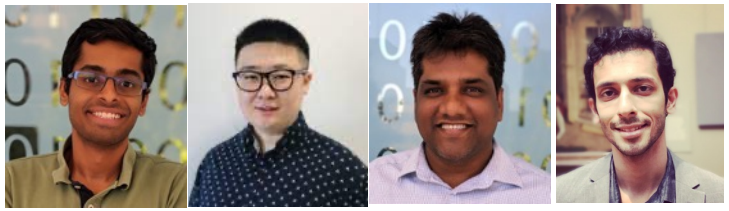
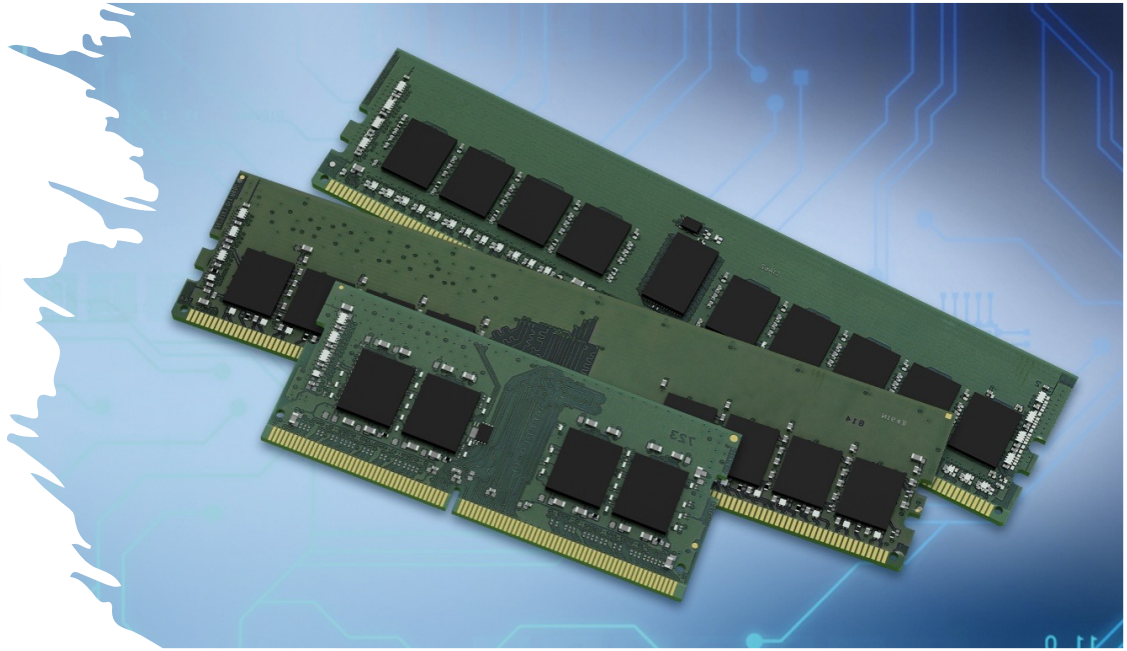
Randomized Row-Swap: Mitigating Row Hammer By Breaking Spatial Correlation Between Aggressor and Victim Rows

Gururaj Saileshwar

Bolin Wang, Moinuddin Qureshi,

Prashant Nair



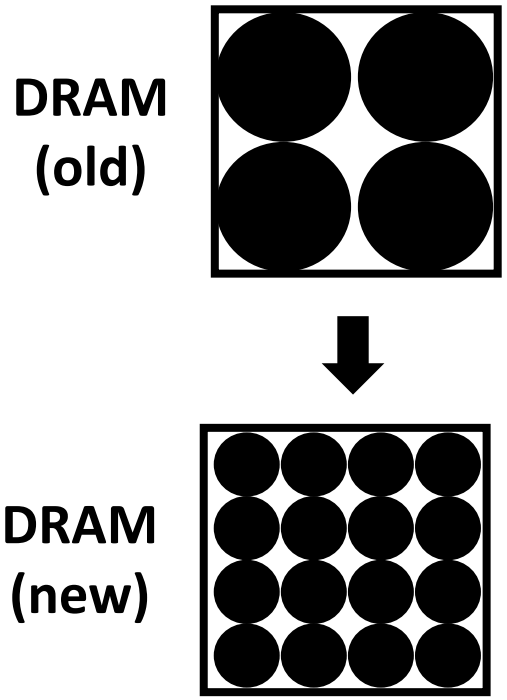


Georgia Tech

UBC THE UNIVERSITY OF BRITISH COLUMBIA

Rowhammer Attacks on DRAM

DRAM Scaling for Increased Capacity



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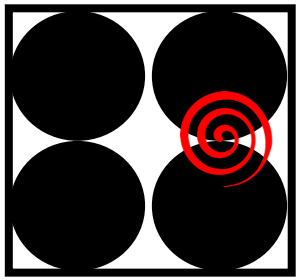
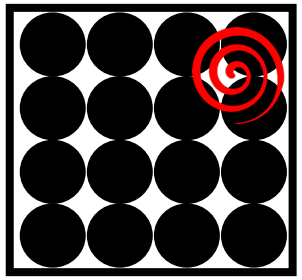
More Inter-Cell Interference

DRAM (old)



DRAM (new)



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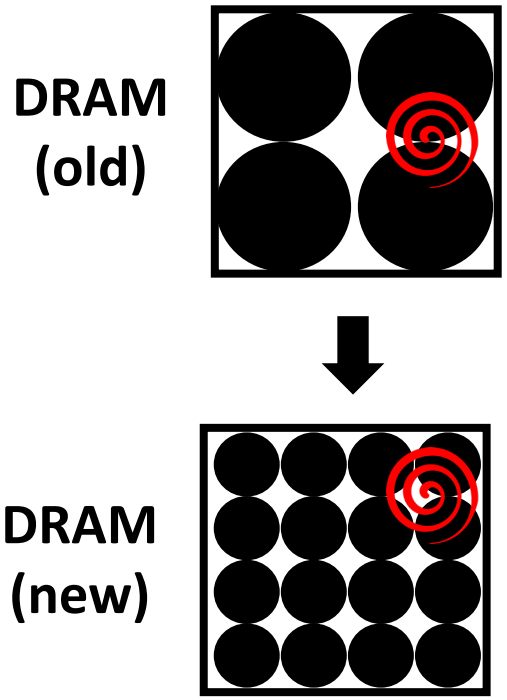

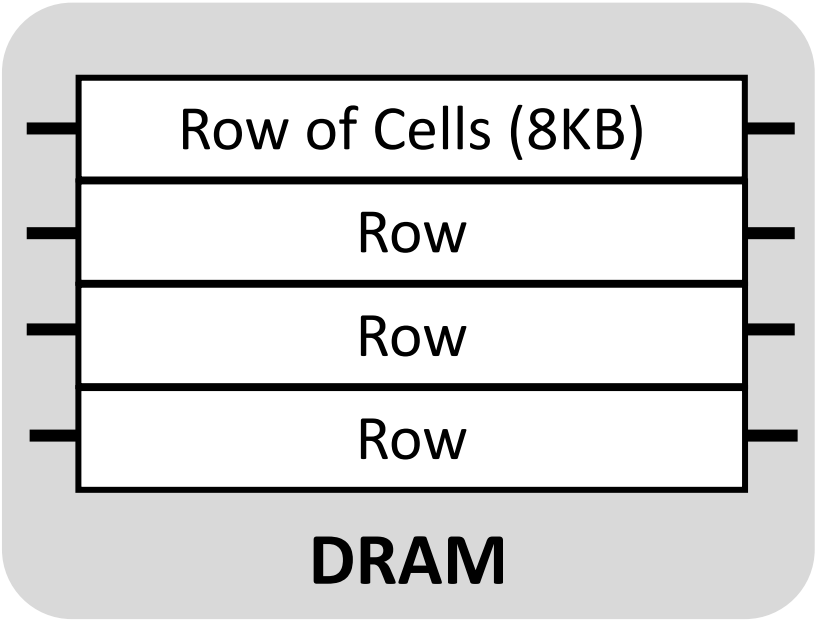

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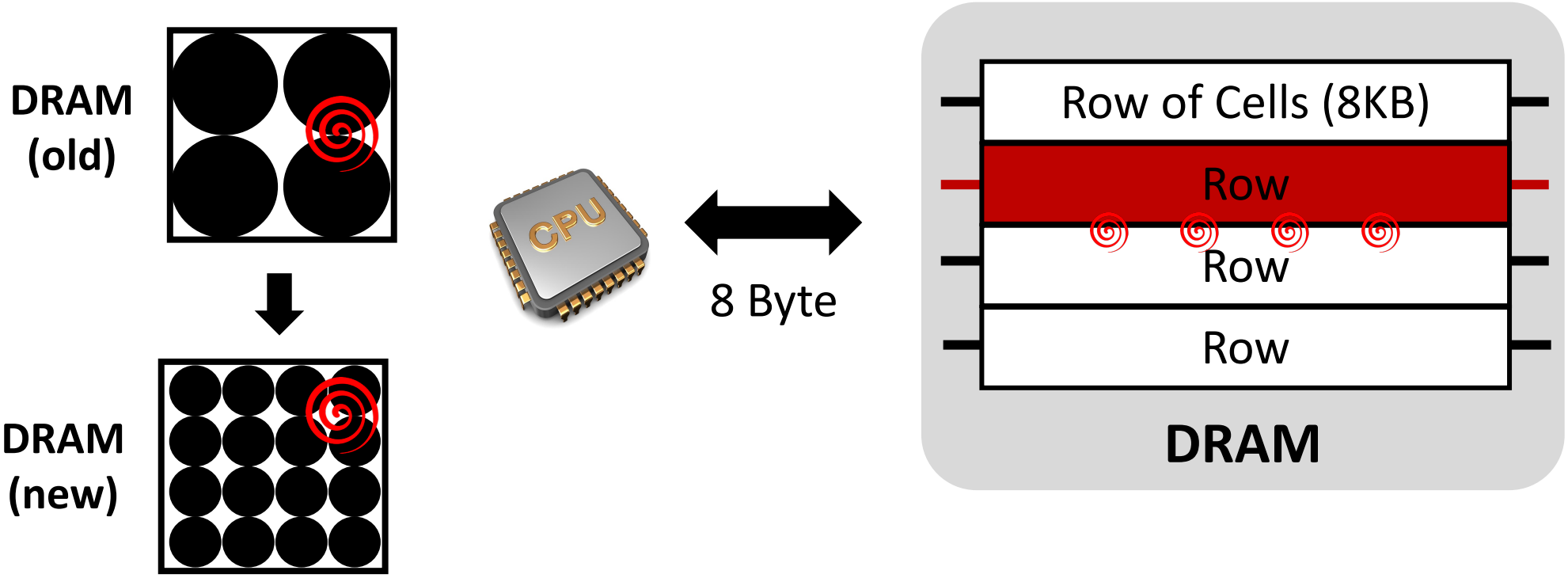

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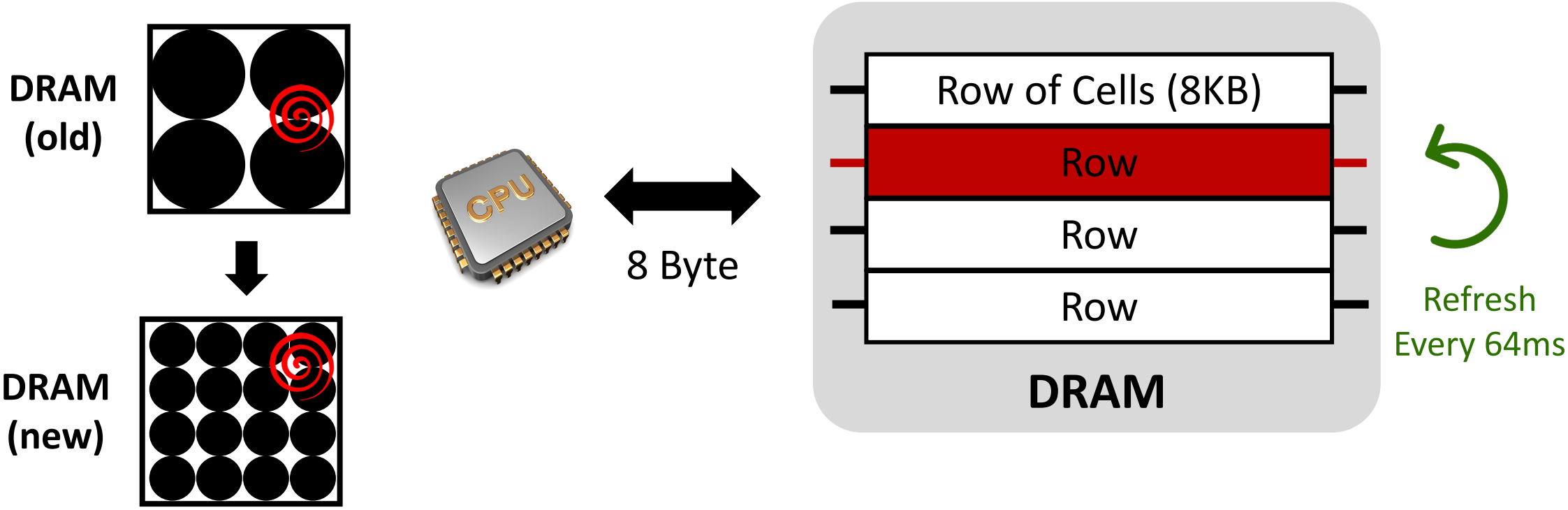

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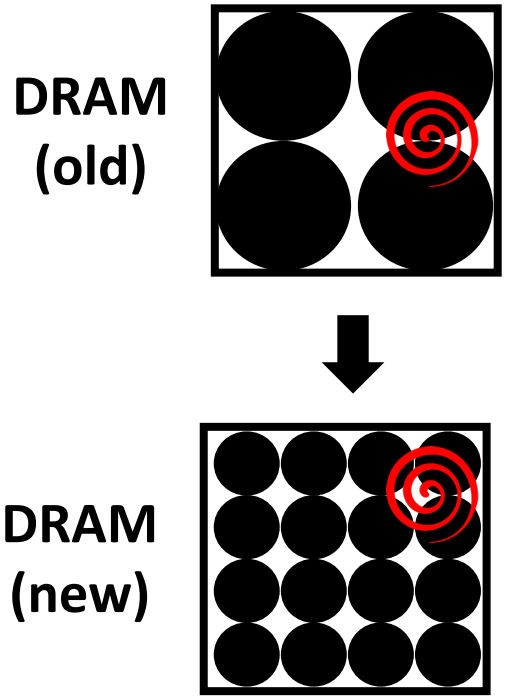
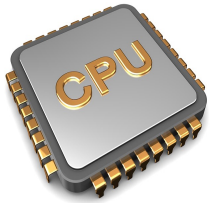
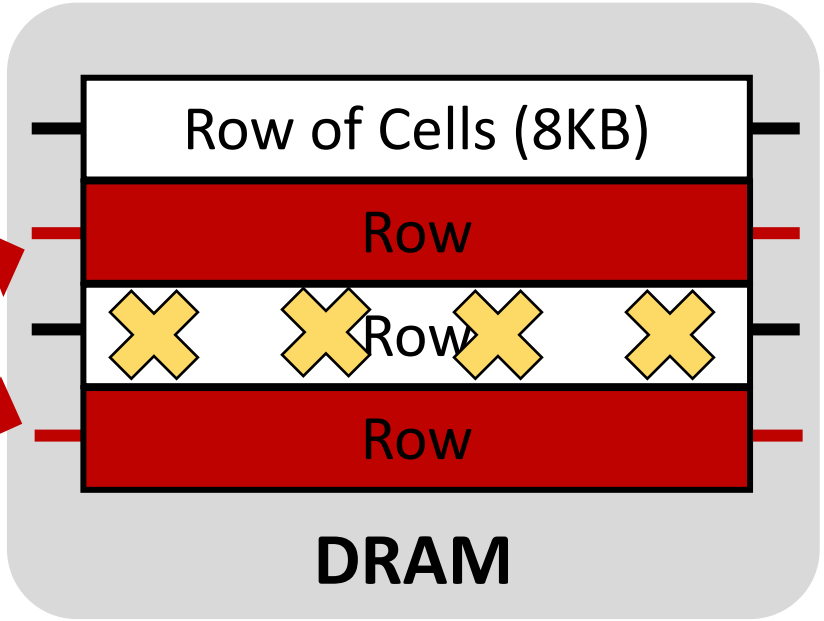




