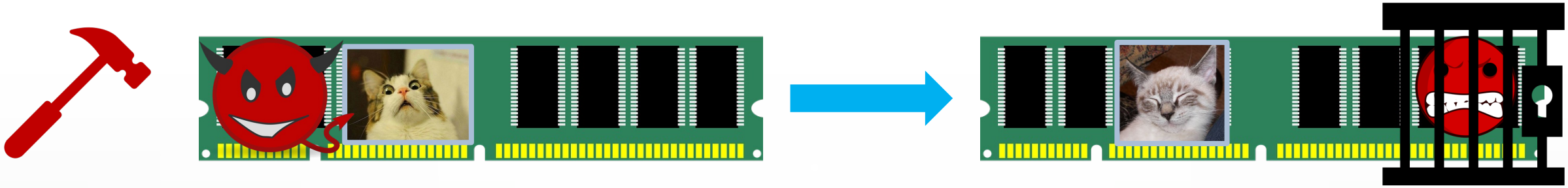


AQUA: SCALABLE ROWHAMMER MITIGATION

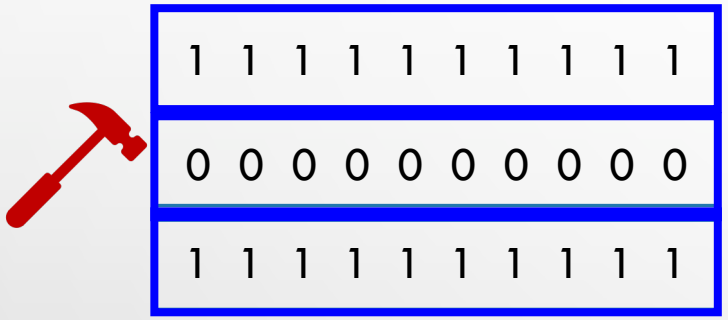
BY QUARANTINING AGGRESSOR ROWS AT RUNTIME

Anish Saxena†, Gururaj Saileshwar†, Prashant J. Nair‡, Moinuddin Qureshi†

†Georgia Institute of Technology, USA

‡University of British Columbia, Canada

ROWHAMMER



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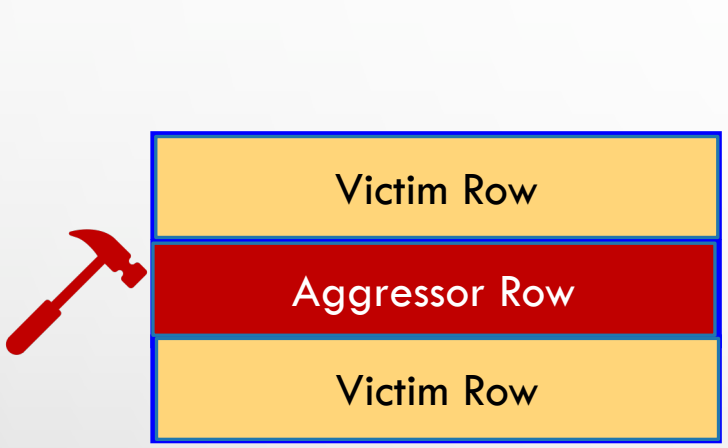
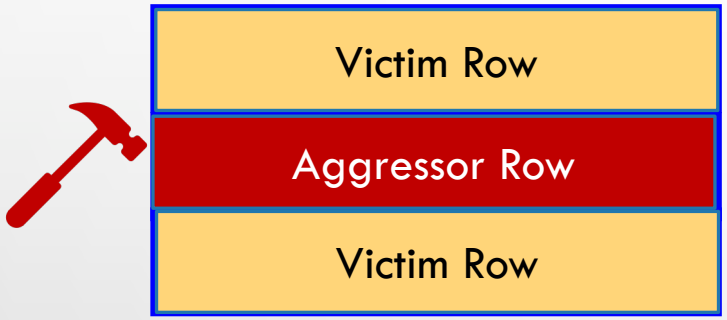
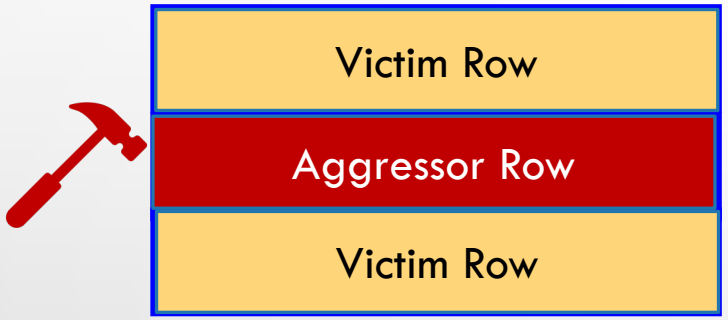
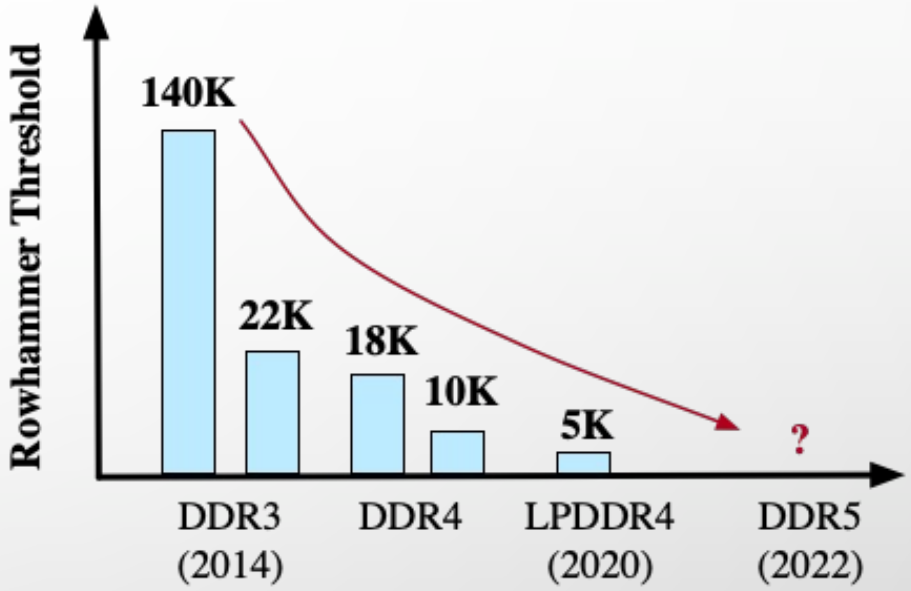


