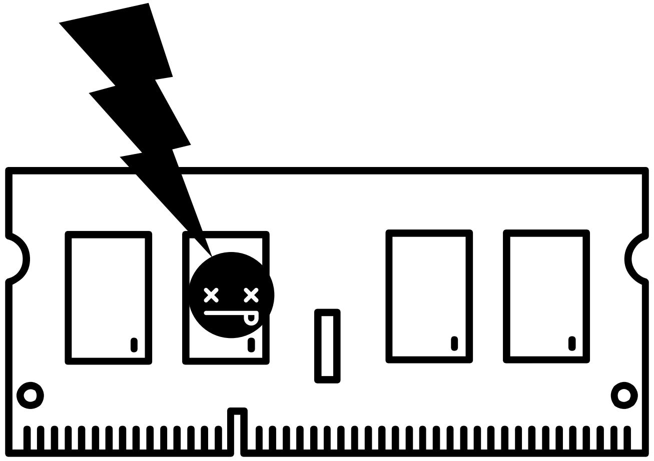
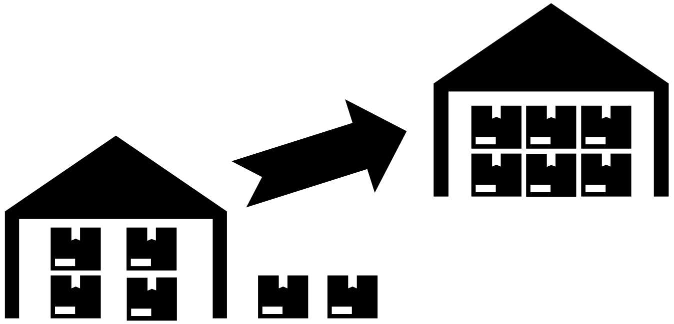


Storage Efficient



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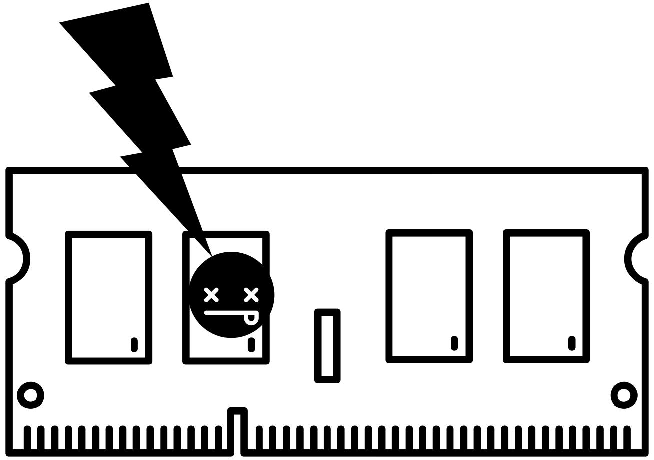

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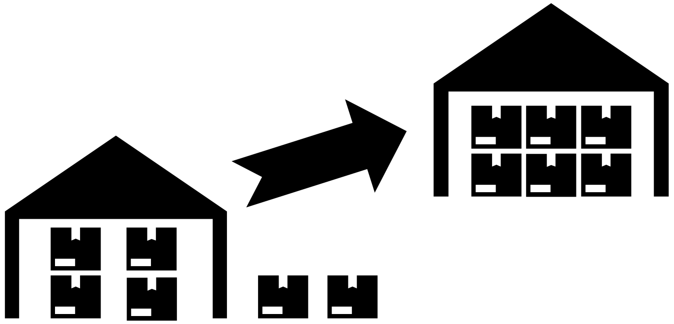
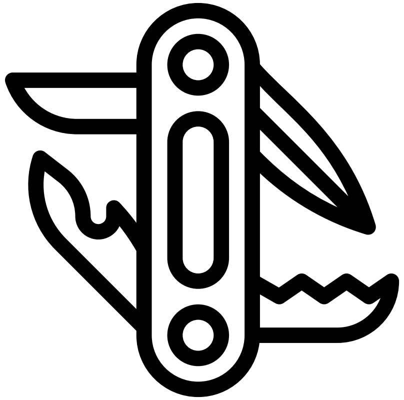