Rapid Accesses



Rowhammer Attack

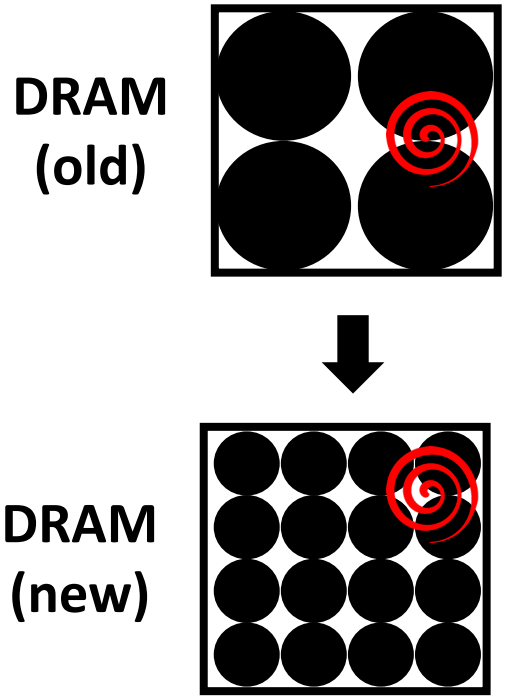
Bit-Flips in Neighboring Rows

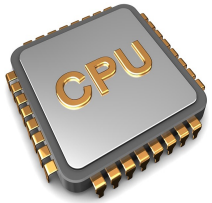
[Kim+, ISCA'15]

Rowhammer Attacks on DRAM

DRAM Scaling for Increased Capacity

More Inter-Cell Interference





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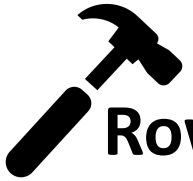

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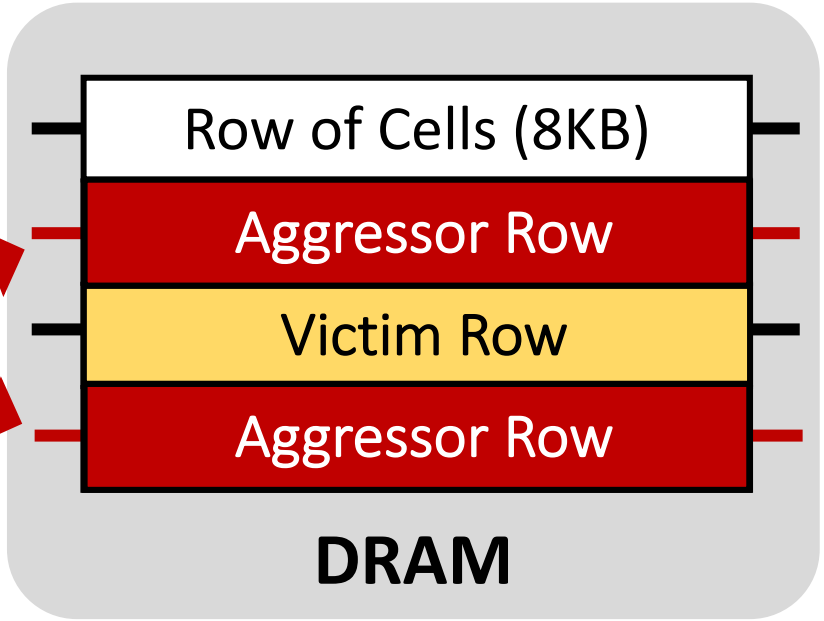

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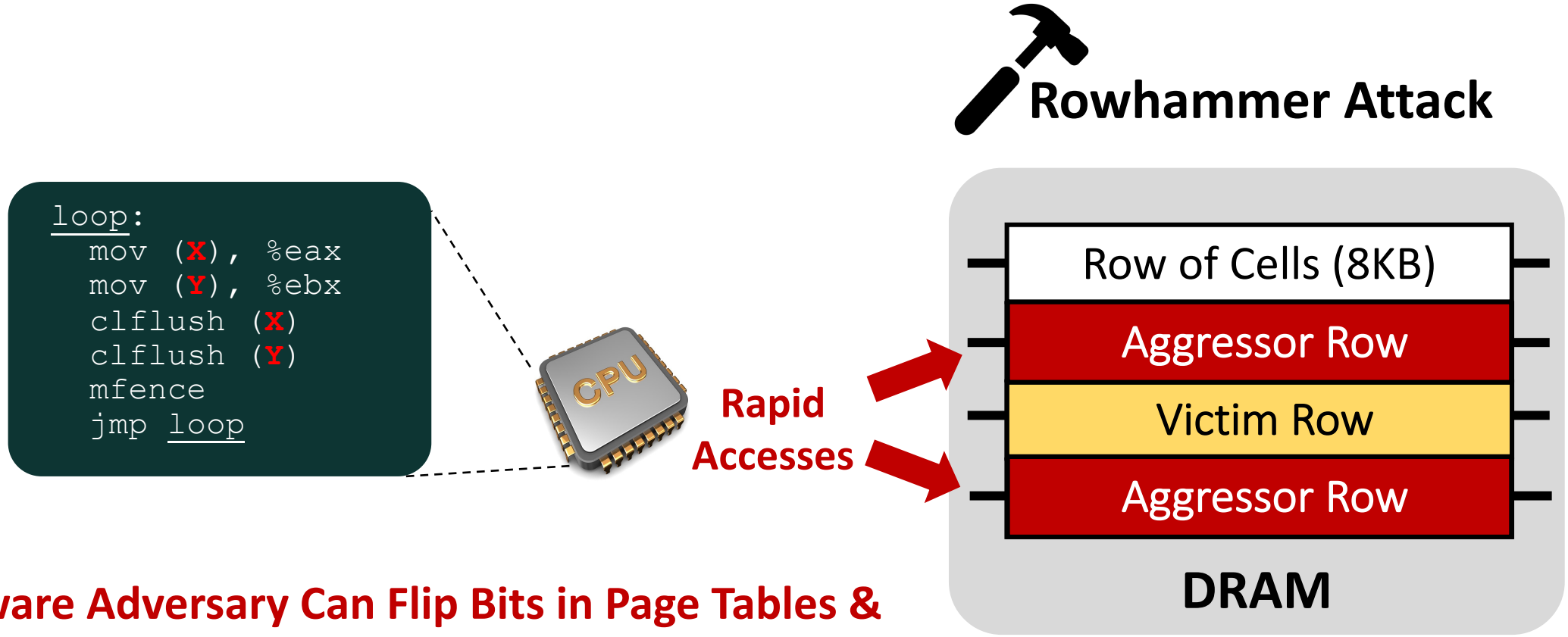
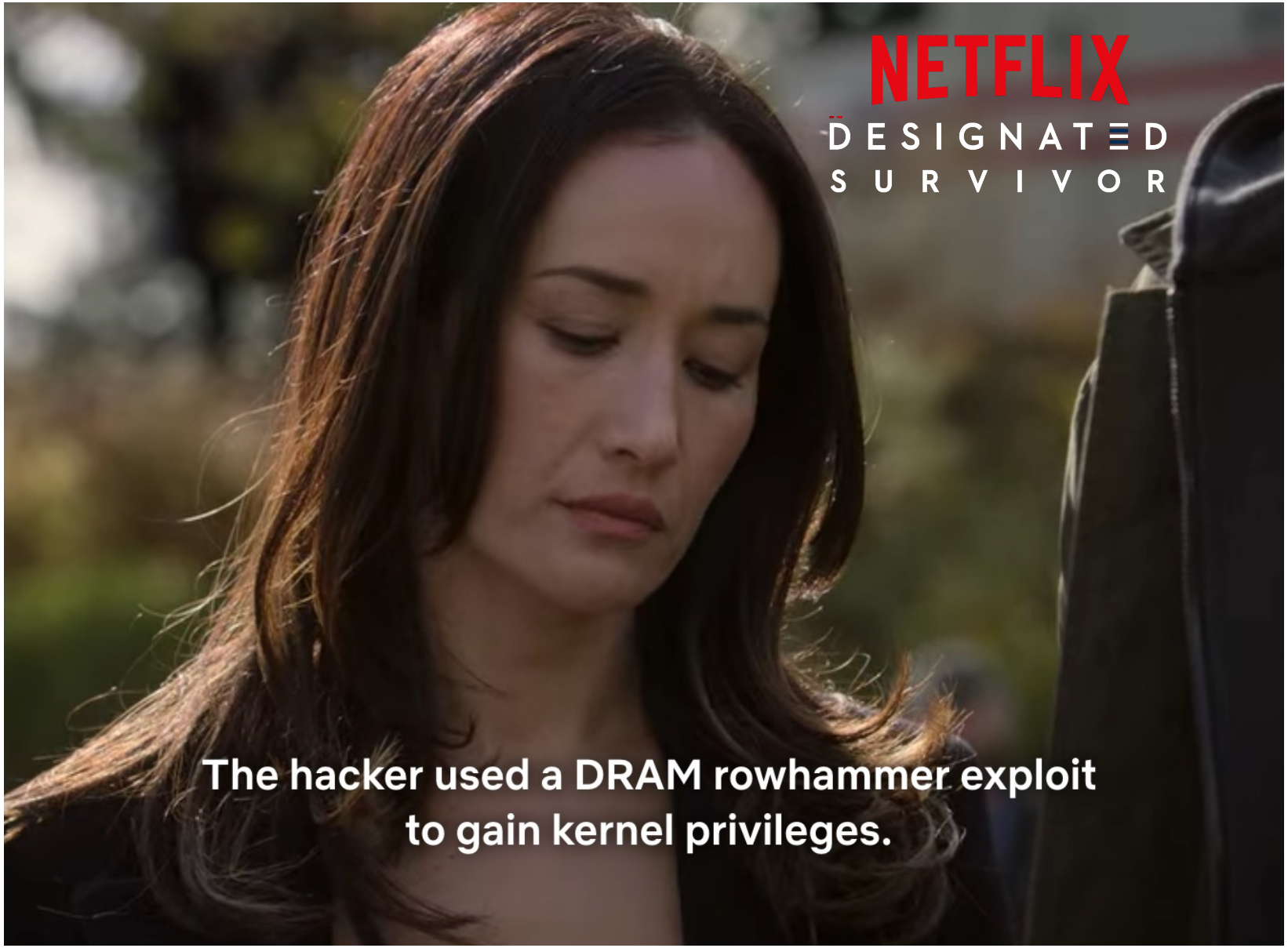


Software Adversary Can Flip Bits in Page Tables & Gain Kernel Privileges (Take Over a System)

[Seaborn+, Blackhat'15]

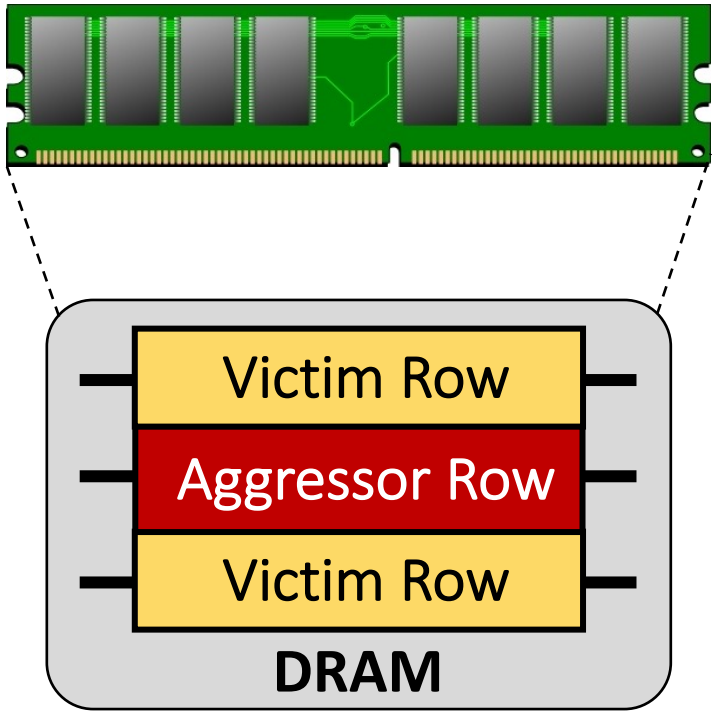
Bit-Flips in Neighboring Rows

[Kim+, ISCA'15]


NETFLIX
DESIGNATED
SURVIVOR
The hacker used a DRAM rowhammer exploit
to gain kernel privileges.

Mitigation in Commercial DDR4

Targeted Row Refresh (TRR) in DDR4 (2015)



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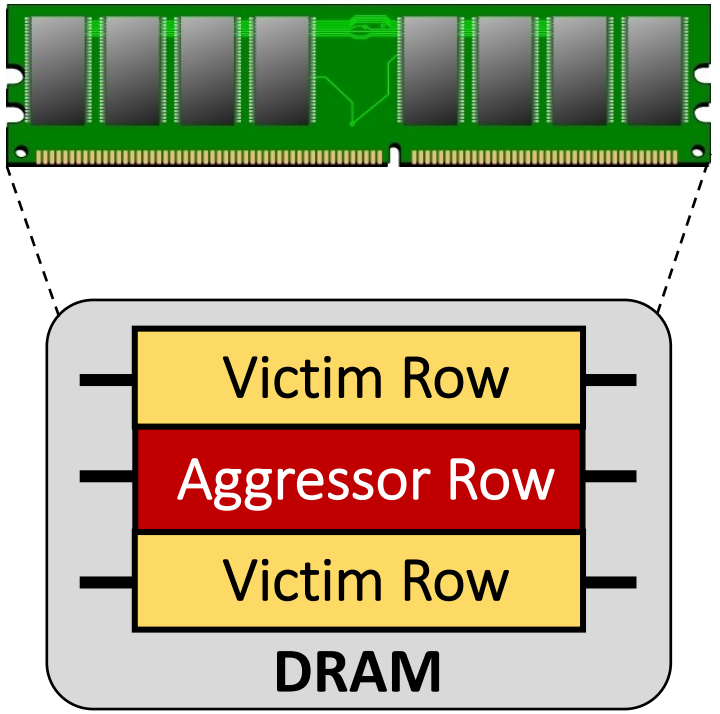
Targeted Row Refresh (TRR) in DDR4 (2015)