ROWHAMMER



ROWHAMMER

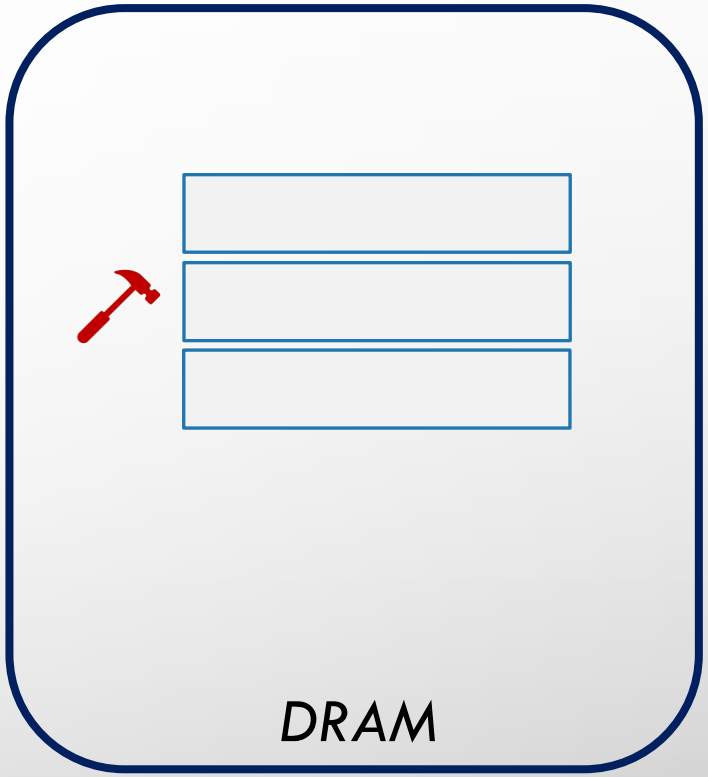




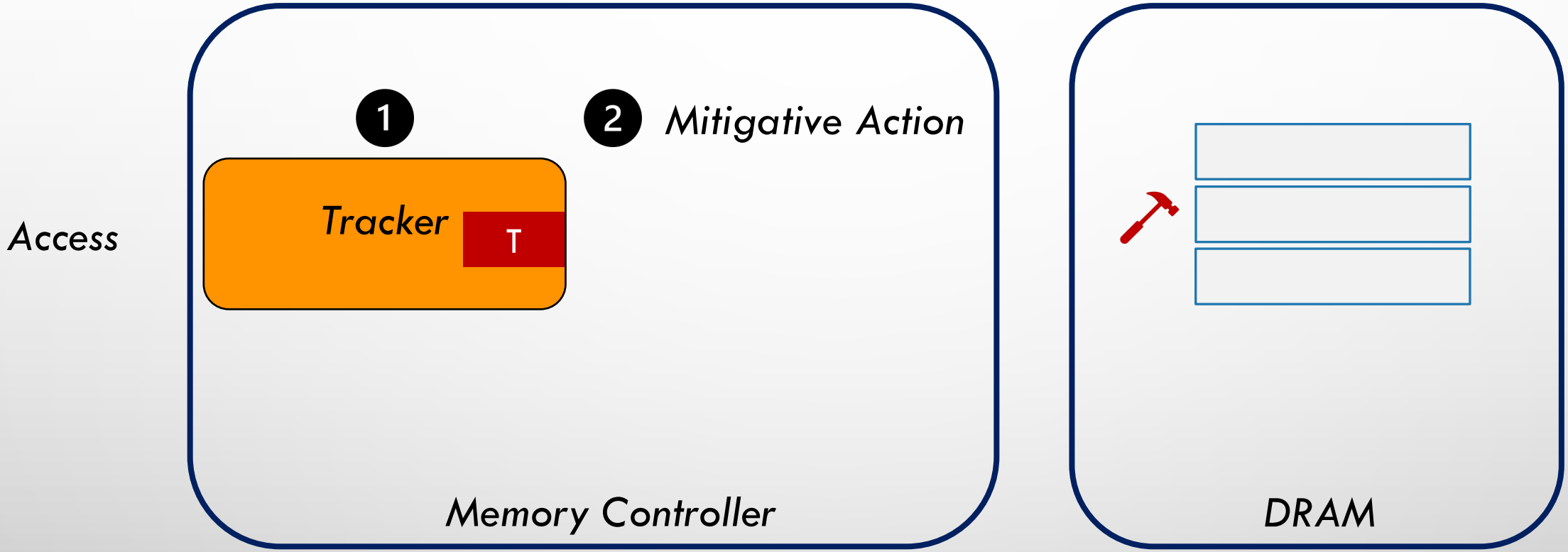
Defenses must scale to plummeting Rowhammer Threshold (TRH)

ROWHAMMER PROTECTION

Access



ROWHAMMER PROTECTION



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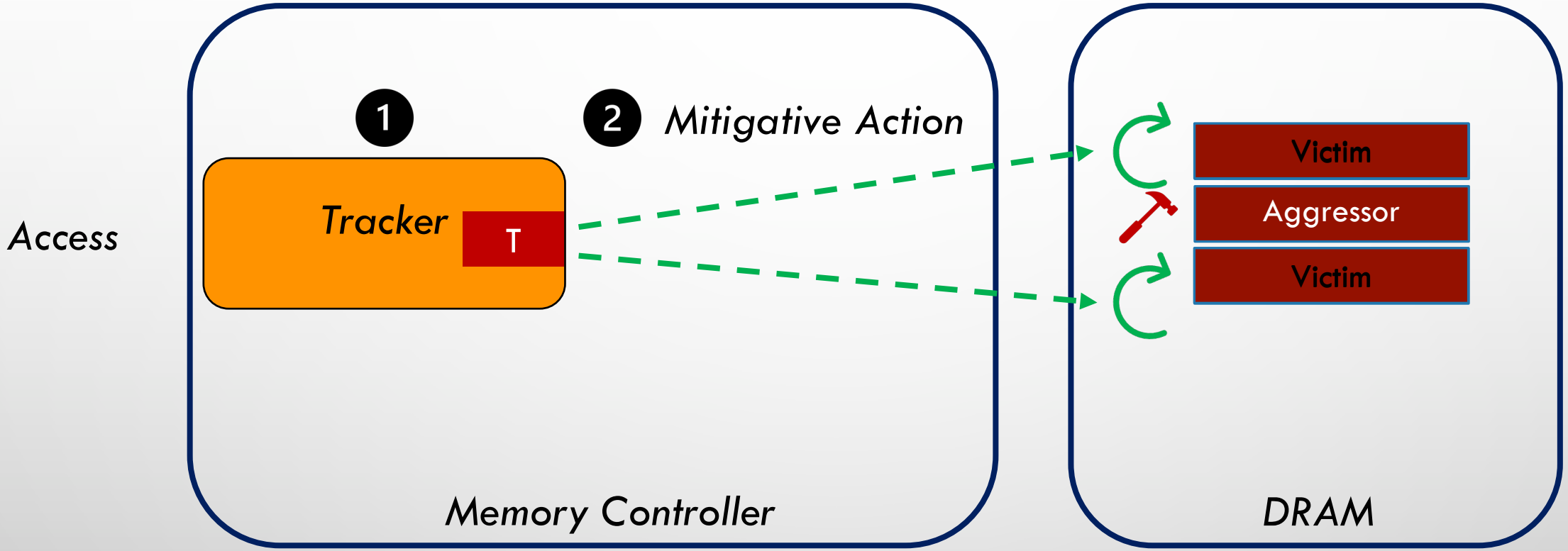
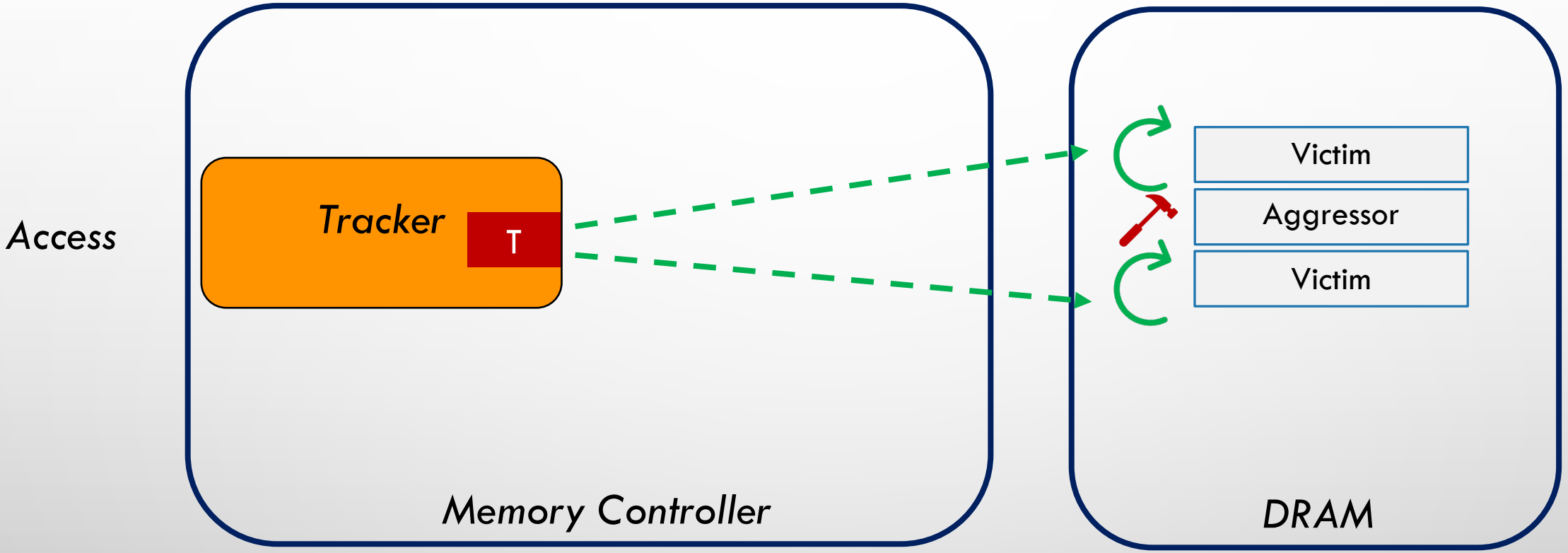
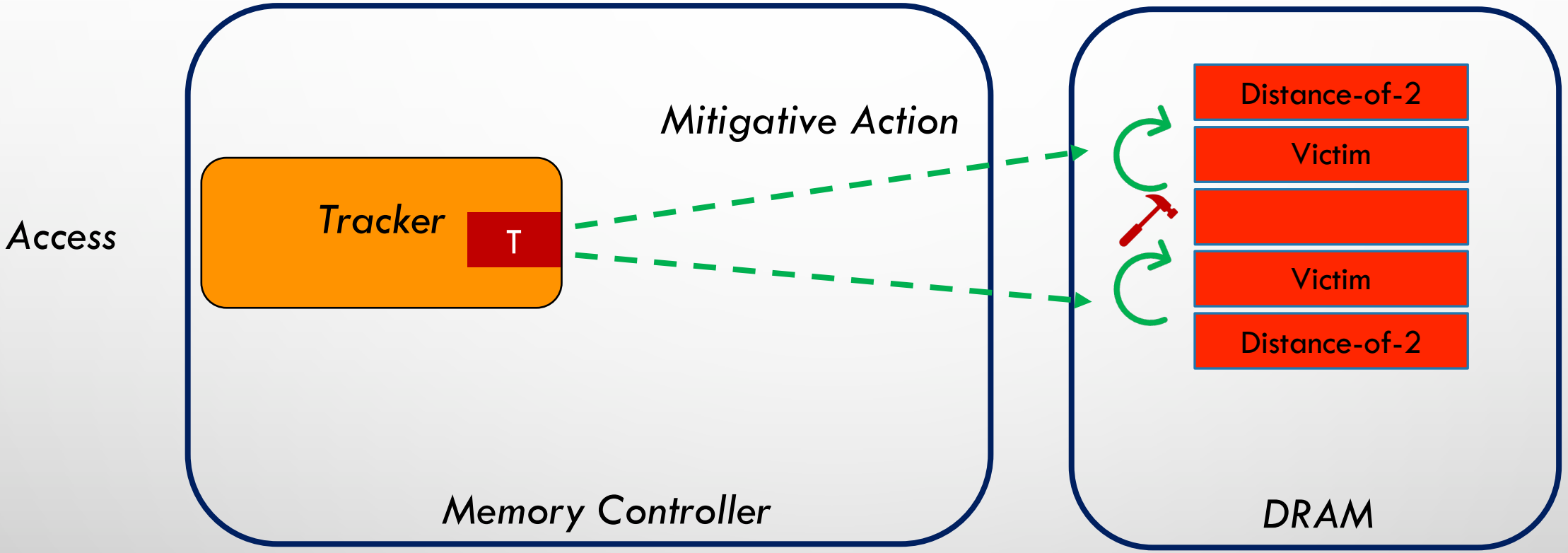