Flexible



Outline

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- Use Cases:
  - Rowhammer defenses
  - PIM Reliability
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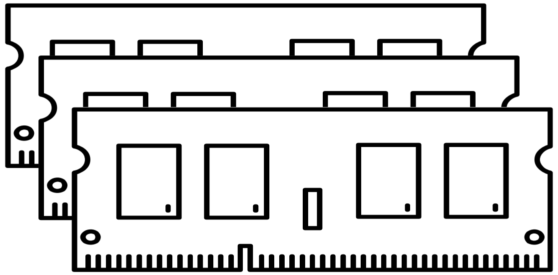
Use Cases

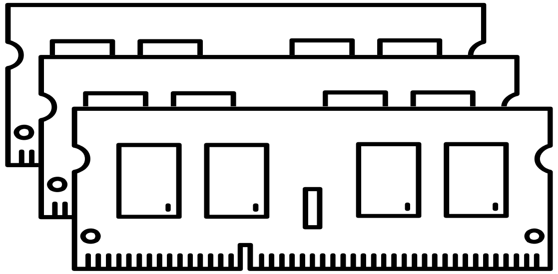
Use Case 1: Rowhammer Defense



DDR5 w/
128B Cache Lines

80b channel

Use Case 1: Rowhammer Defense



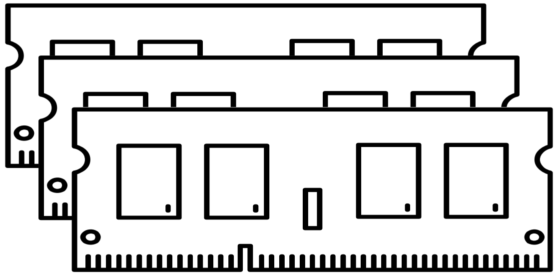
**DDR5 w/
128B Cache Lines**

+

MUSE(80,69) ECC

80b codeword with 64b data and 5b metadata

Use Case 1: Rowhammer Defense



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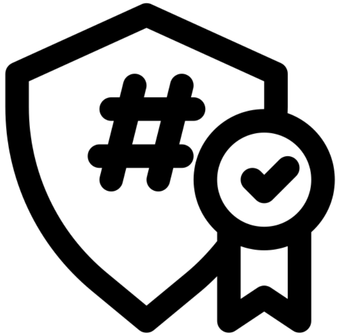
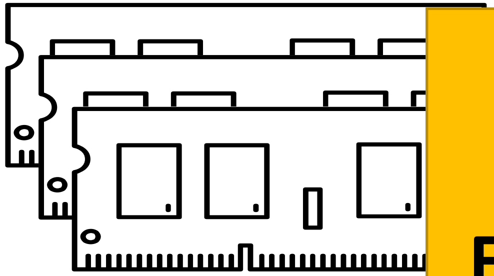
=



40b hash for
64B data

40b aggregated across 8 DRAM transactions

Use Case 1: Rowhammer Defense

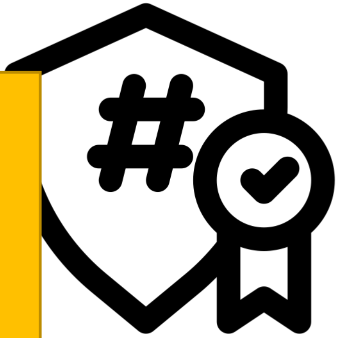


DDR5 w/

128B Cache Lines

Chance of successful attack is 2^{-40}

Faking hash value will take a lot of time [1]



b hash for

64B data

[1]: Exploiting correcting codes: On the effectiveness of ECC memory against rowhammer attacks.
Cojocar, L., Razavi, K., Giuffrida, C. and Bos, H., In 2019 IEEE Symposium on Security and Privacy.