1. **Track Aggressor Rows**



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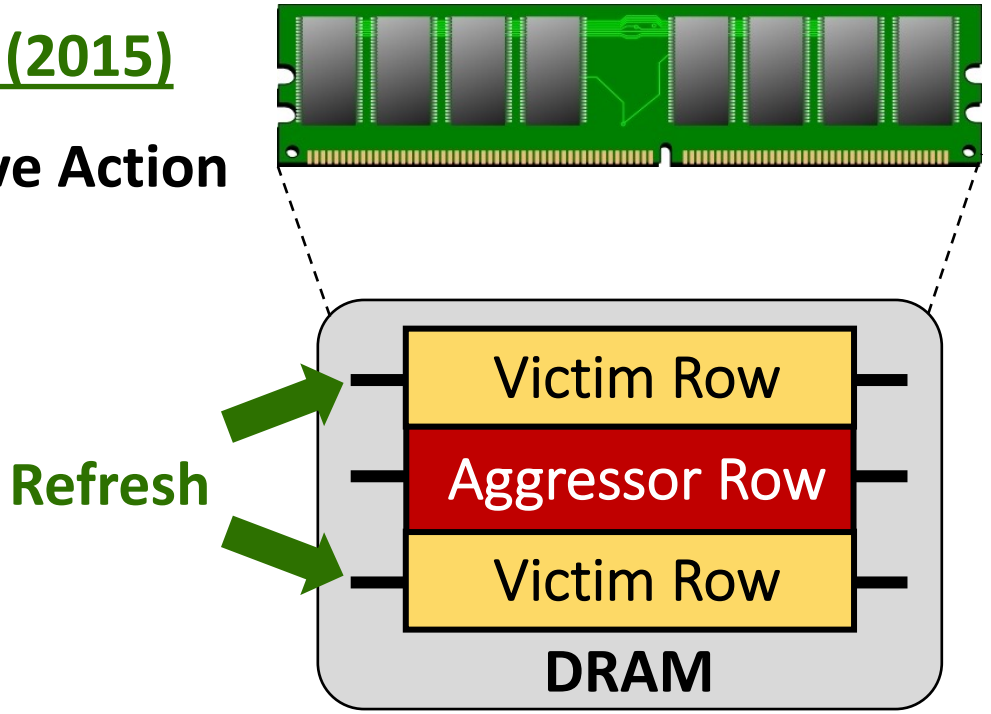
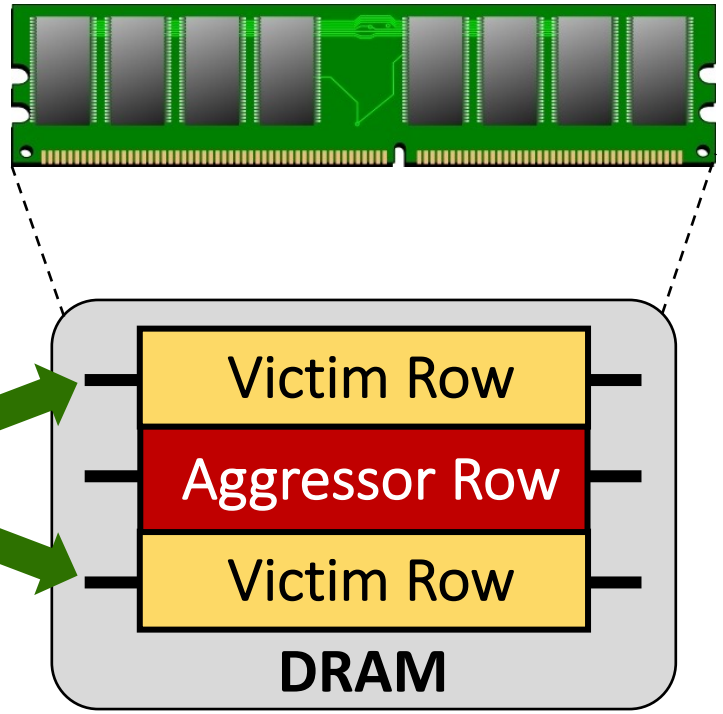
❶ Track Aggressor Rows ❷ Mitigative Action



Mitigation in Commercial DDR4: Broken!

Targeted Row Refresh (TRR) in DDR4 (2014)

❶ ~~Track Aggressor Rows~~ ❷ Mitigative Action



TRResspass Breaks TRR Tracker [Frigo+, SP'20]

> **Poor Rowhammer Fixes On DDR4 DRAM Chips Re-Enable Bit Flipping Attacks**
>
> Source: The Hacker News

Blacksmith Attack: All DRAM Shown Vulnerable [Jattke+, SP'22]

> **When the world ends, all that will be left are cockroaches and new Rowhammer attacks: RAM defenses broken again**
>
> Blacksmith is latest hammer horror
>
> Source: The Register

Recent Victim Focused Mitigations

✓ Track Aggressor Rows ❷ Mitigative Action

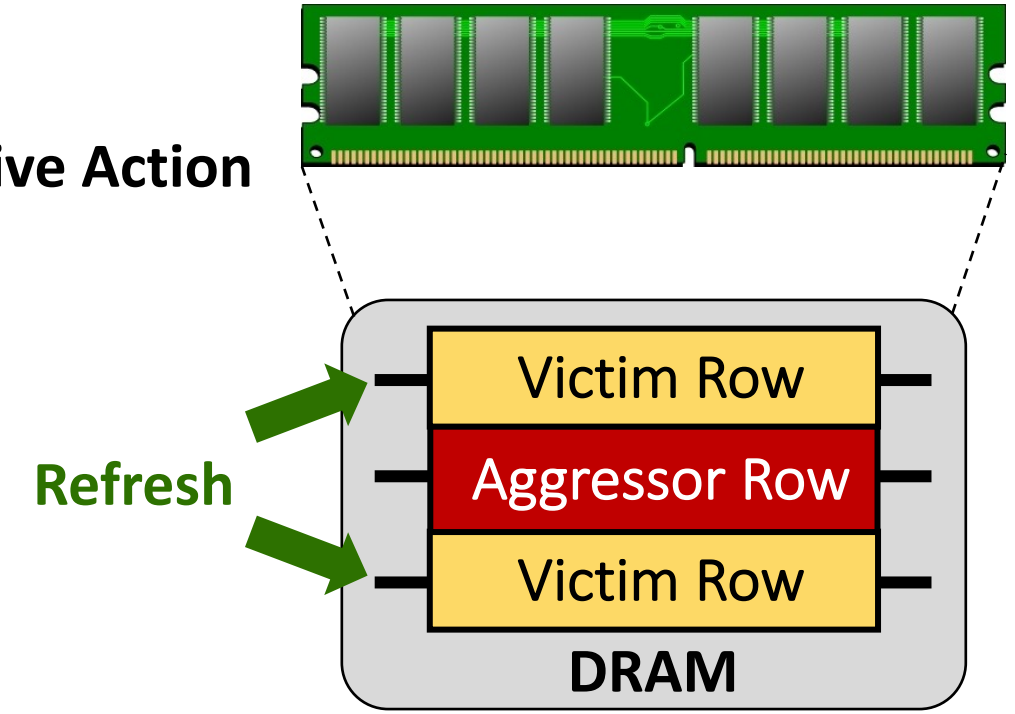
Principled Tracking

Graphene [MICRO'20]

TWICE [ISCA'19]

CRA [CAL'14]

and others …



Recent Victim Focused Mitigations

Track Aggressor Rows

❷ Mitigative Action

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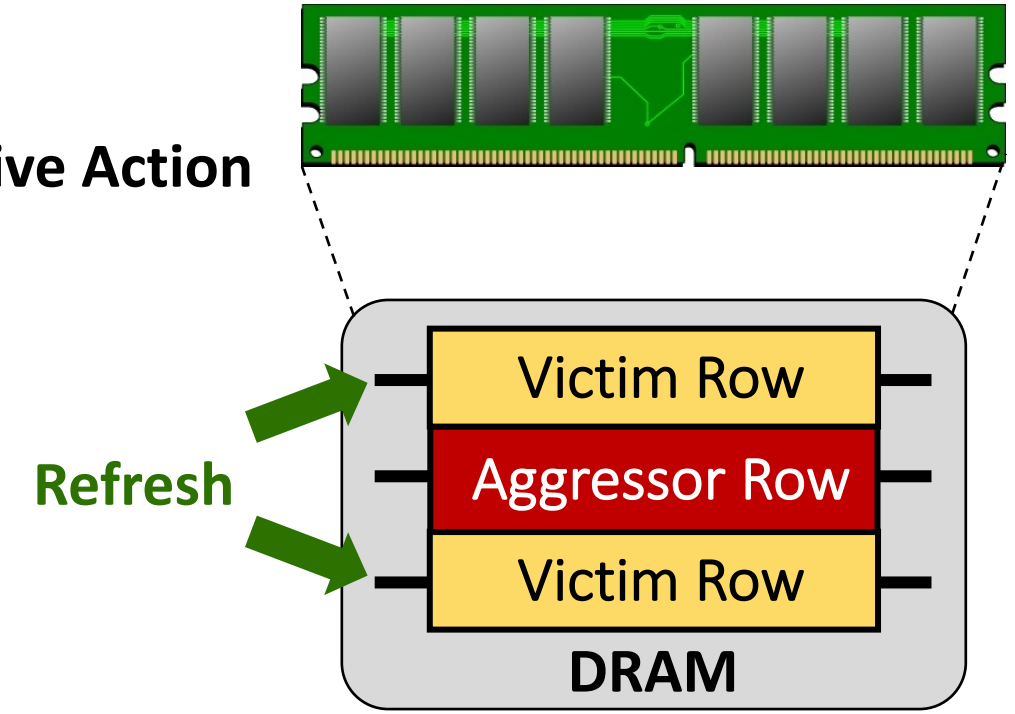

Arms Race in Rowhammer

Track Aggressor Rows ❷ Mitigative Action

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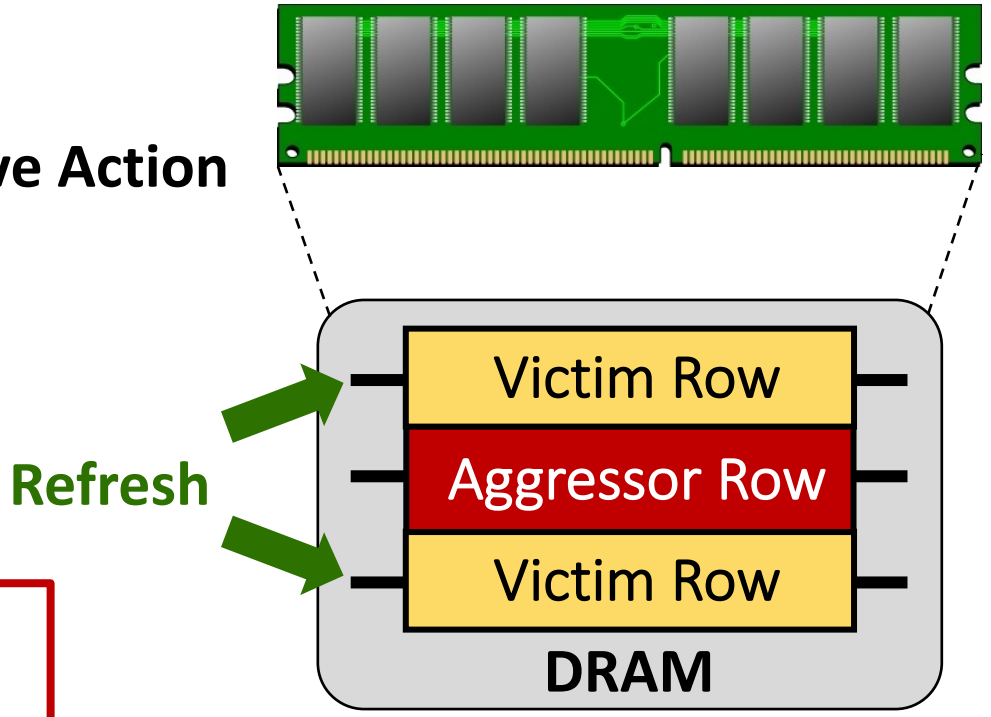
Google's Half-Double Attack: Exploits Mitigative Refresh [2021]

As Chips Shrink, Rowhammer Attacks Get Harder to Stop

A full fix for the "Half-Double" technique will require rethinking how memory semiconductors are designed.

Source: ArsTechnica



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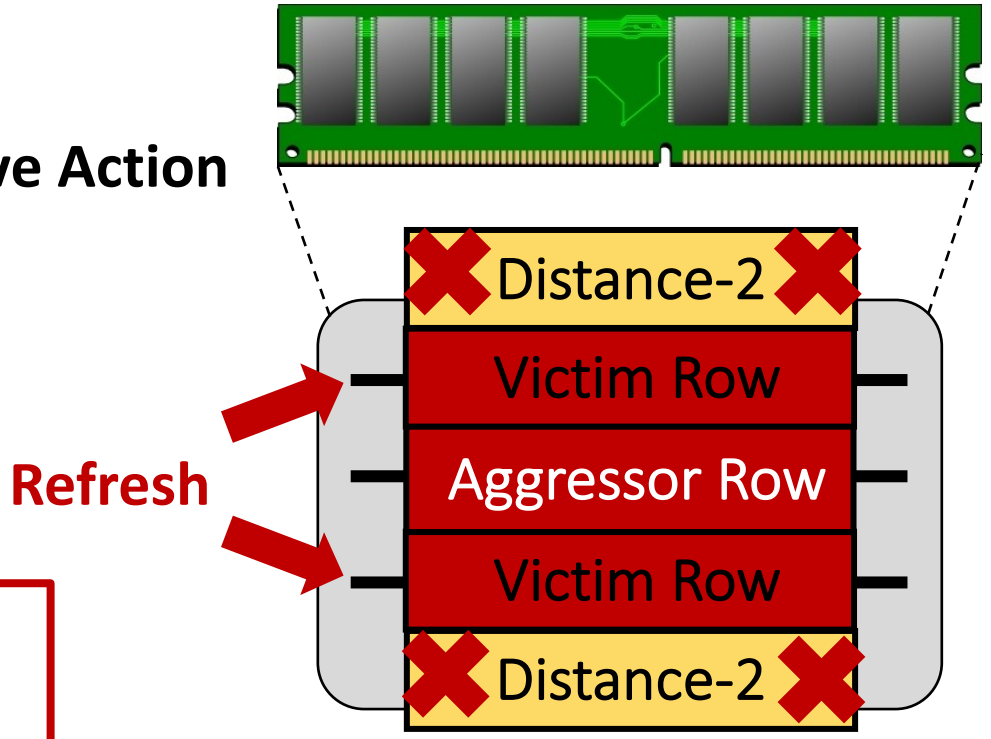

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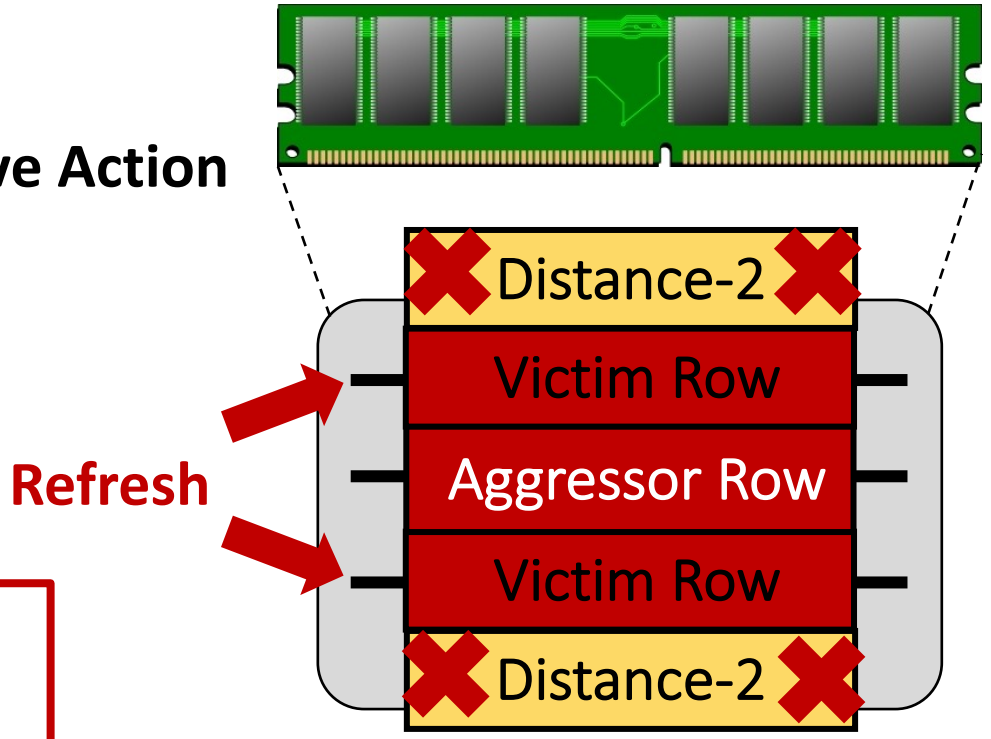
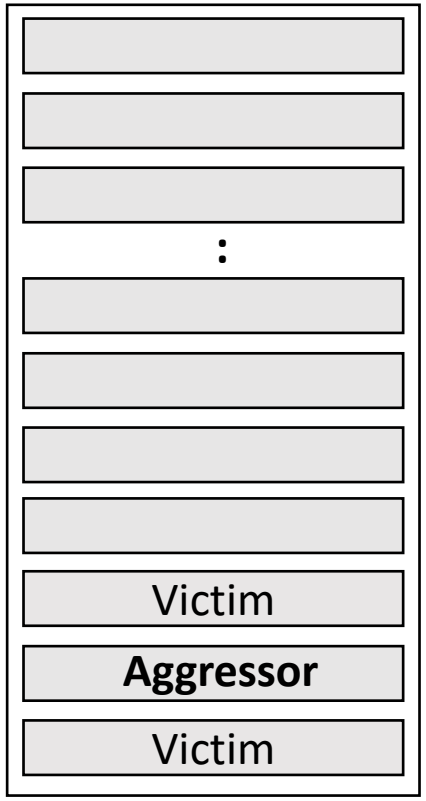