Commerical Rowhammer mitigations rely on victim refresh

HALF-DOUBLE ATTACK

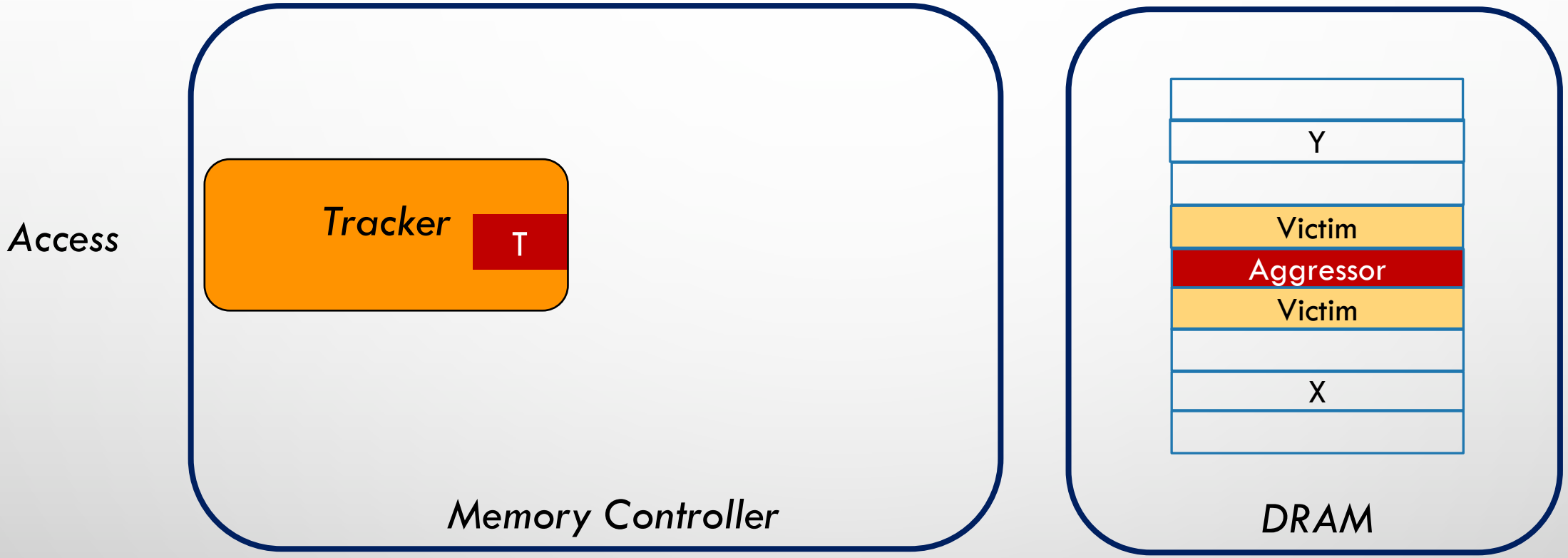


HALF-DOUBLE ATTACK



Half-Double breaks all commercial defenses by leveraging victim refreshes

RANDOMIZED ROW-SWAP [ASPLOS'22]



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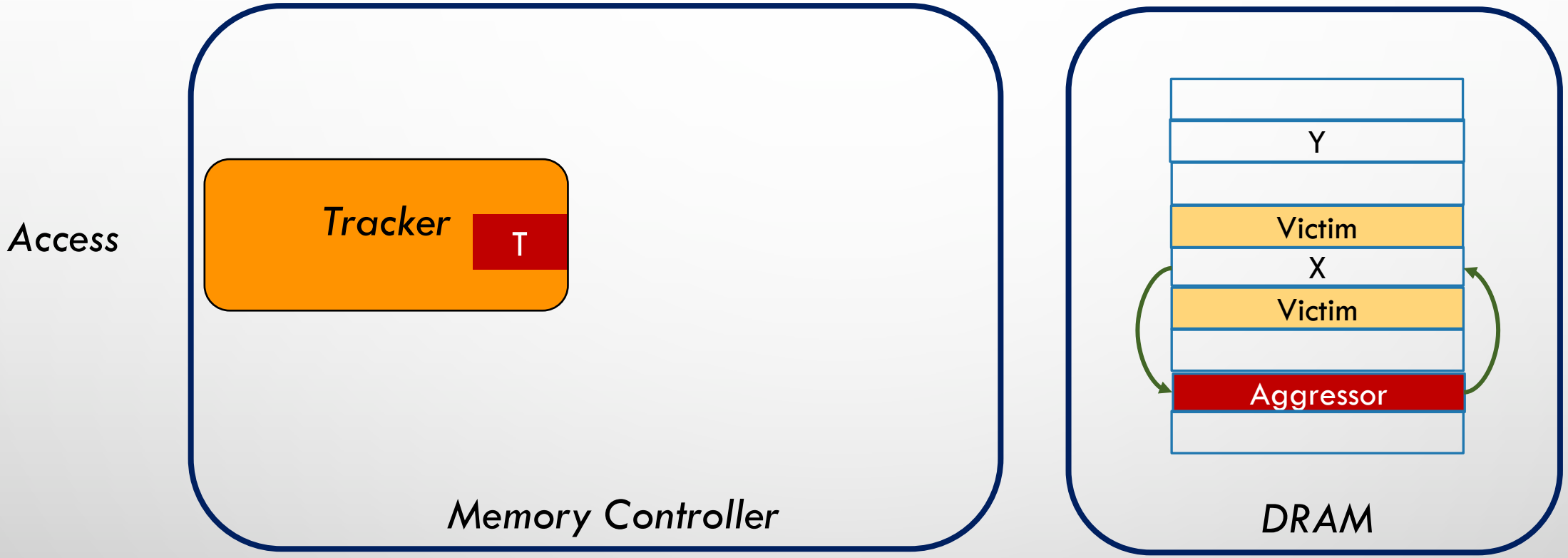

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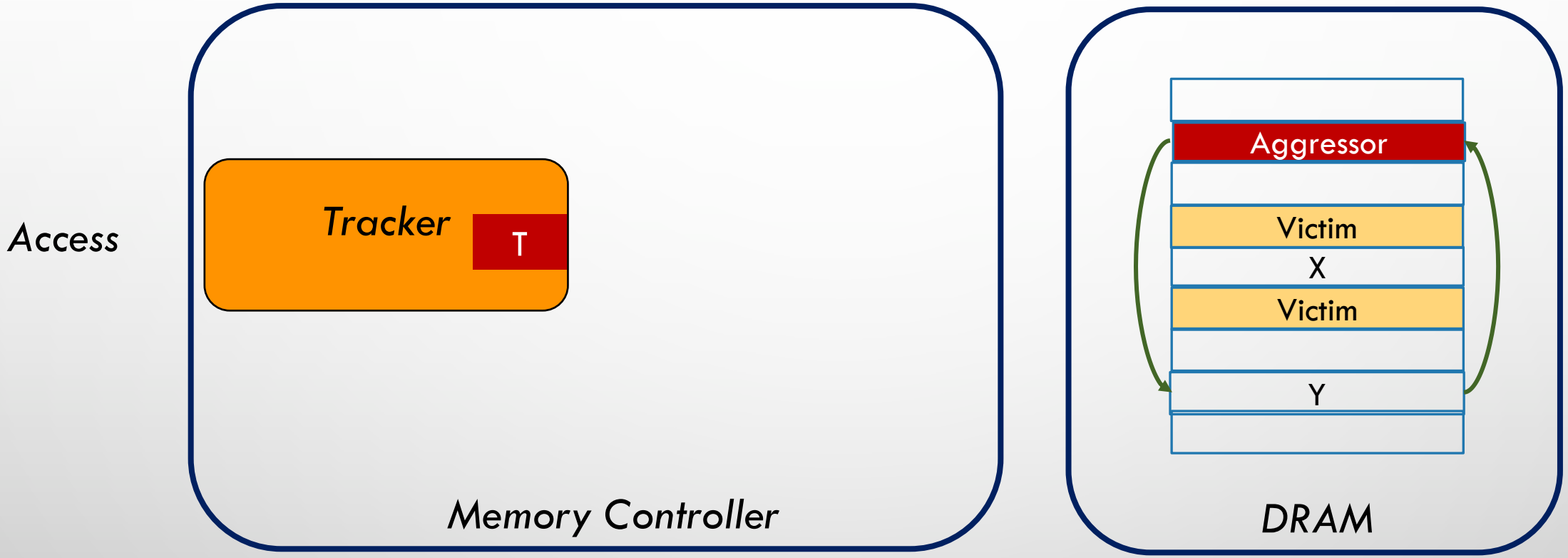