Use Case 2: Processing-In-Memory

PIM with MUSE:

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✓**Single code for both storage and arithmetic reliability**

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✓**Single code for both storage and arithmetic reliability**

✓**ECC check is done in parallel to compute**

Use Case 2: Processing-In-Memory

PIM with MUSE:

- ✓ **Single code for both storage and arithmetic reliability**
- ✓ **ECC check is done in parallel to compute**
- ✓ **Storage efficient: 256b data needs 12b ECC (out of 32b)**

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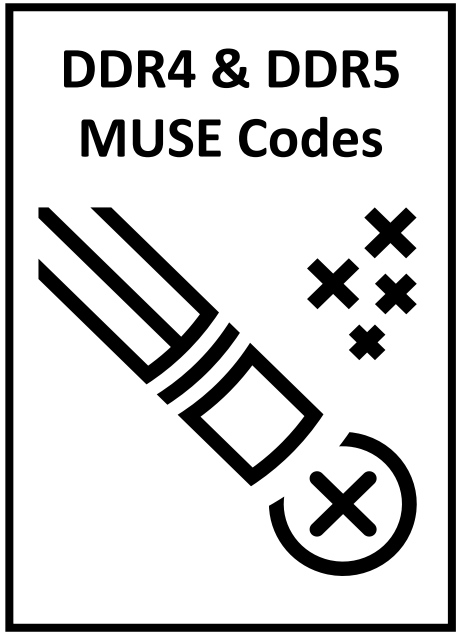
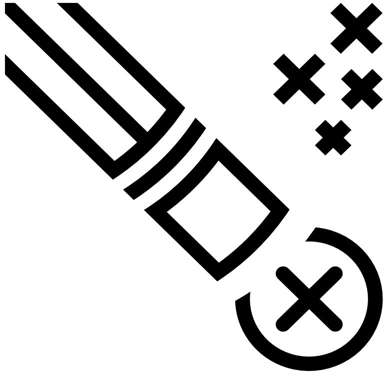
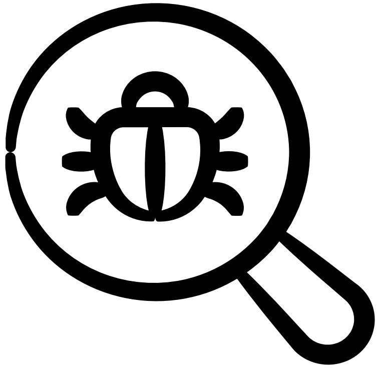


In the paper

DDR4 & DDR5 MUSE Codes



More Case Studies



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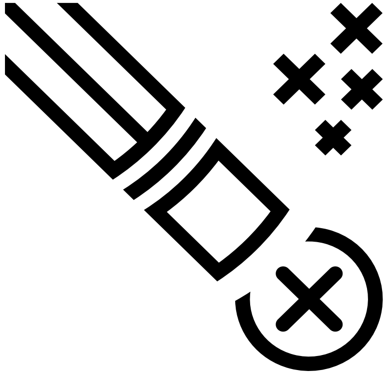

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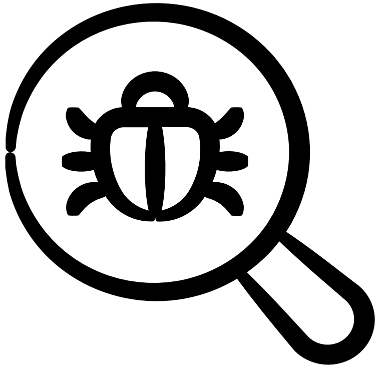
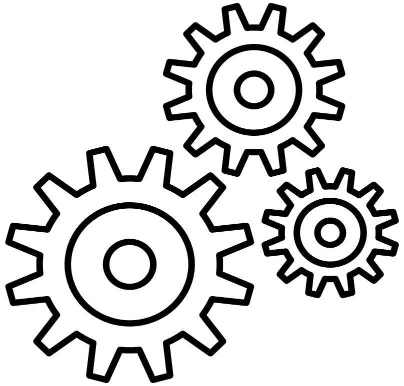