Need New Mitigative Action Resilient to Current and Emerging Attack Patterns (preferably without requiring knowledge of DRAM mapping function)

Aggressor Focused Mitigation: Randomized Row-Swap

Key Idea: Remap Aggressor Rows to Break Spatial Correlation with Victim Rows



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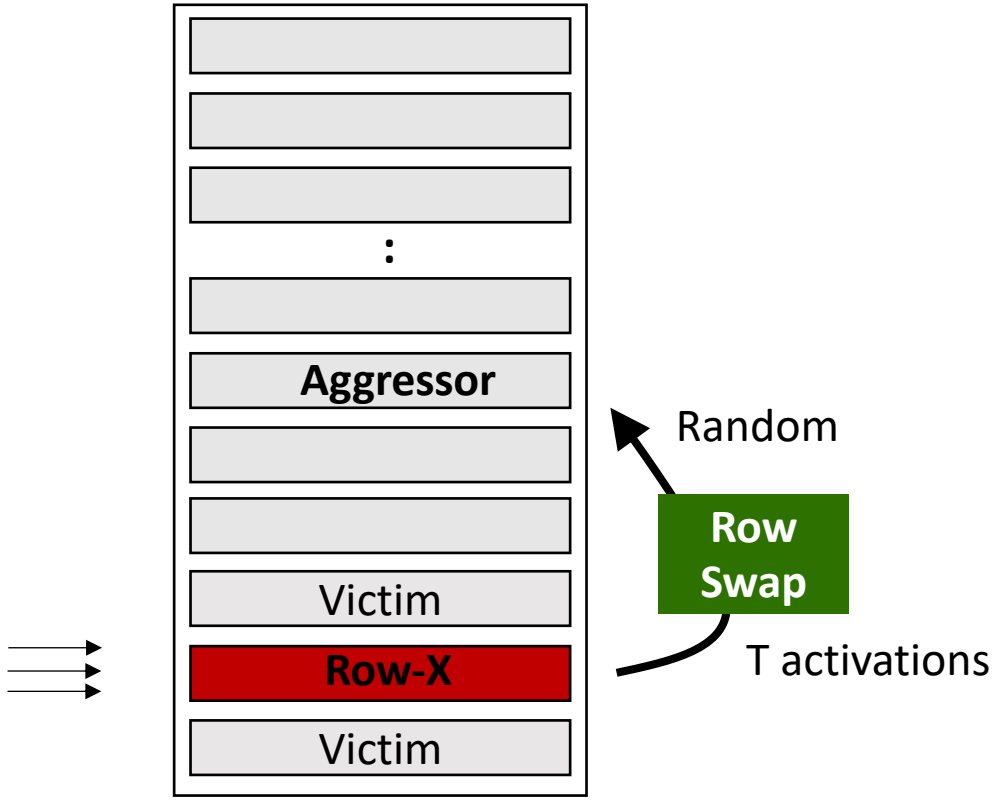

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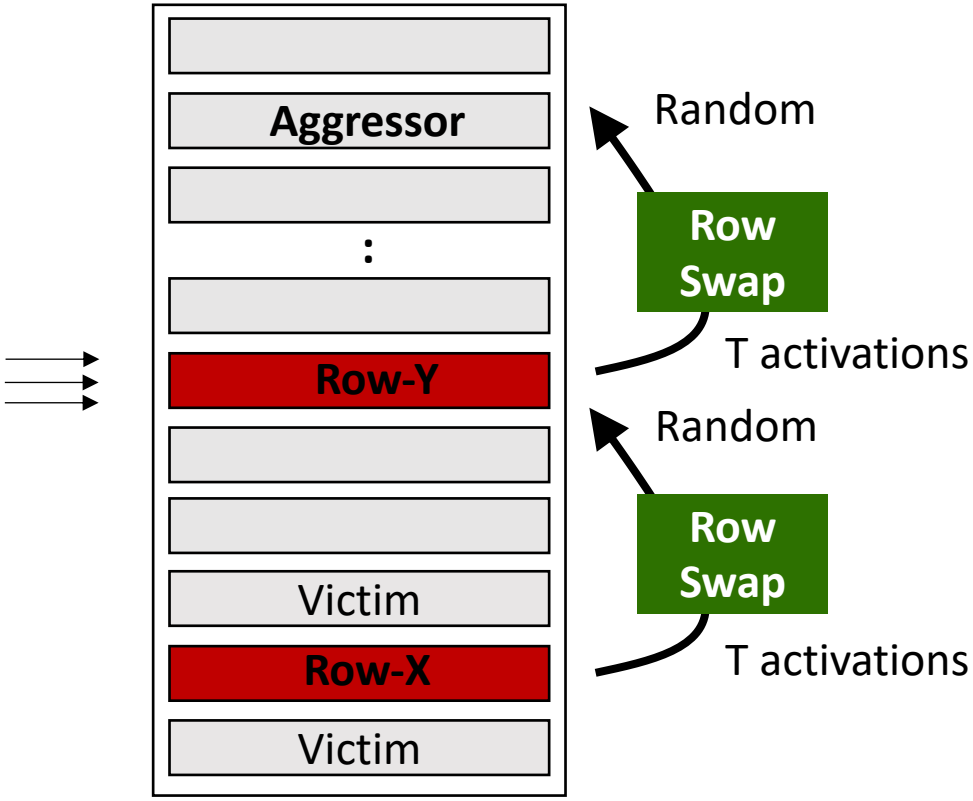

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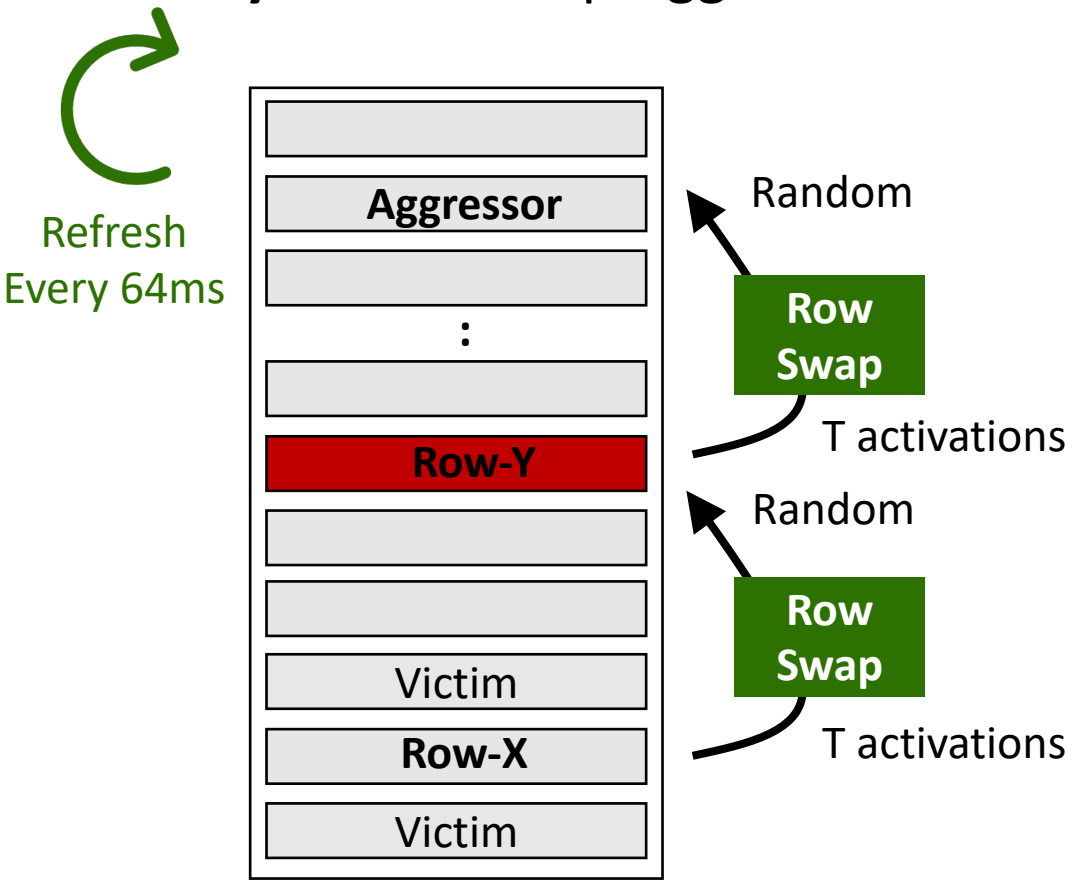

Security Guarantee: No Row Crosses Rowhammer Threshold Activations within 64ms

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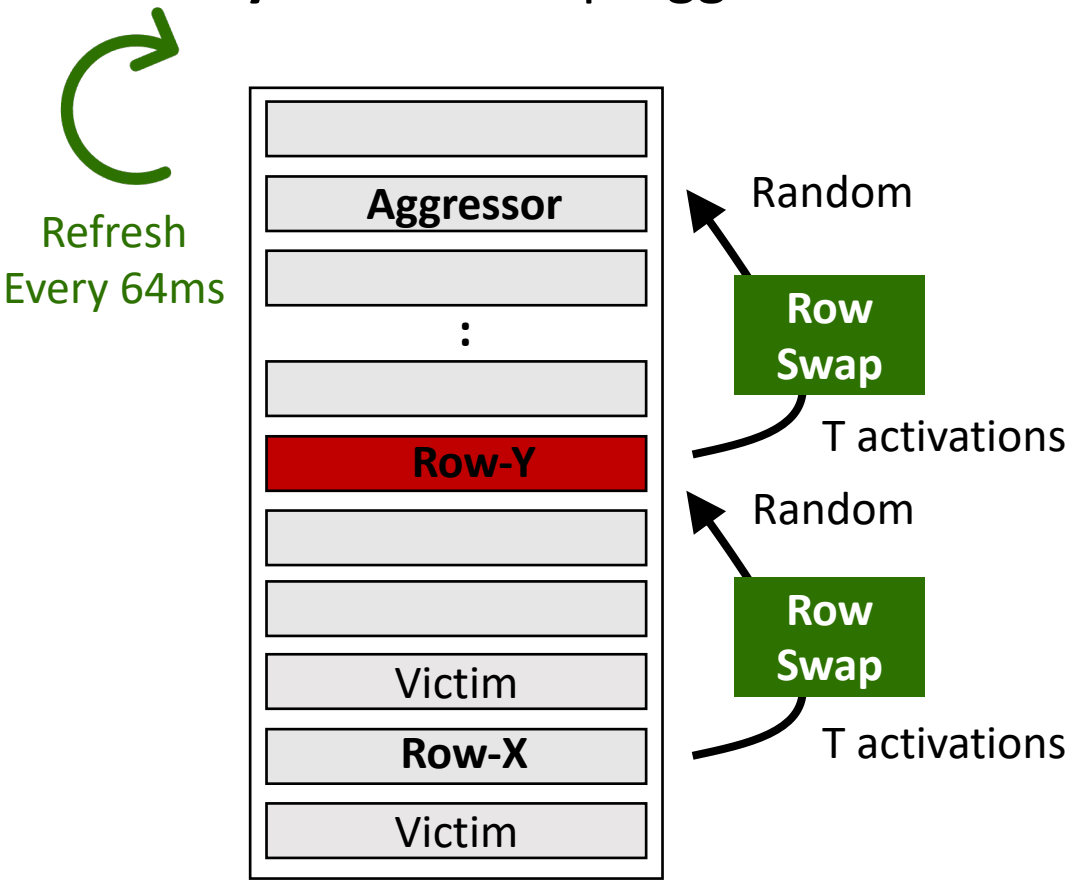

Security Guarantee: No Row Crosses Rowhammer Threshold Activations within 64ms

Lower T (Swap Threshold) → Better Security

Security Analysis

TRH=4800 → Minimum Activations in 64ms on Row for Rowhammer via Any Pattern

(Single-sided, Double-Sided, Half-Double)

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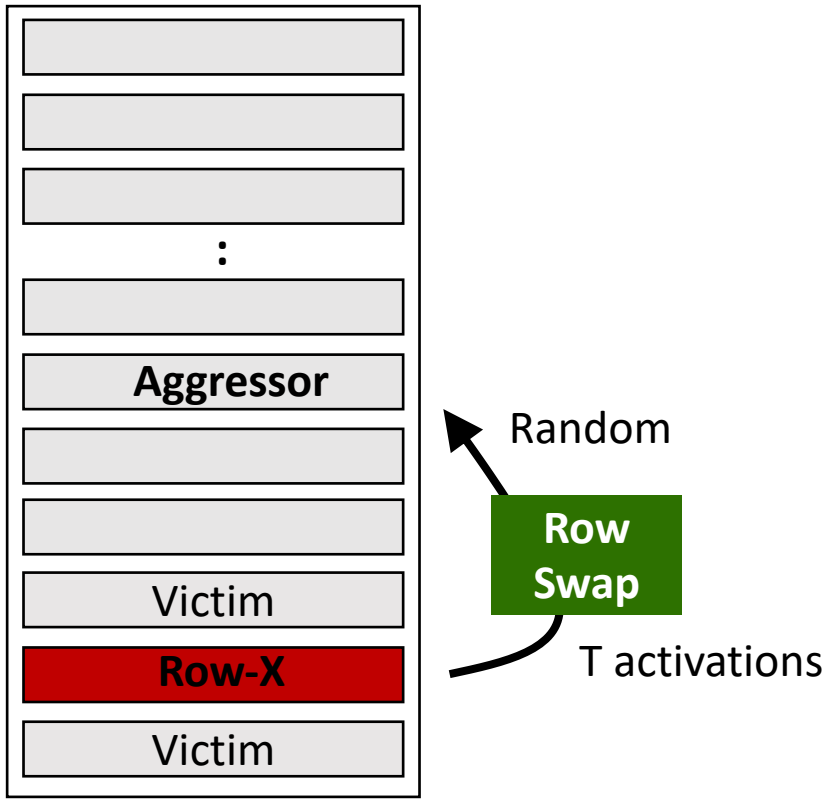