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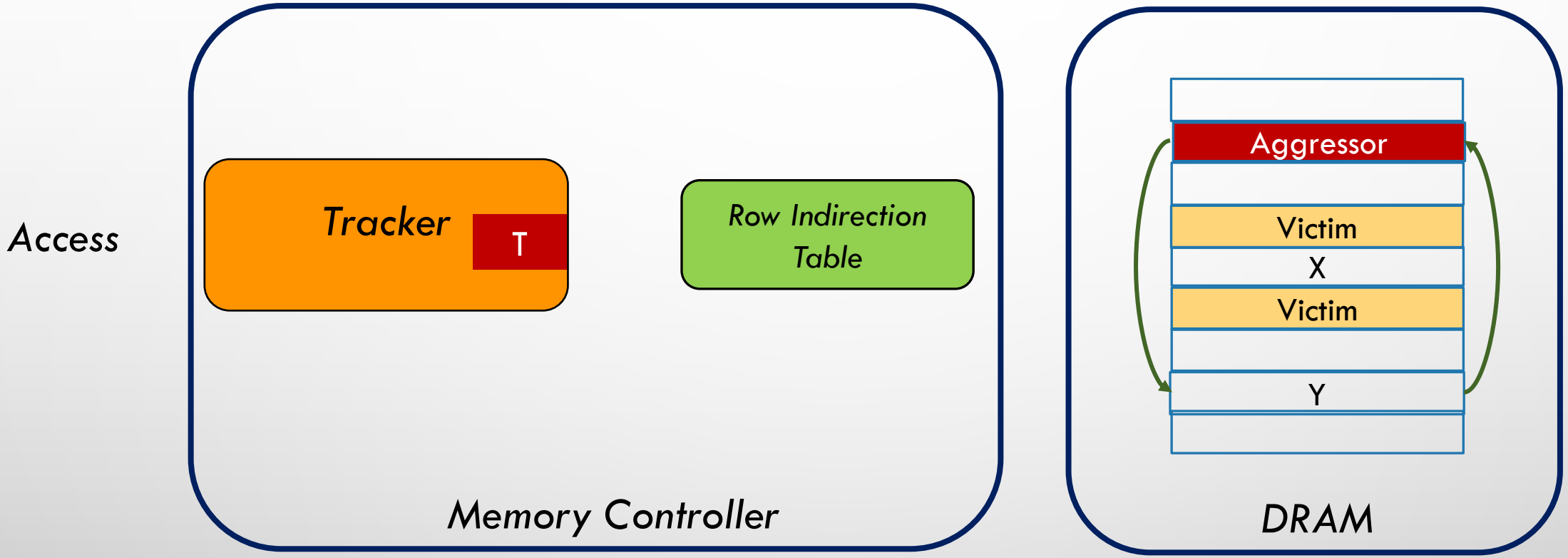

RRS breaks spatial proximity by swapping the aggressor with a randomly selected row

LIMITATIONS OF RANDOMIZED SWAPS

Security via Randomization

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$$T = TRH/6$$

Current TRH

TRH	T = TRH/6
4K	666

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1K	**166**

Our default TRH

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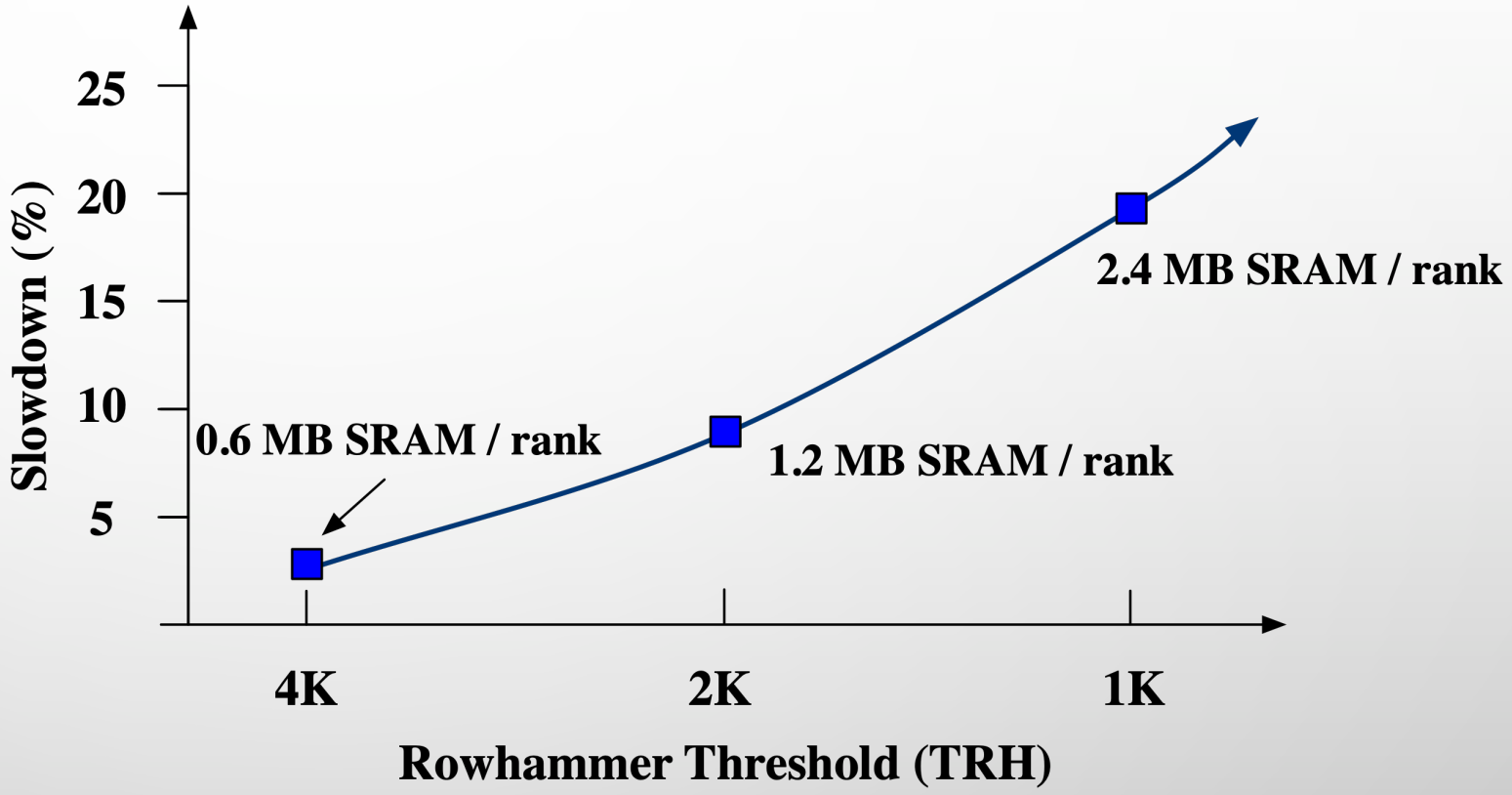
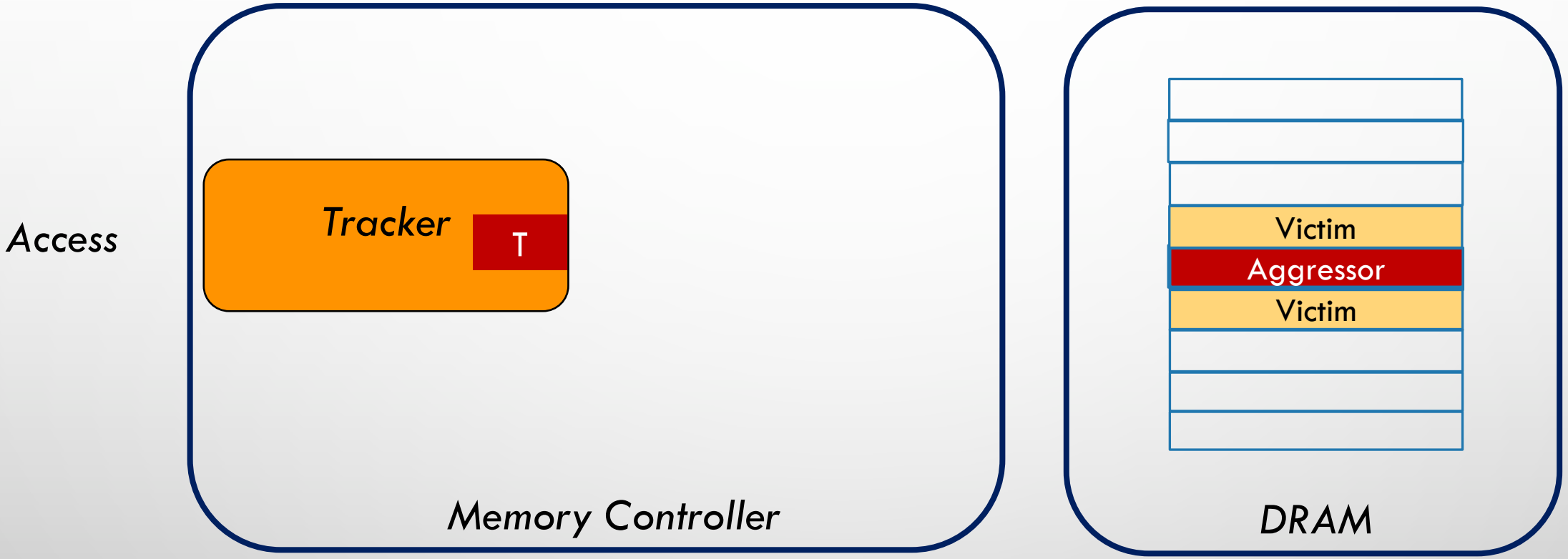