uArch details



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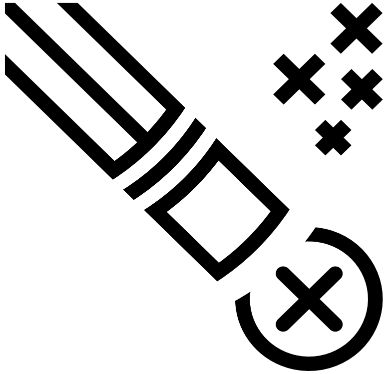

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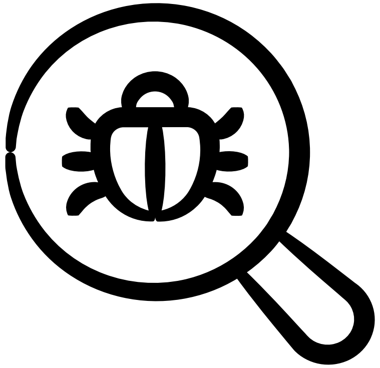

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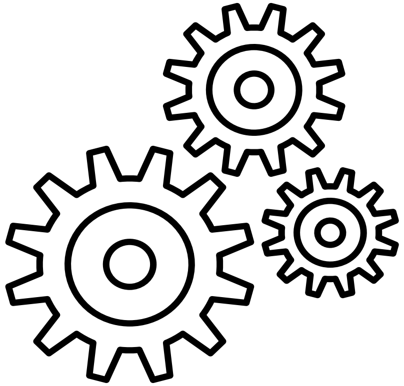
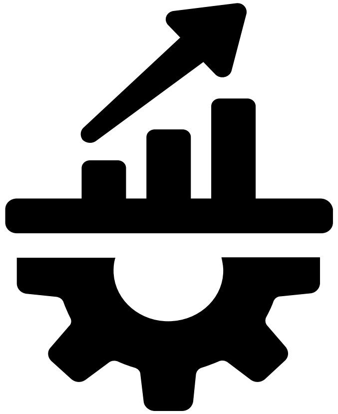


Performance Evaluation



Conclusion

MUSE ECC is the only ECC scheme that:

- Provides ChipKill with only **9.3%** storage overhead
- Offers in-lined metadata storage for any purpose
- Drop-in replacement for existing ECC schemes

Backup slides

Background: Residue Codes

$$codeword\text{: } 1101111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

Background: Residue Codes

LSB MSB

$$codeword': 11{\color{red}1}1111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

Background: Residue Codes

$$codeword': 11\mathbf{\color{red}1}1111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

$$codeword' = codeword + \mathbf{\color{red}2^2}$$

decoding

Background: Residue Codes

$$codeword': 111\mathbf{1}1111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

$$remainder = (codeword + \mathbf{2^2}) \bmod m$$

decoding

Background: Residue Codes

$$codeword': 111\mathbf{1}1111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

$$remainder = (codeword + \mathbf{2^2}) \bmod m = \mathbf{2^2} \bmod m$$

decoding

Background: Residue Codes

$$codeword': 11\mathbf{1}1111 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 11001010$$

$$remainder = \left(codeword + \mathbf{2^2}\right) \mathrm{mod}\ m = \mathbf{2^2} \mathrm{mod}\ m$$

$$remainder \neq 0 \Longrightarrow data = \frac{codeword - f_{err}\left(\mathbf{2^2} mod\ m\right)}{m}$$

decoding

Background: Linearity of Residue Codes

$$(x \ \mathbf{OP} \ y) \bmod M = (x \bmod M \ \mathbf{OP} \ y \bmod M) \bmod M$$

e.g., $(x + y) \bmod M = (x \bmod M + y \bmod M) \bmod M$