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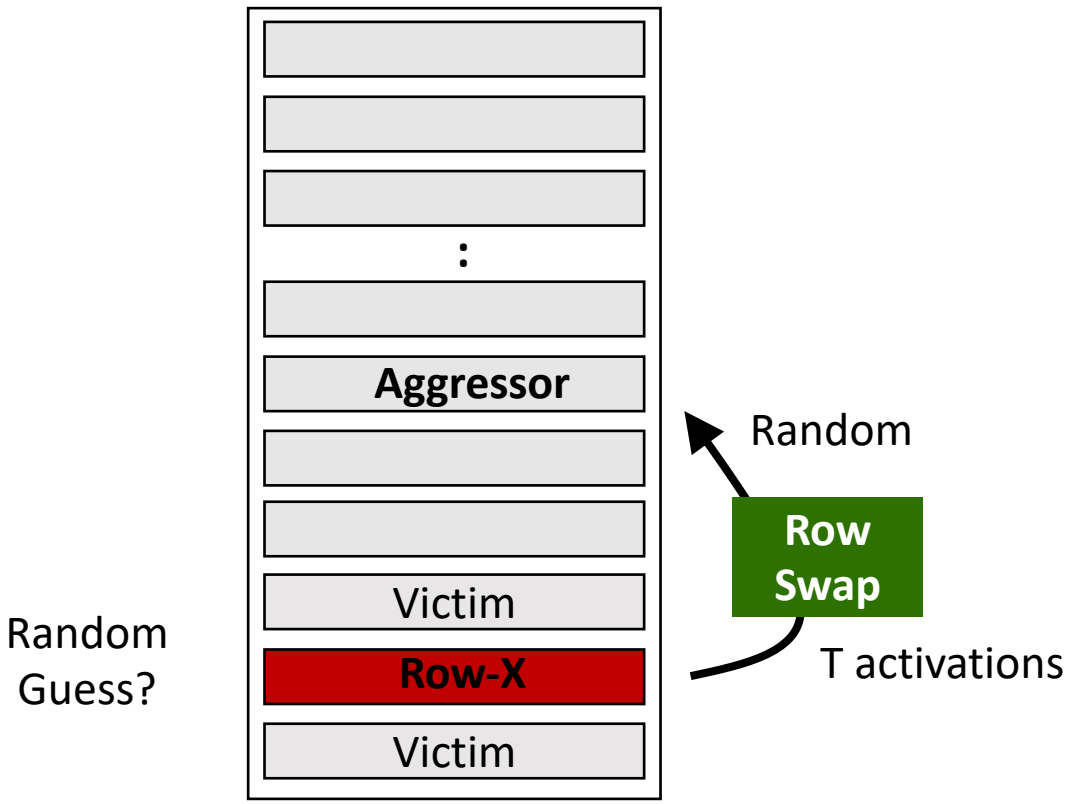

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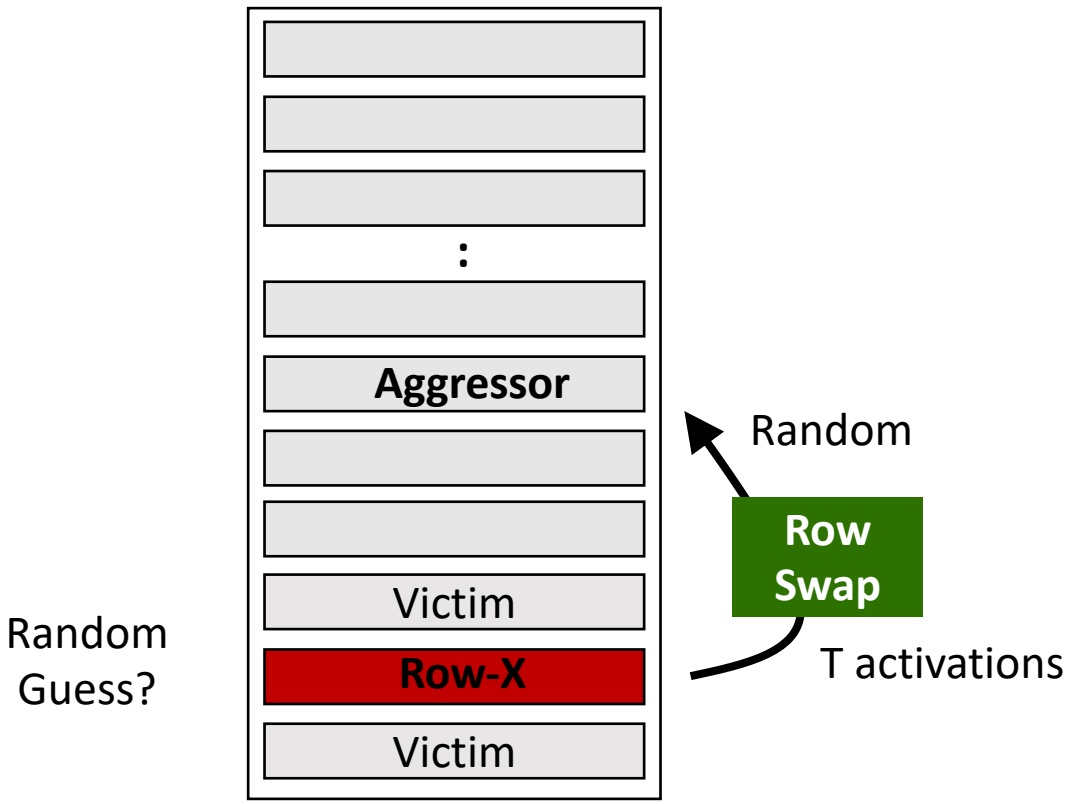
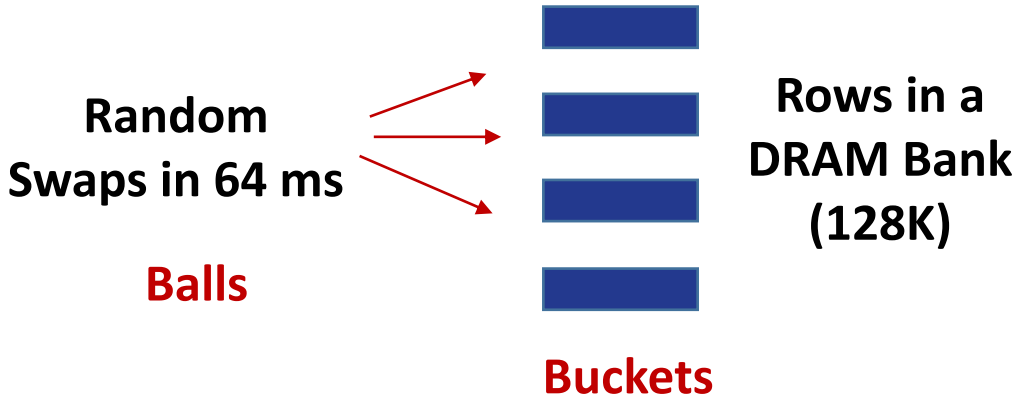


Buckets and Balls Problem



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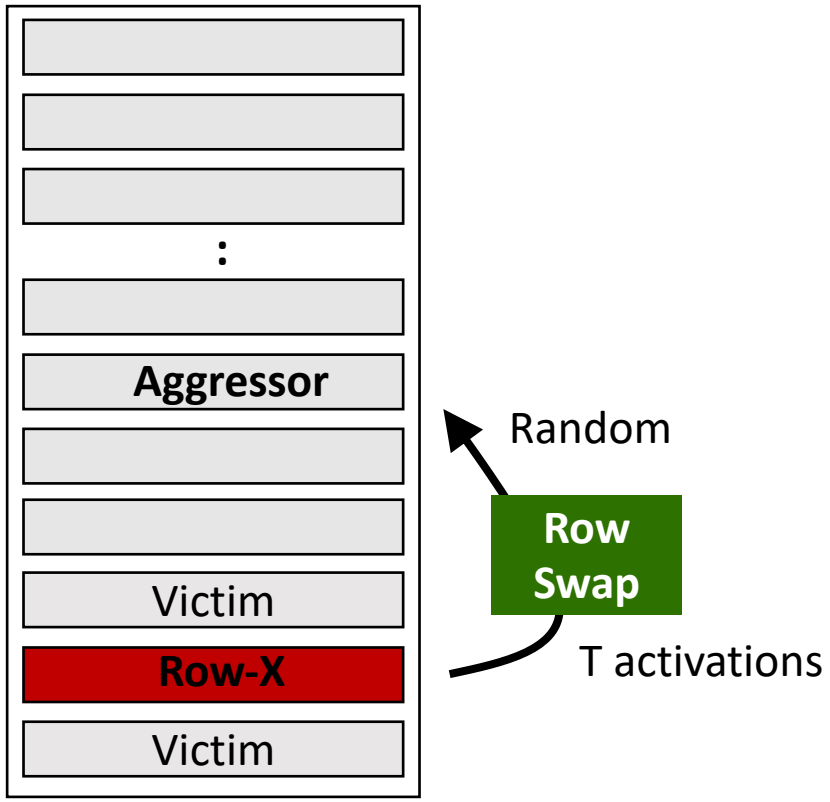

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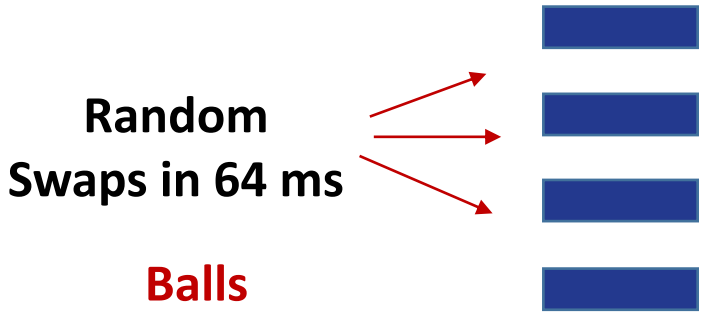

Swap Every T Activations	Attack Time
T = TRH/5	6.9 days
T = TRH/6	**3.8 years**
T = TRH/7	762 years

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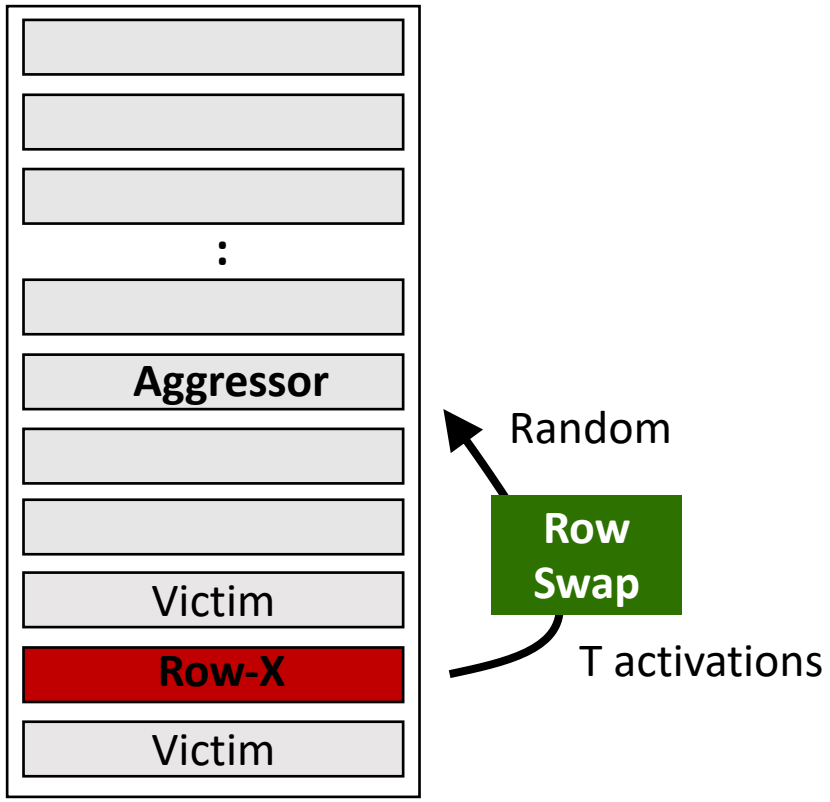

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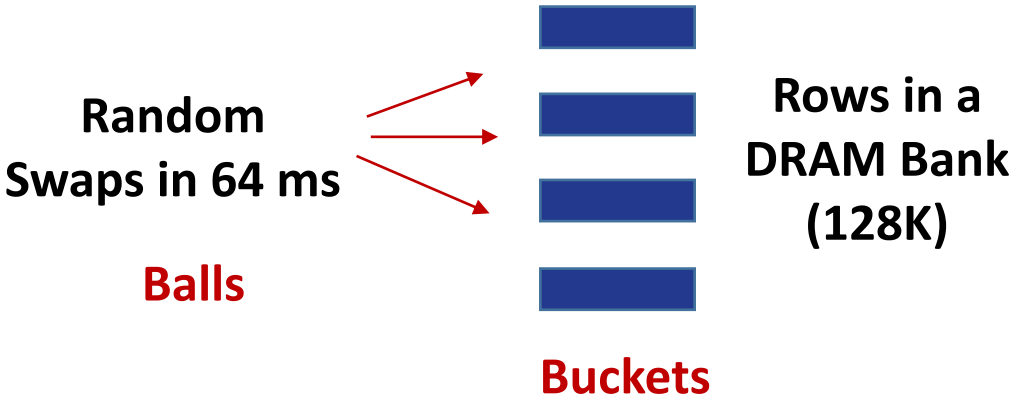

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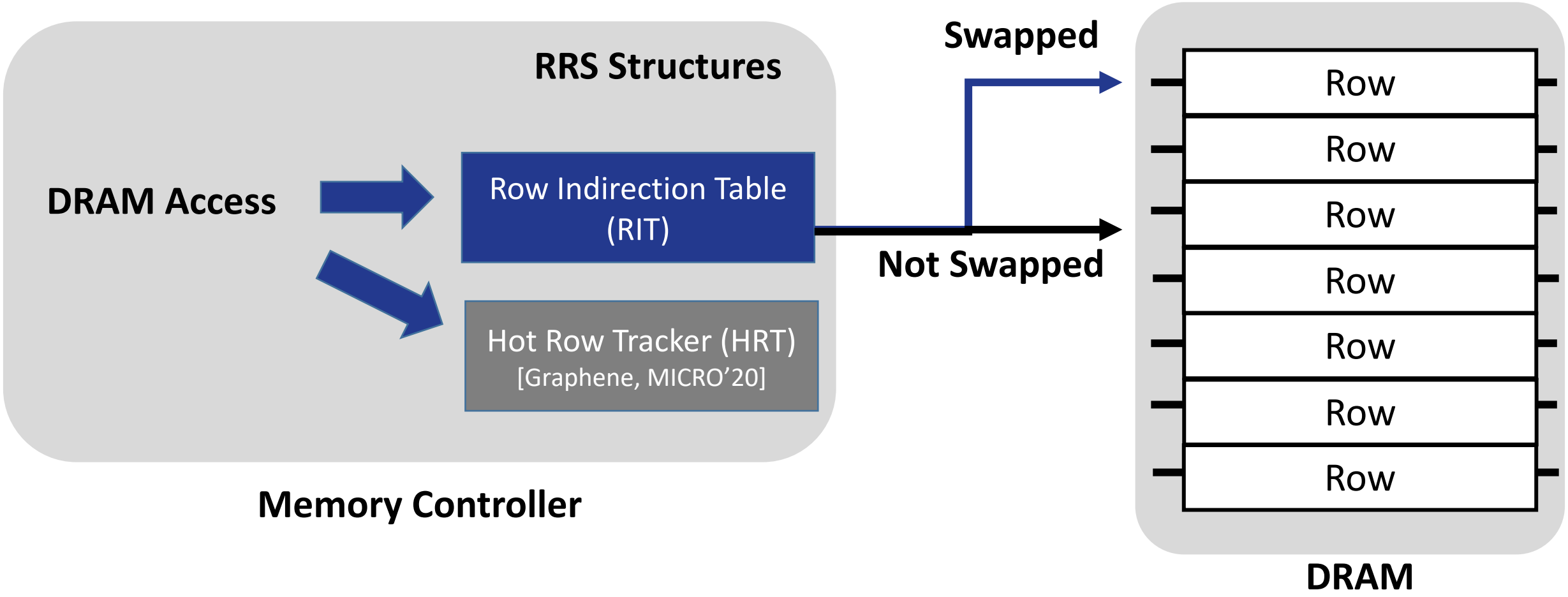
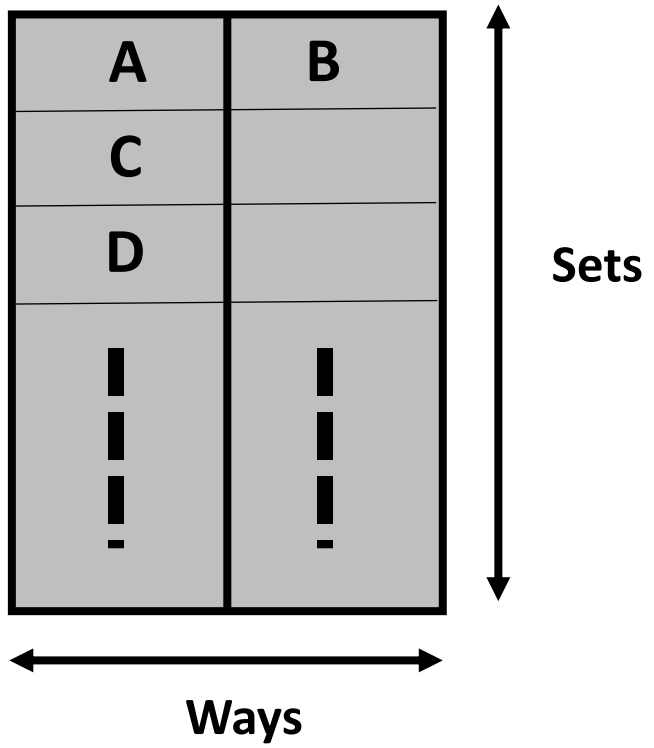
Continuous Remapping of Aggressor Rows Provides Principled Security for Years of Attack