Our goal is to develop a scalable Rowhammer mitigation with low overheads

AQUA: QUARANTINING AGGRESSORS



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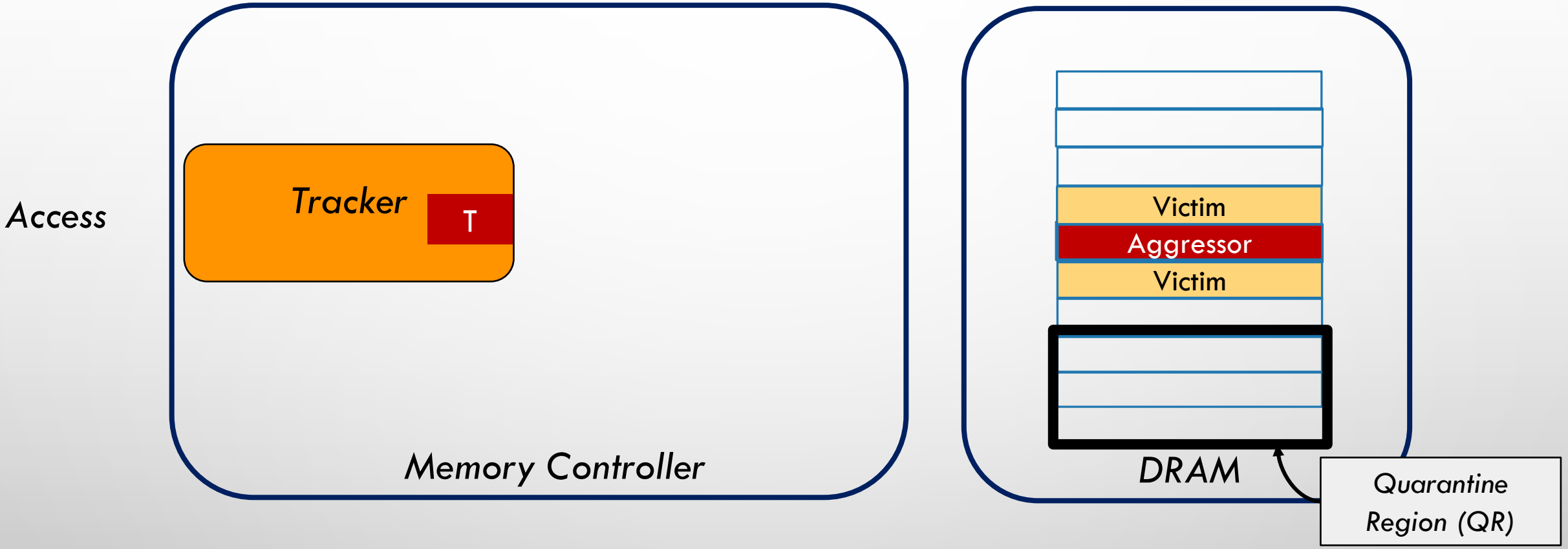

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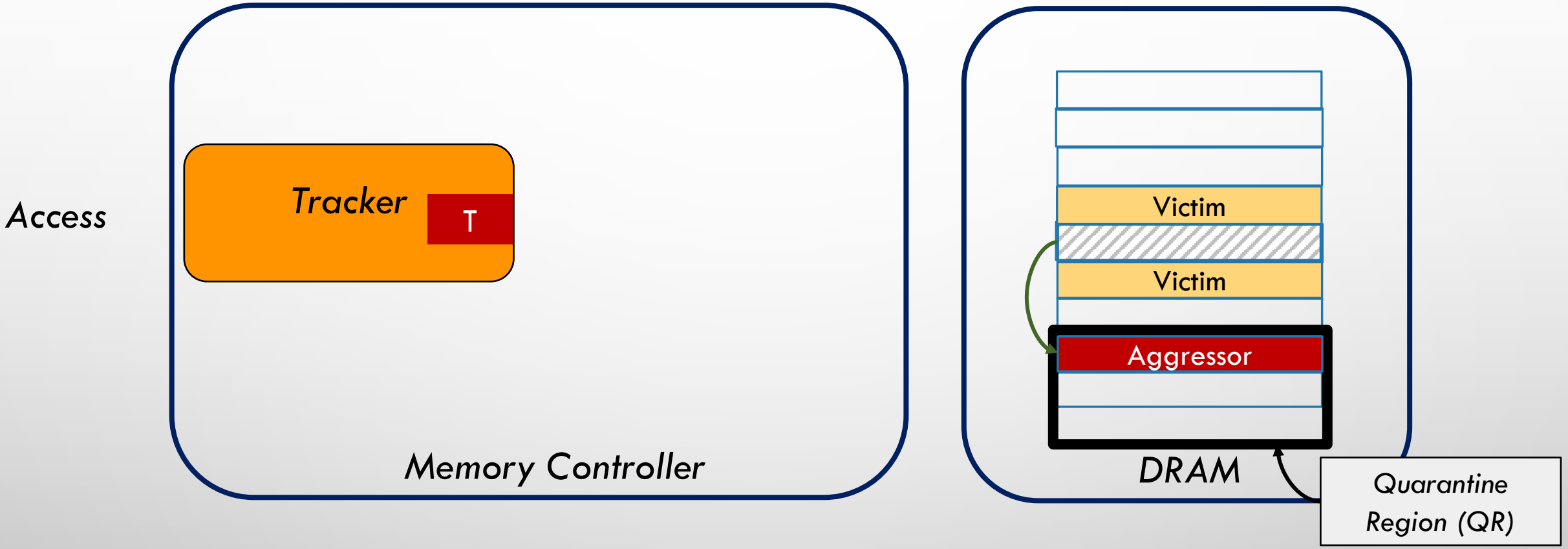

Security via Isolation: AQUA moves rows to a dedicated region of memory

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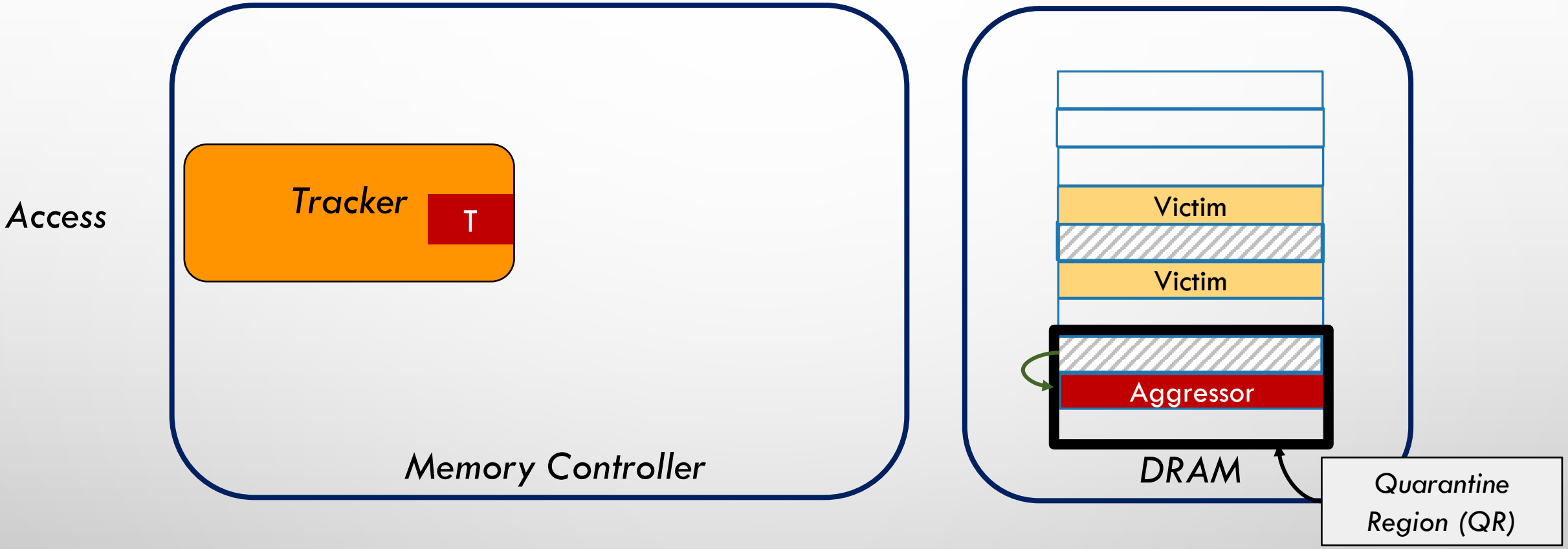

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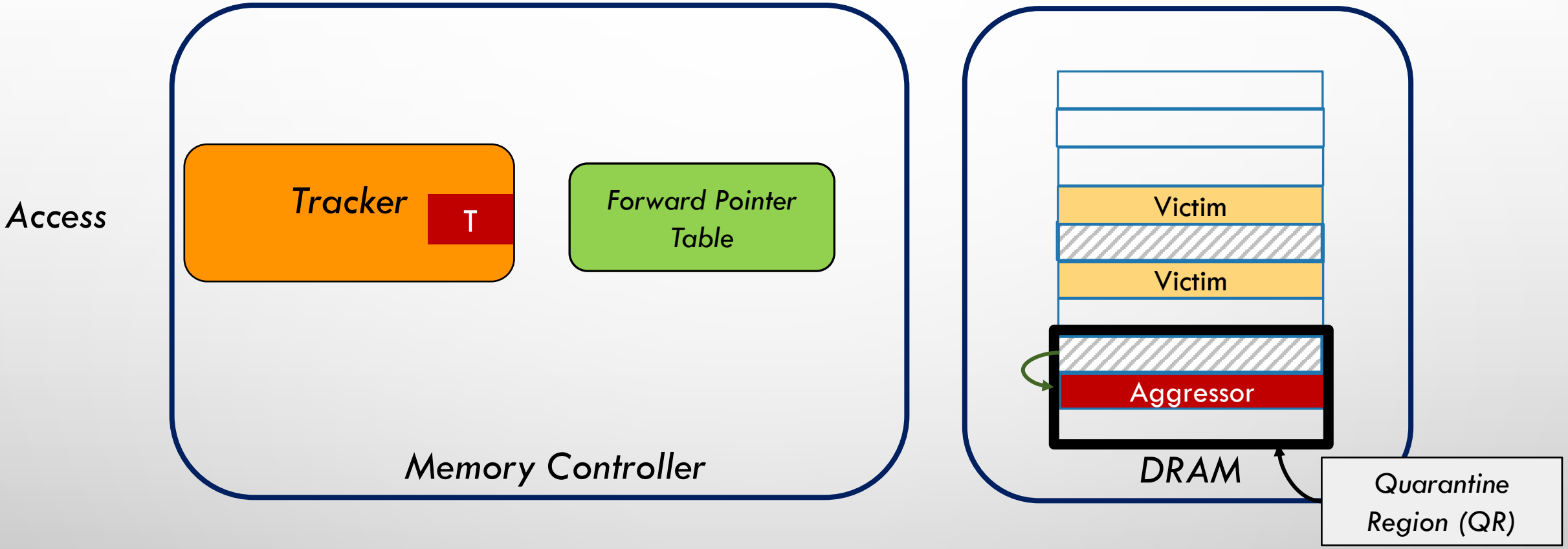

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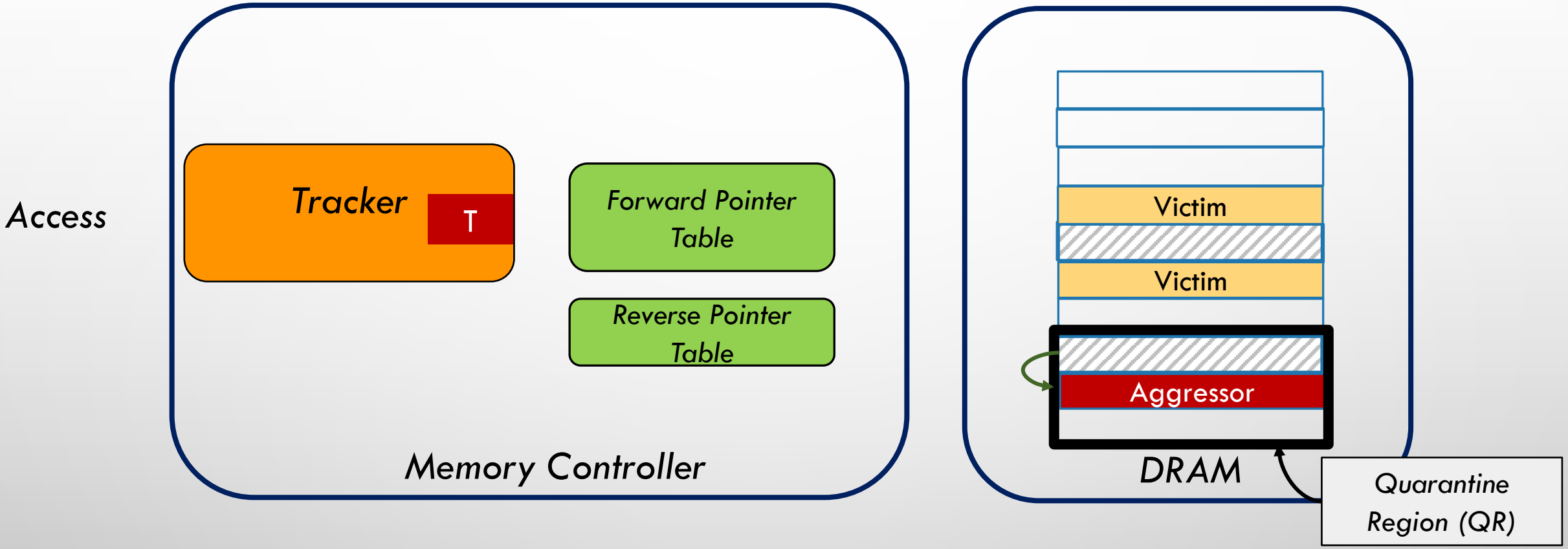

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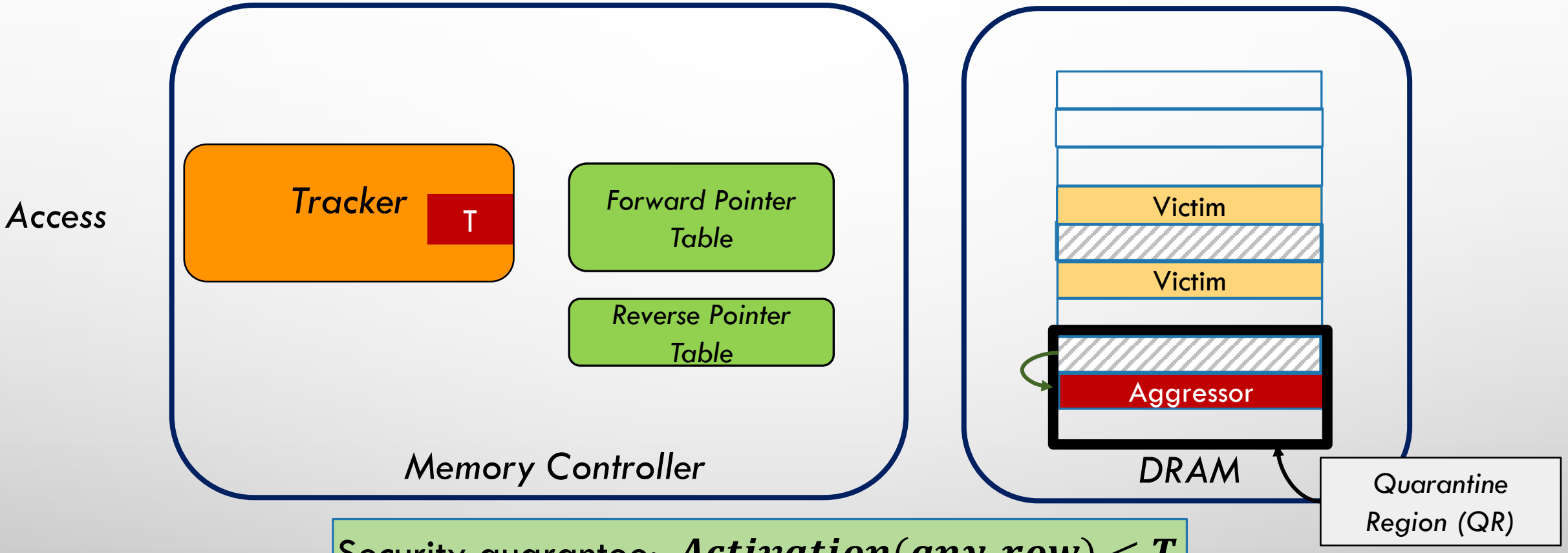

Security guarantee: $Activation(any\_row) < T$

Security via Isolation: AQUA moves rows to a dedicated region of memory

SIZING THE QUARANTINE REGION

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$$T = \frac{TRH}{2}$$

T	DRAM overhead (16GB memory)
500	1.1%
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125	1.8%

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$$\text{Max-Rows} \propto \frac{1}{\text{T, time-to-move}}$$

Time spent performing row migration

Reserving 1-2% of DRAM for the quarantine region prevents Rowhammer

ROW MIGRATIONS

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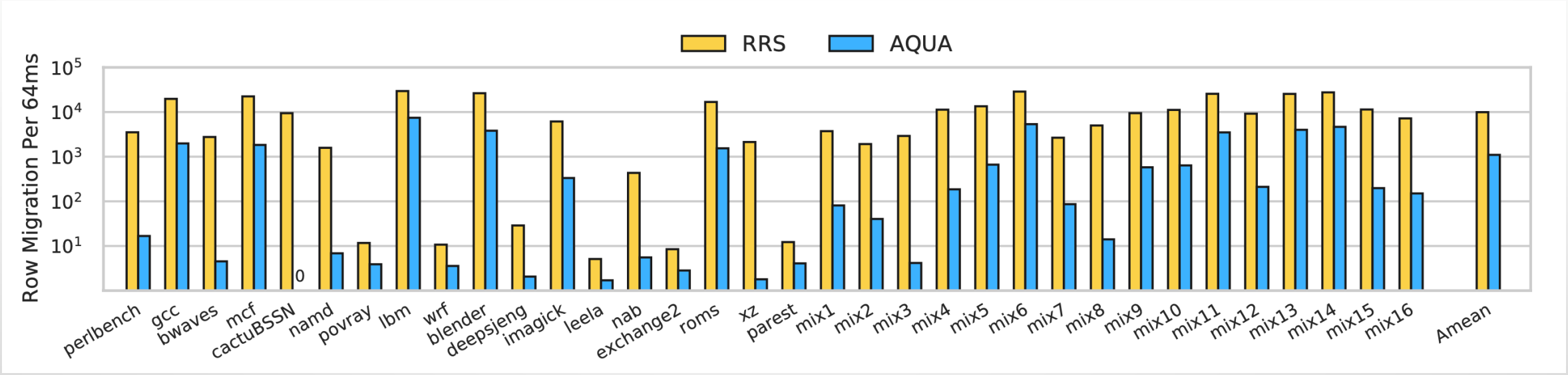
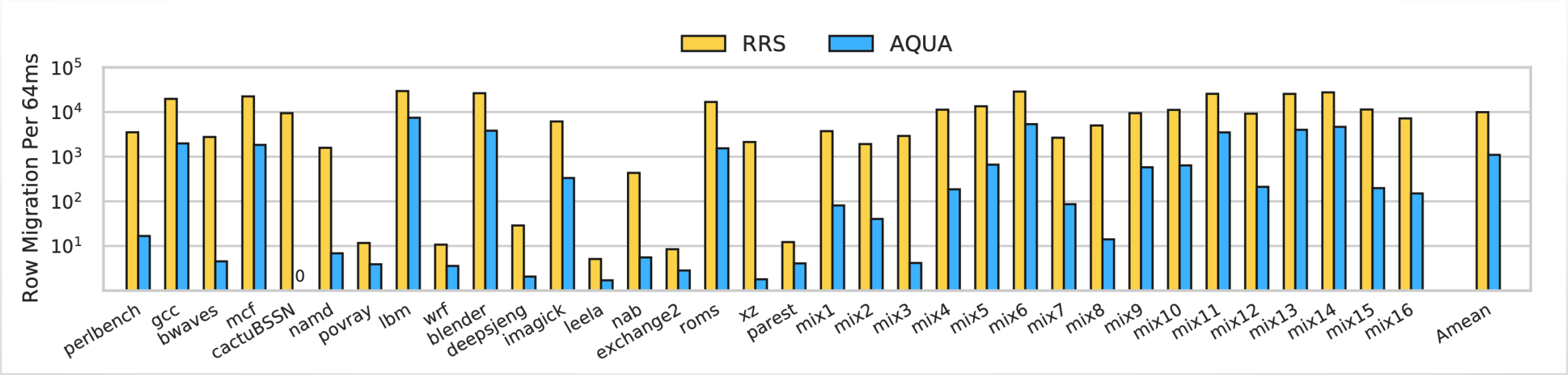
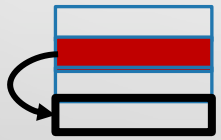