Implementation of Randomized Row Swap



Collision Avoidance Table (CAT) for RIT and HRT

Problem: The tracking structures can be overwhelmed by repeated accesses



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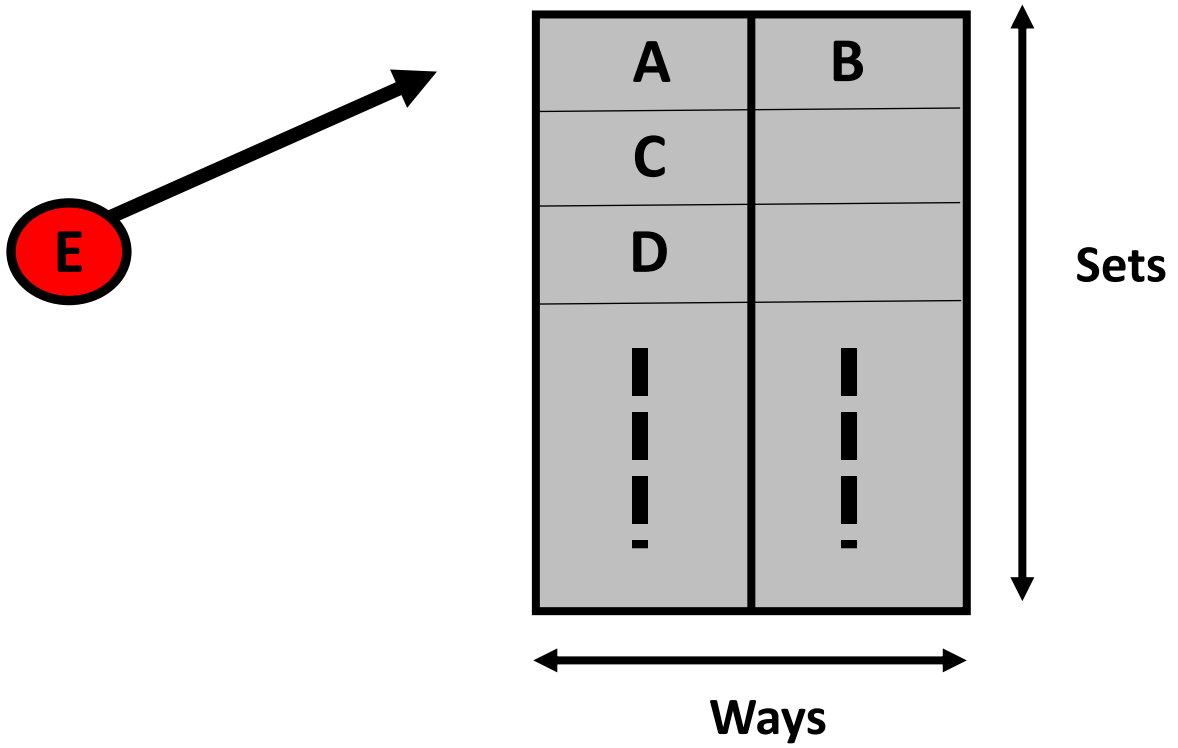

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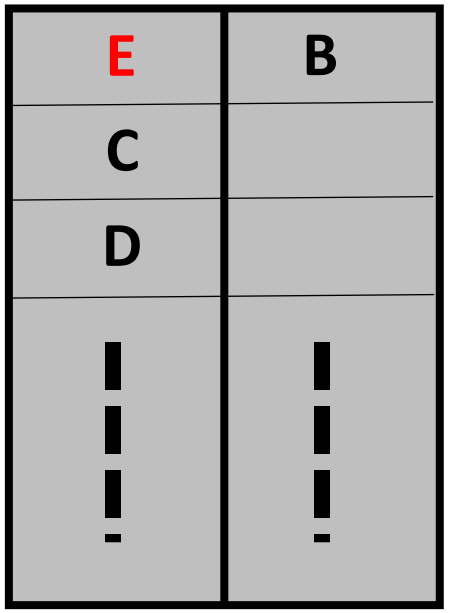

Conflicts in tracking structures → targeted row addresses to be expelled → Lose tracking of some rows

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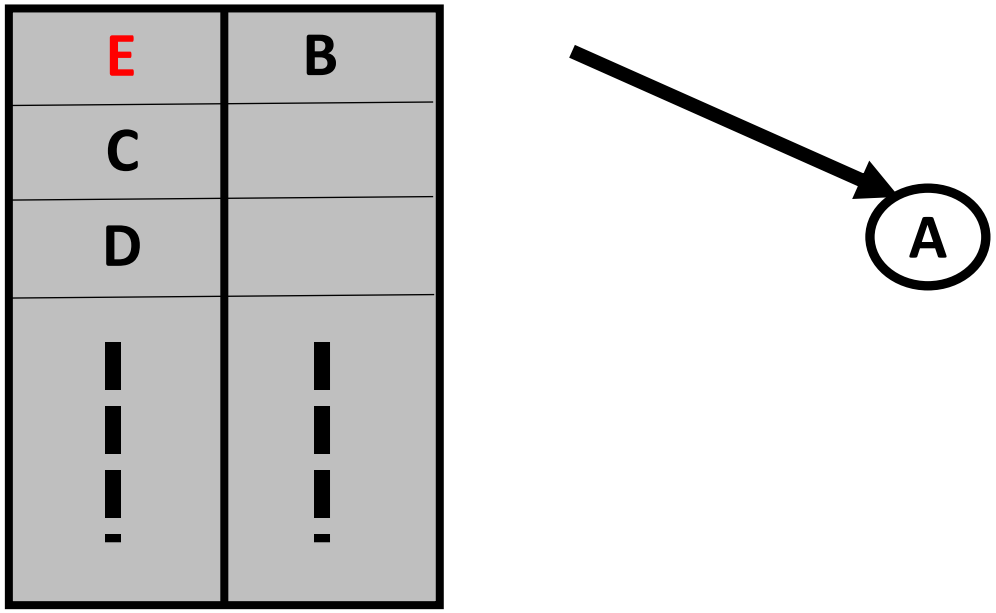

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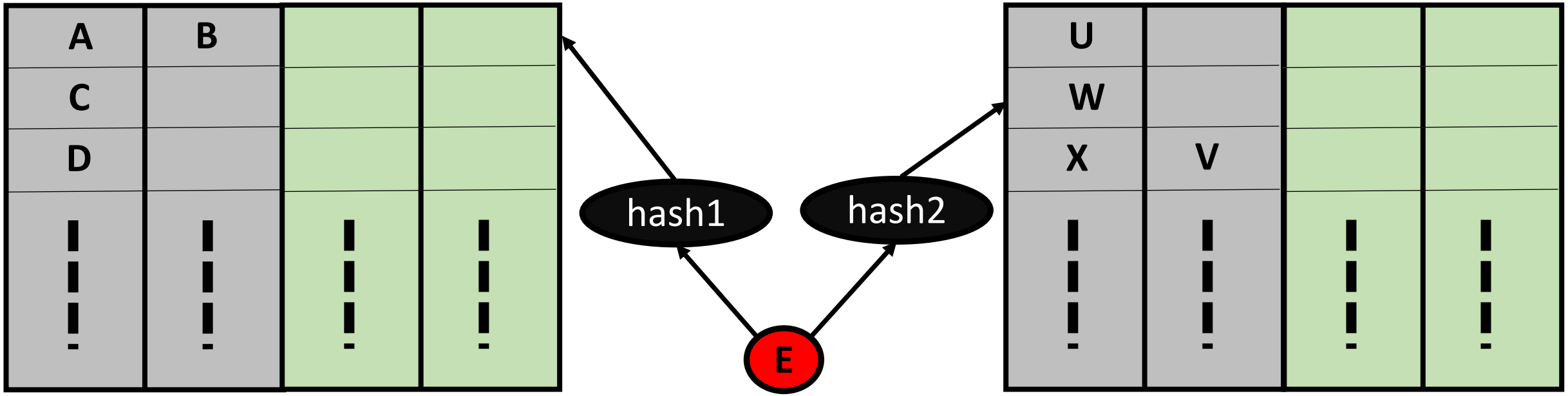
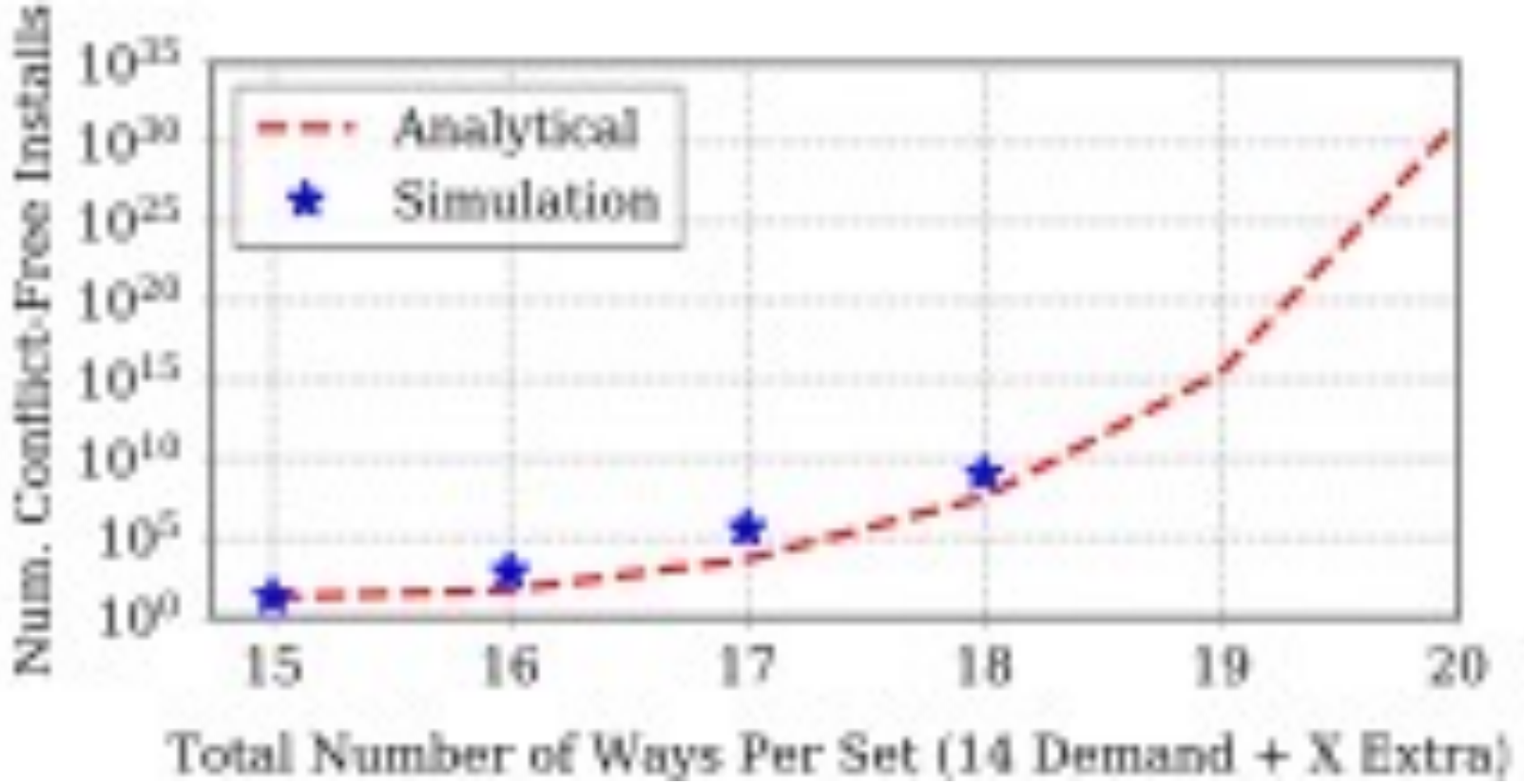
Solution: Leverage Power of Two Choices [MIRAGE – USENIX SEC'21]



Additional Ways + Multiple Hashes + Load Balancing + Random Replacement

Collision Avoidance Table (CAT) for RIT and HRT

Solution: Leverage Power of Two Choices [MIRAGE – USENIX SEC'21]



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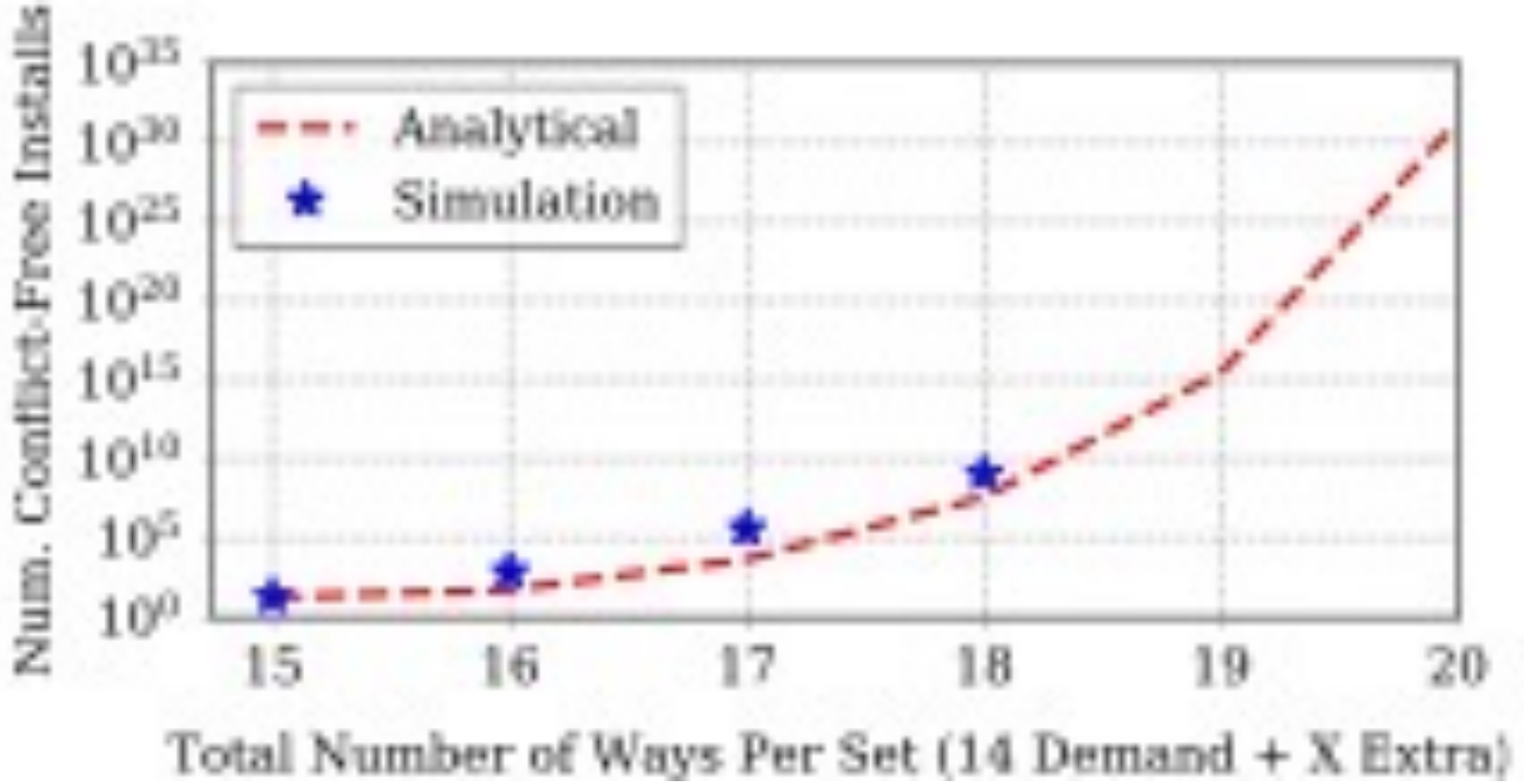

With 14 Demand Ways and 6 Extra Ways → 10^{30} installs are needed to create a conflict

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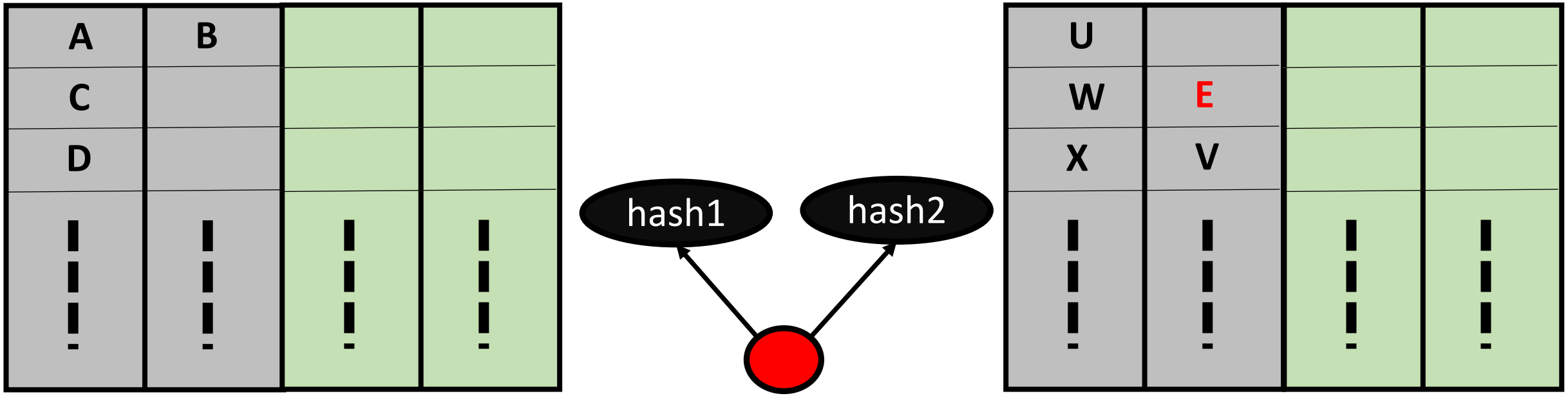

Additional Ways + Multiple Hashes + Load Balancing + Random Replacement

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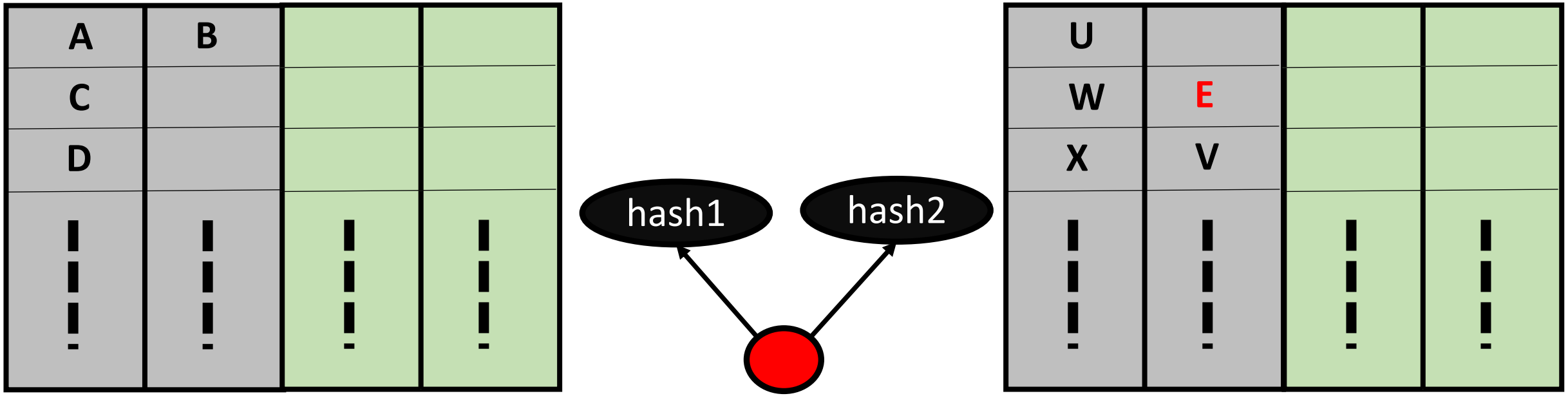
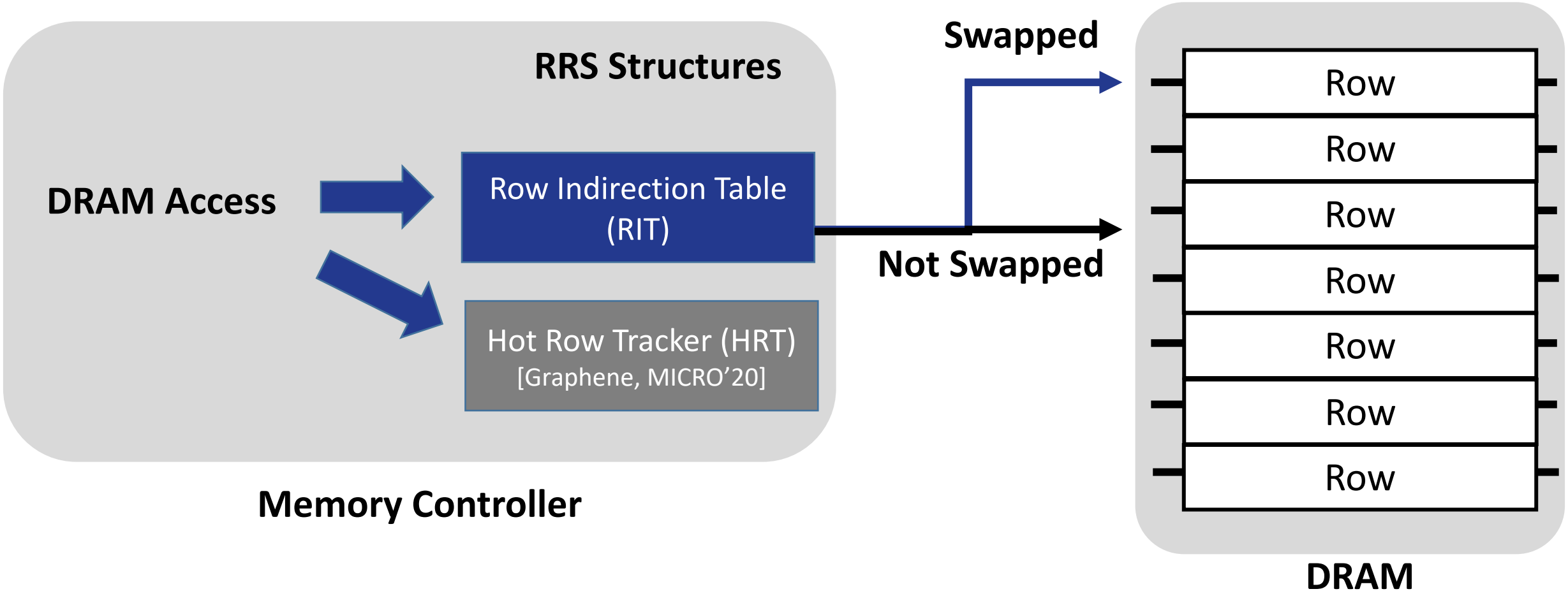


Additional Ways + Multiple Hashes + Load Balancing + Random Replacement

RIT and HRT use the CAT to avoid collisions → Prevents Conflict-Based Attacks

Implementation of Randomized Row Swap



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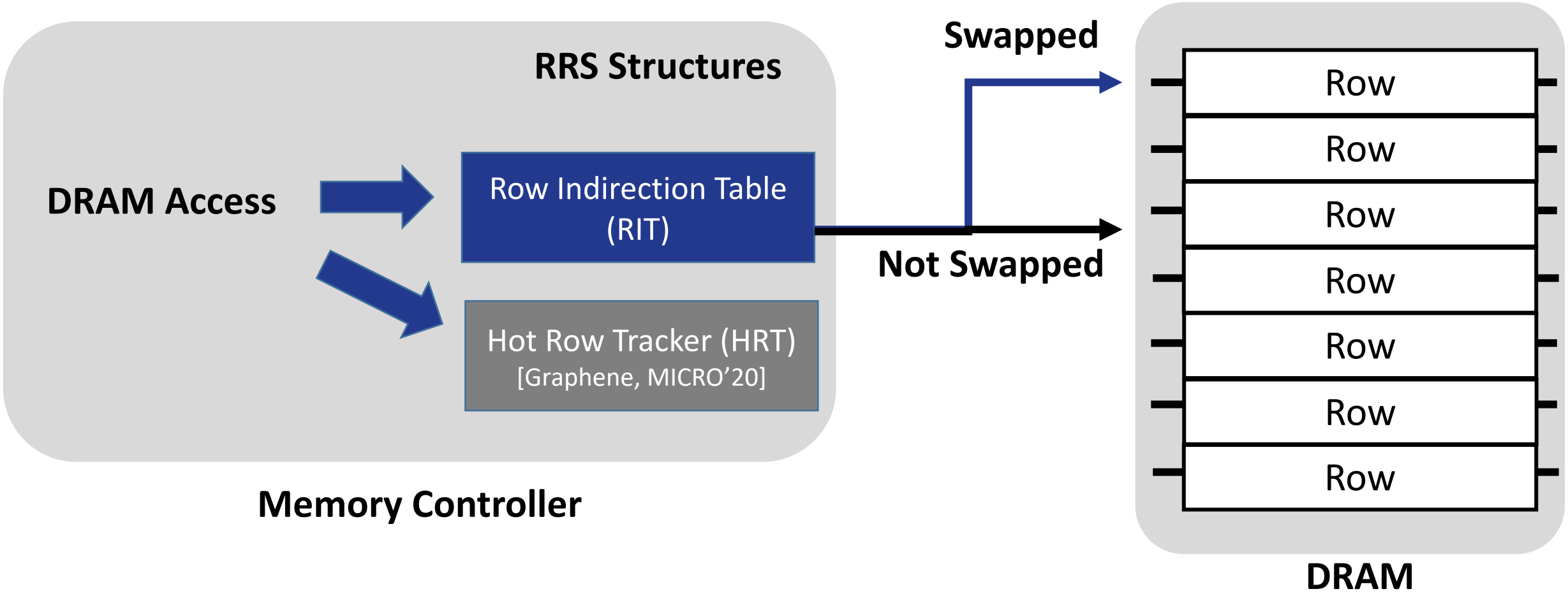
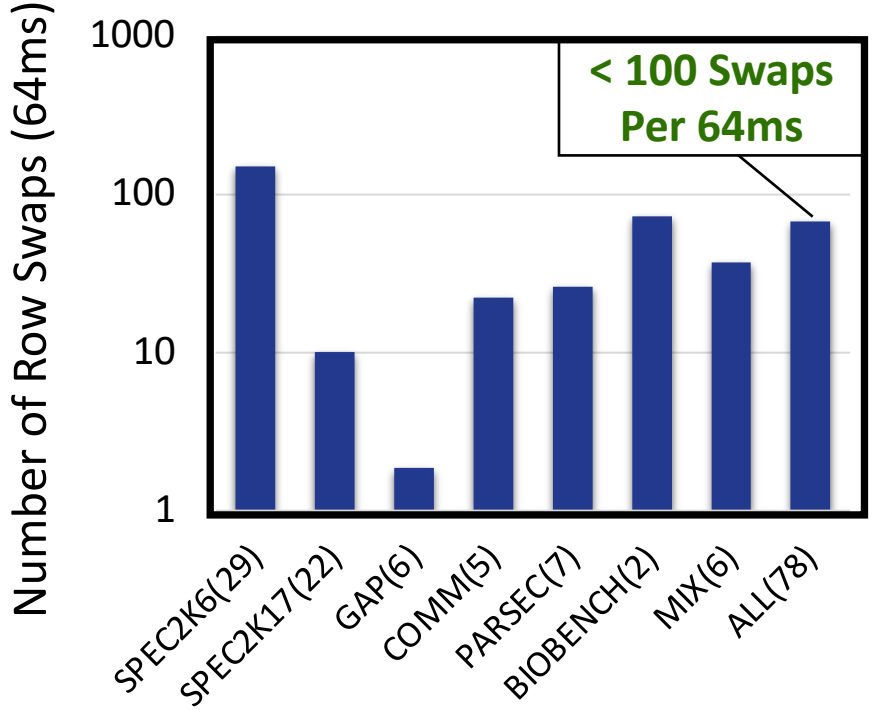


SRAM Storage Overheads (RIT, HRT) → 45 KB Per DRAM Bank x 16 Banks → 720 KB of SRAM

Performance Impact of Row Swaps

Frequency of Row Swaps Per 64ms

(1.5 microseconds per swap)



Saileshwar et al. Randomized Row-Swap: Mitigating Row Hammer by Breaking Spatial Correlation. In ASPLOS 2022