Row migrations reduce by 9X as less mitigations are performed

ROW MIGRATIONS





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PERFORMANCE

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$$Slowdown \propto Migrations$$

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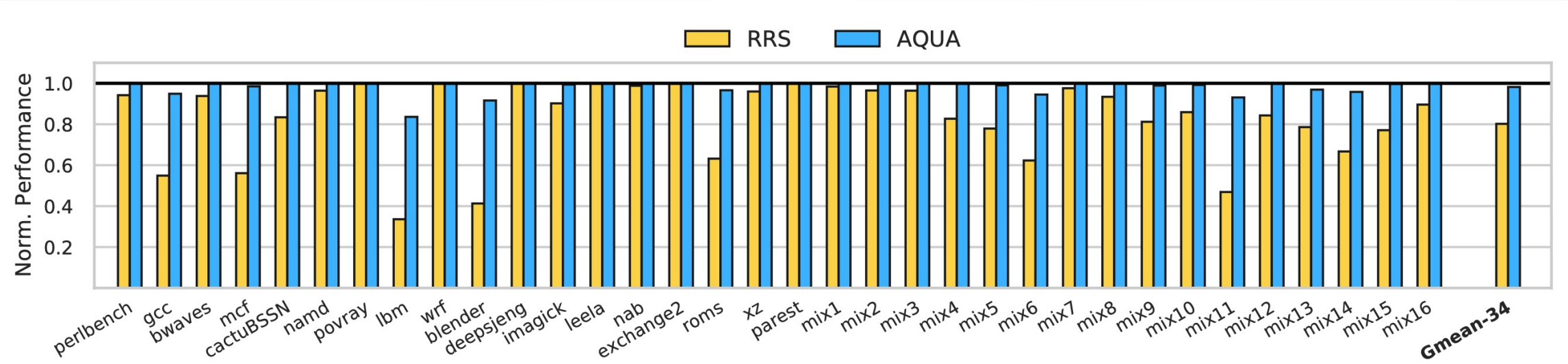

Slowdown in AQUA: 1.8%

Slowdown in RRS: 19.8%

Less migrations leads to 11X reduction in slowdown

SRAM OVERHEAD

Indirection Tables

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RRS	2.4 MB/rank
AQUA-SRAM	172 KB/rank

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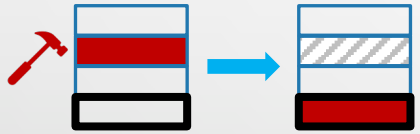

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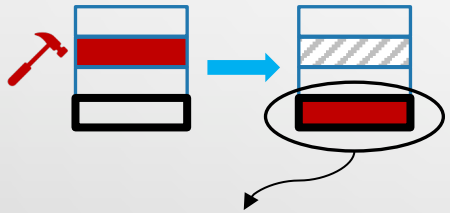

Not a secret

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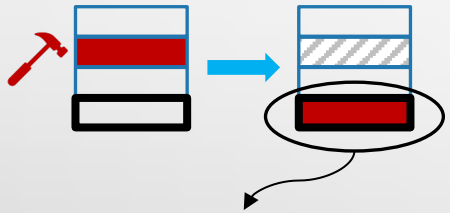

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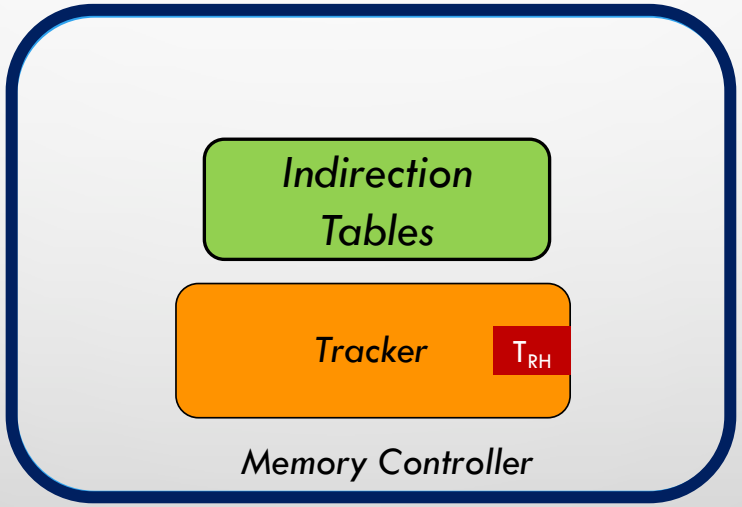
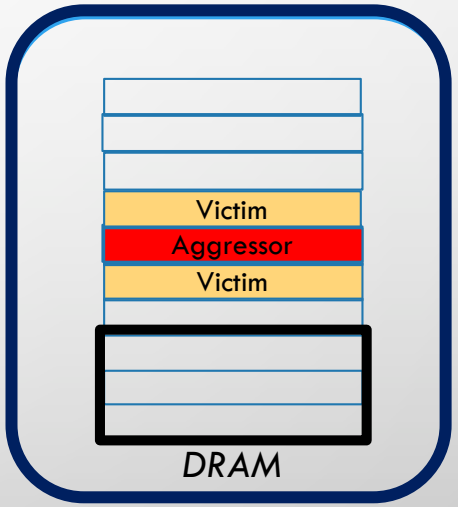


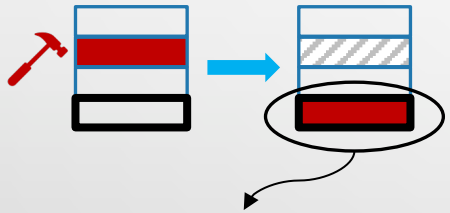


SRAM OVERHEAD

Indirection Tables

RRS	2.4 MB/rank
AQUA-SRAM	172 KB/rank
AQUA-DRAM	**32 KB /rank**

Slowdown
1.8% → 2.1%



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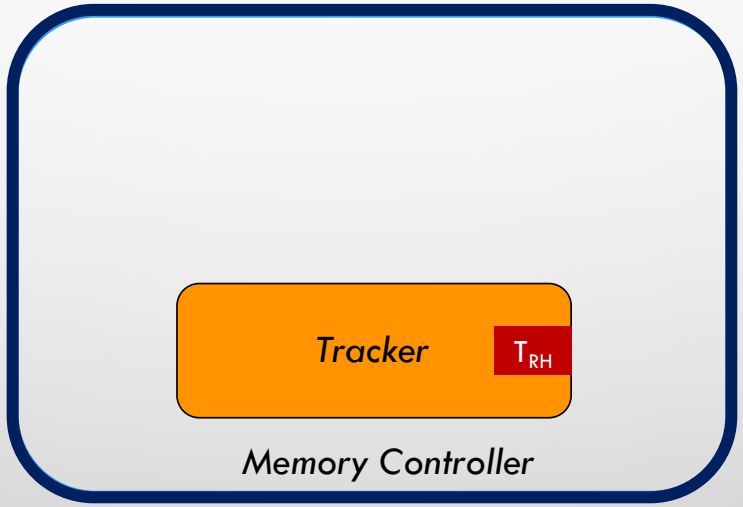
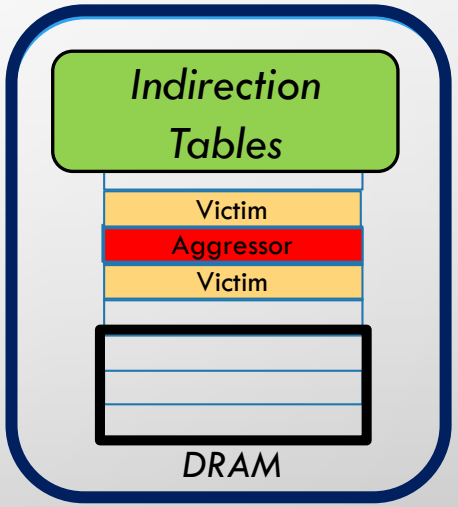
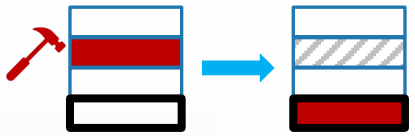