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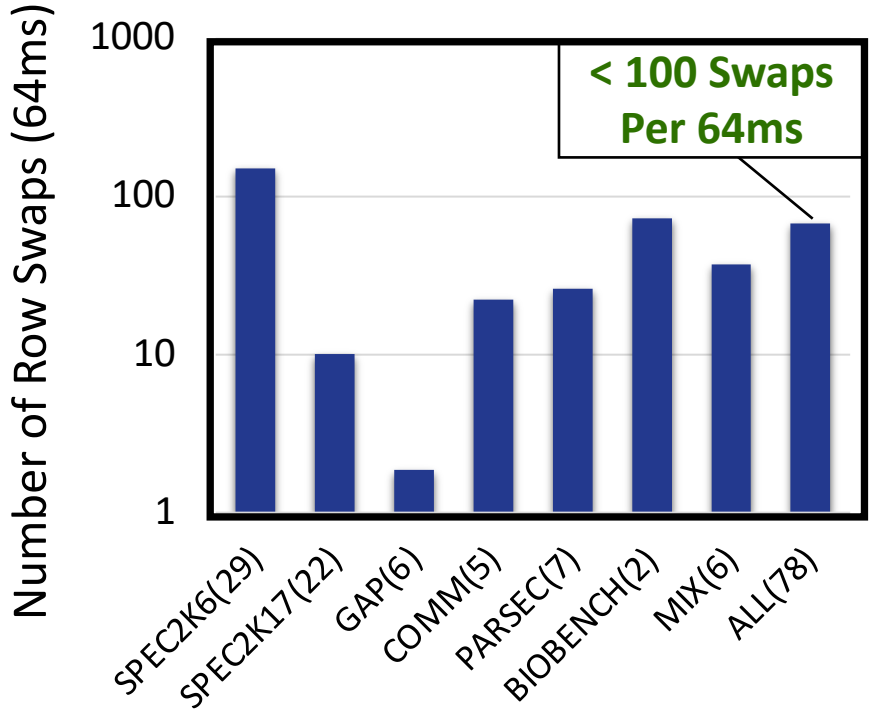
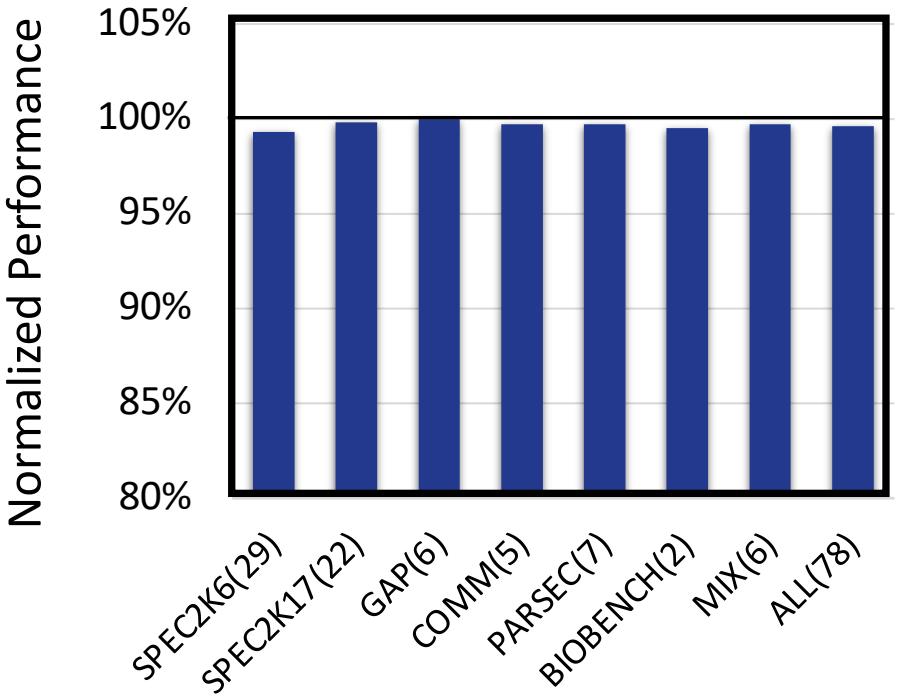


Negligible Performance Impact

(0.4% slowdown on average)



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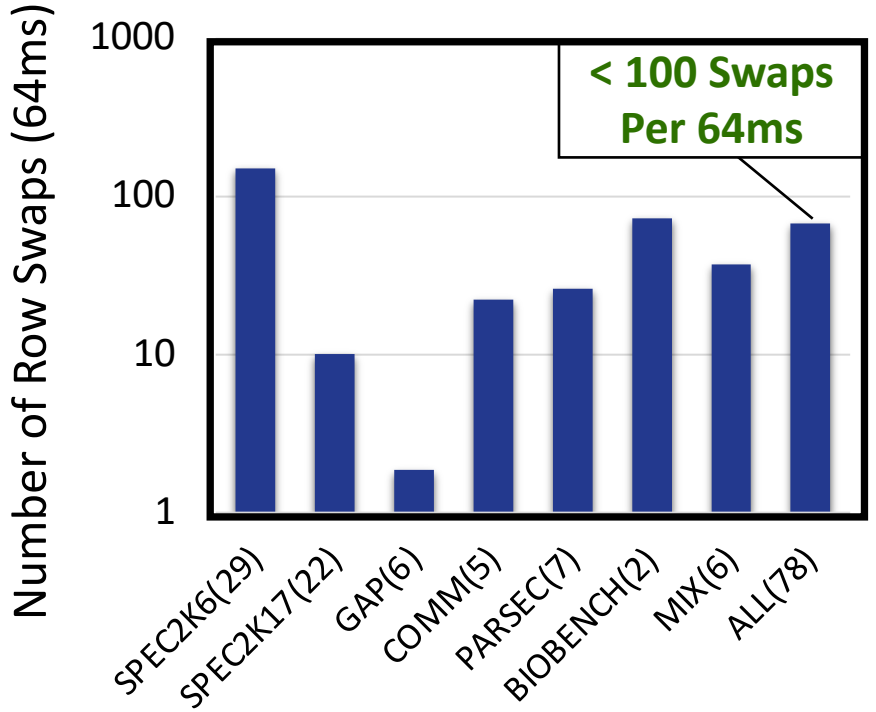

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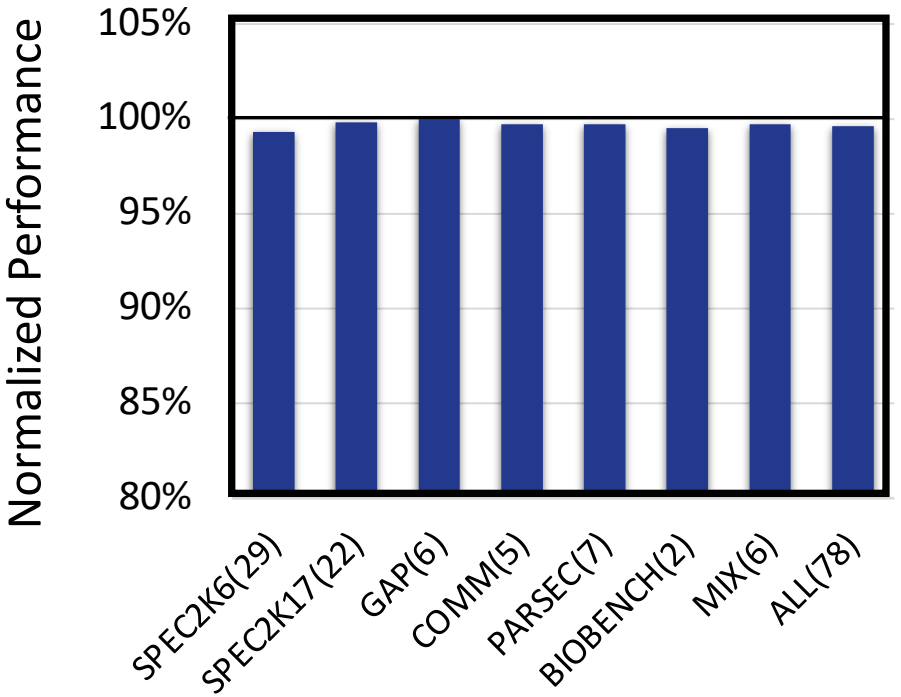
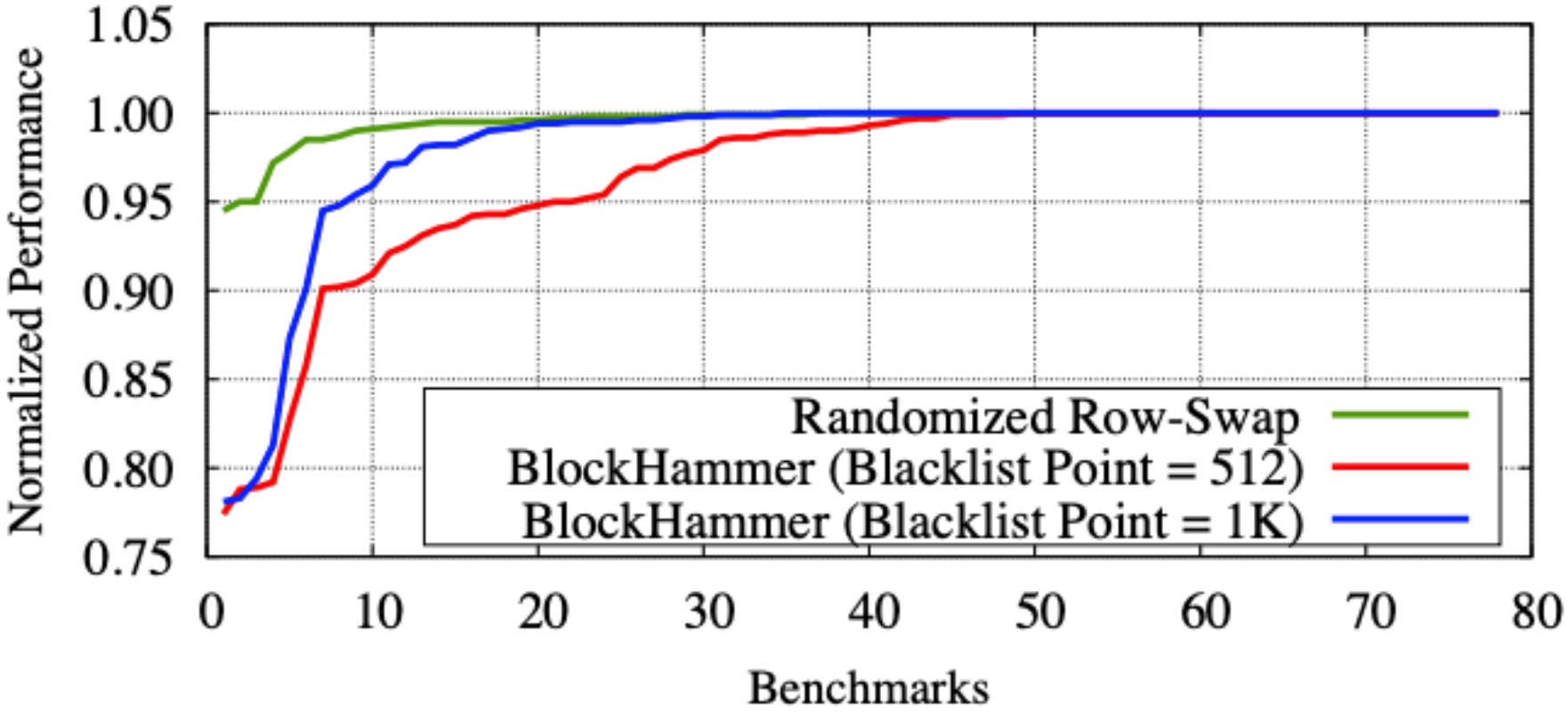


Randomized Row Swap has negligible performance impact due to infrequent swaps

Comparison with Prior Aggressor Focused Mitigation

Blockhammer [HPCA'21]

Rate-Throttles Aggressors at Blacklist Point (Earlier Than RTH) For Entire 64ms



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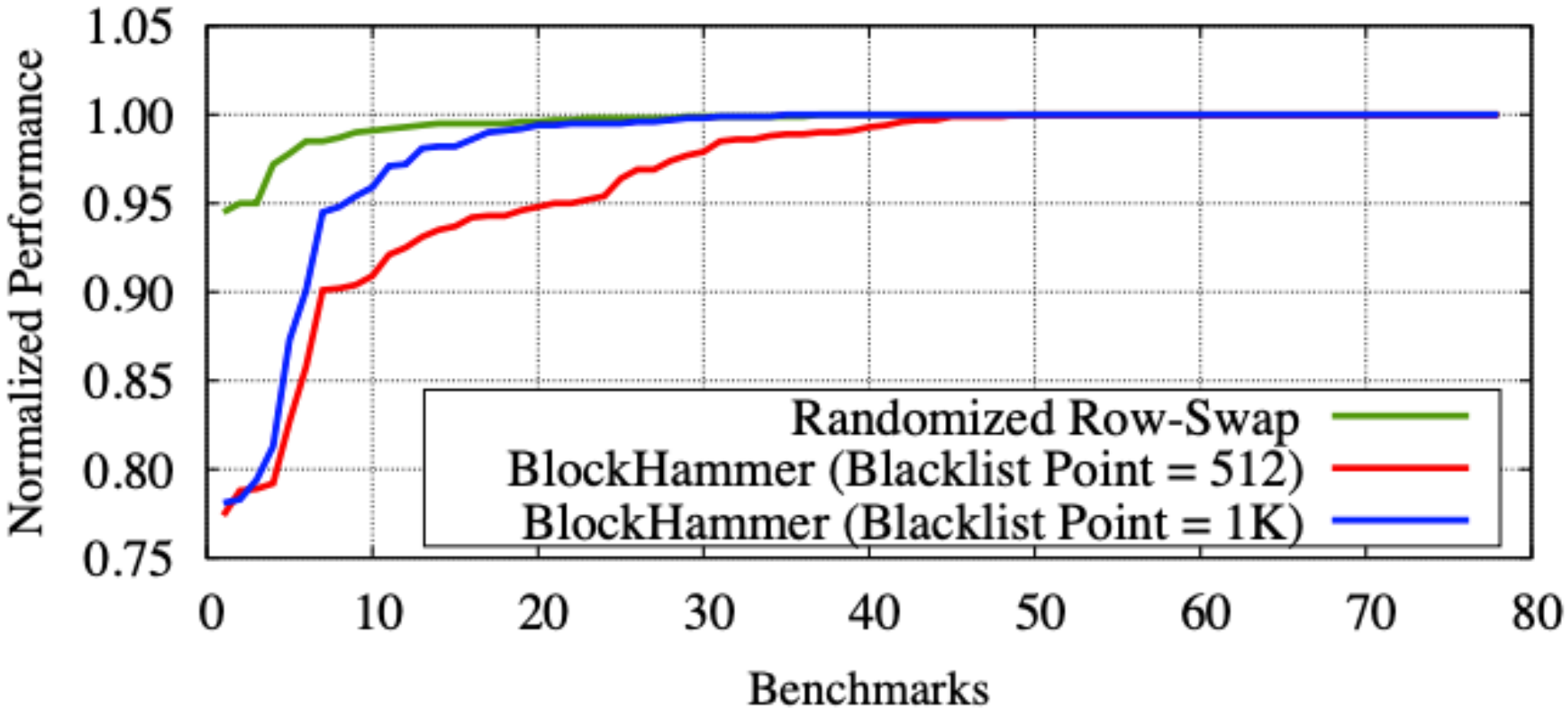
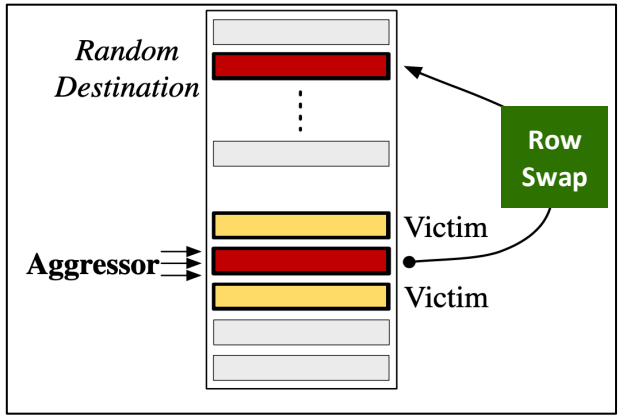


Randomized Row Swap Incurs Much Lower Worst-Case Slowdowns vs Blockhammer

(mitigation is less expensive and hence adds less overheads in benign workloads)

Takeways from Randomized Row Swap



New Aggressor-Focused Mitigation – Swaps Aggressors with Random Destinations & Successively Remaps --> No Row Crosses Rowhammer Threshold

Randomized Row Swap incurs modest costs (0.4% slowdown, ~40KB SRAM/bank) while providing security against years of continuous attack

Resilient to TRResspass [SP'20], Half-Double (2021), Blacksmith [SP'22] attacks & potentially future attacks?