SRAM overhead for AQUA's mitigation is 41KB per rank, 60X lower than RRS

CONCLUSION

- ✓ Breaks spatial proximity by isolating aggressors in 1-2% DRAM
- ✓ Uses the same effective threshold as the tracker
- ✓ Fewer rows need mitigation and fewer mitigations per row
- ✓ 60X less SRAM and 11X less slowdown compared to RRS



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THANK YOU

https://tinyurl.com/AQUA-code

BACKUP SLIDES

TRACKER OVERHEADS

Structure	**RRS-MG**	**AQUA-MG**	**RRS-Hydra**	**AQUA-Hydra**
Tracker	396 KB	396 KB	28.3 KB	30.3 KB
Mapping Table(s)	2.4 MB	32.6 KB	2.4 MB	32.6 KB
Buffer(s)	16 KB	8 KB	16 KB	8 KB
Total	2,870 KB	437 KB	2,502 KB	71 KB

TRH = 1K

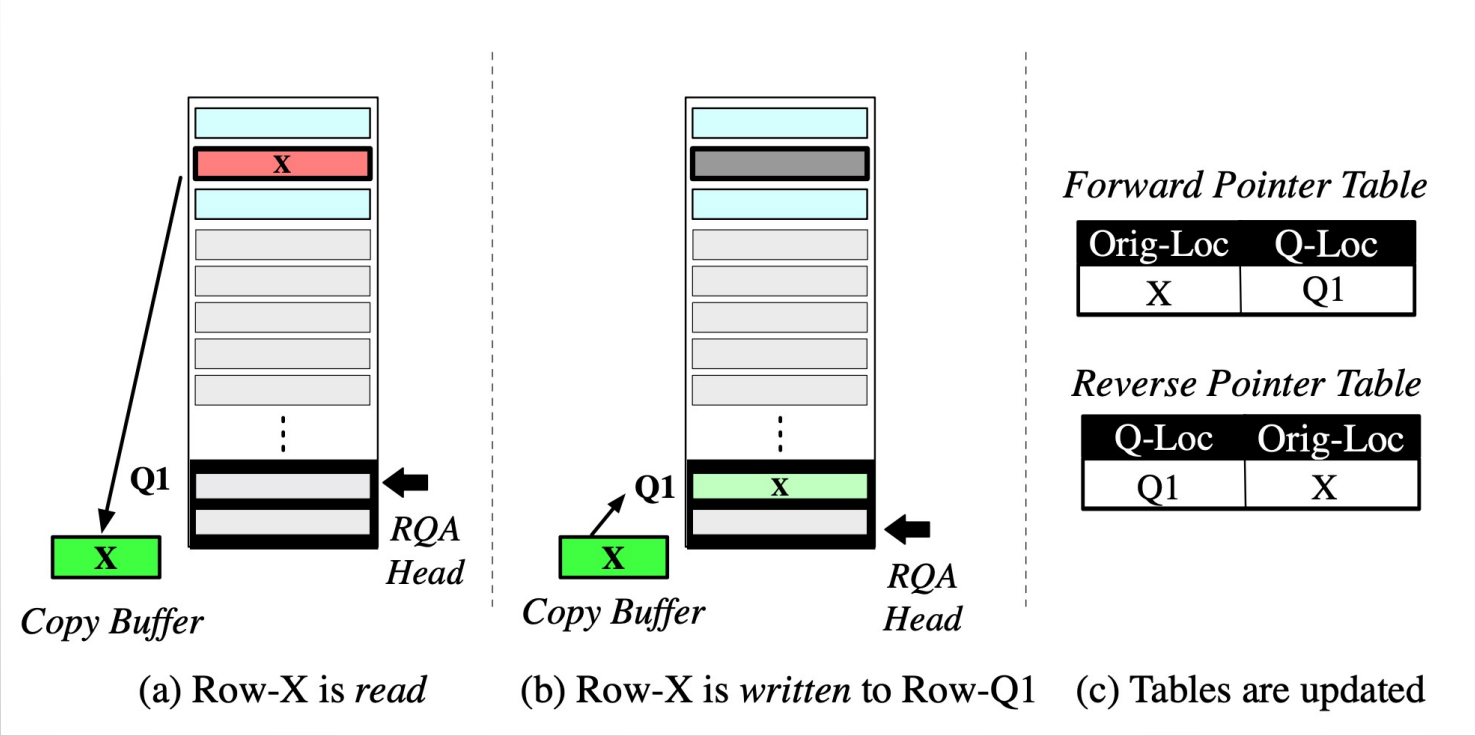
AQUA COMPARED TO VICTIM REFRESH

Attribute	Victim-Refresh	AQUA
Slowdown	<0.2%	2.1%
Mitigates Classic Rowhammer (Neighboring Row Bit Flips)	✓	✓
Mitigates Complex Patterns (Far Aggressors of Half-Double)	✗	✓
Works Without Knowing DRAM Mapping	✗	✓

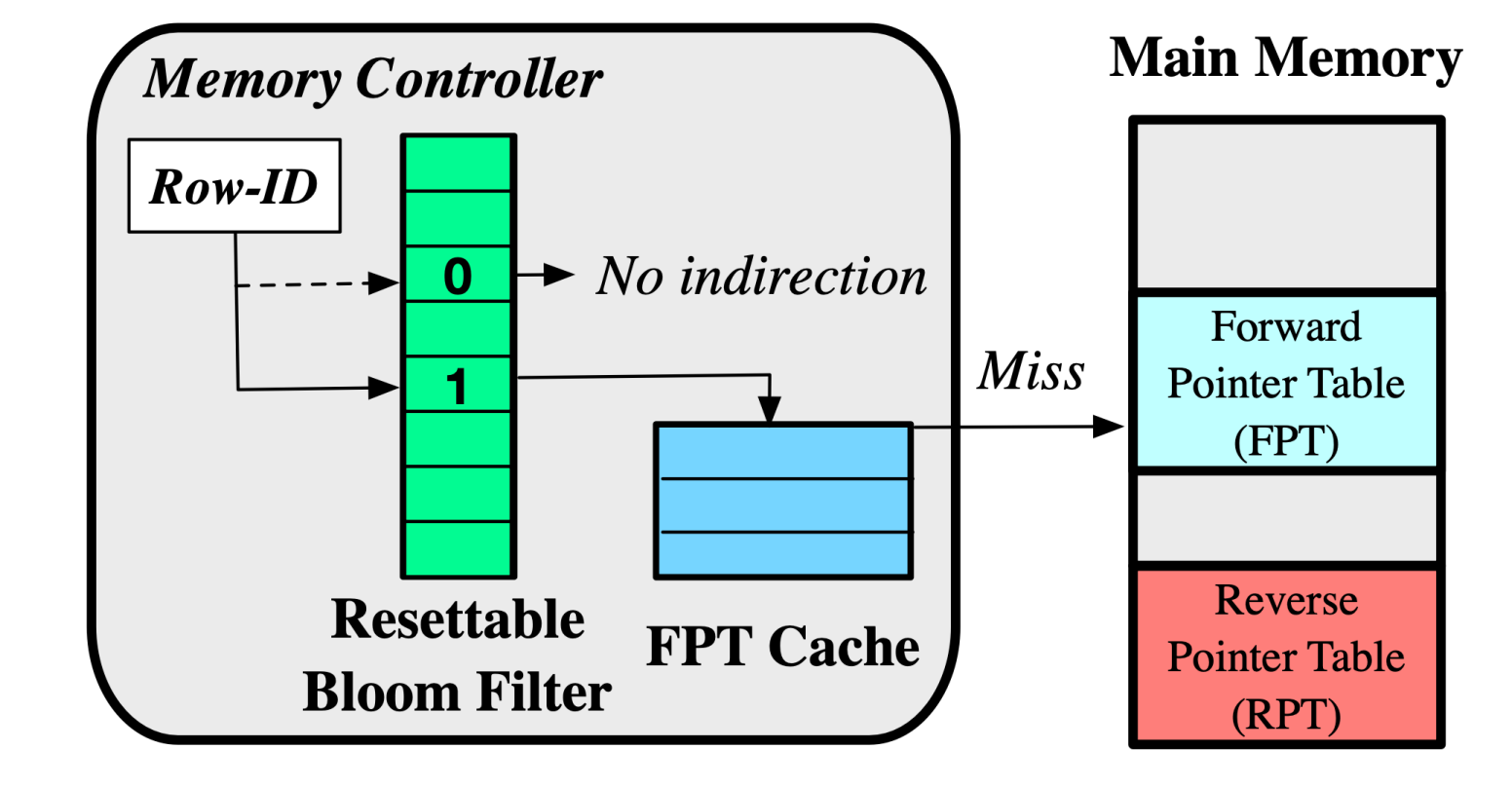
AQUA COMPARED TO PRIOR WORKS

Metric	Blockhammer	CROW	CROW-Agg	RRS	AQUA
SRAM for Mapping Tables	N/A	**26 MB**	32 KB	**2.4 MB**	41KB
DRAM Storage Overhead	0%	**1060%**	**530%**	0%	1.1%
Normalized Perf. Loss (Avg)	**36%**	<0.1%	<0.1%	**19.8%**	2.1%
Worst-Case Slowdown	**1280**×	<1%	<1%	11×	3×
Commodity DRAM	Yes	**NO**	**NO**	Yes	Yes

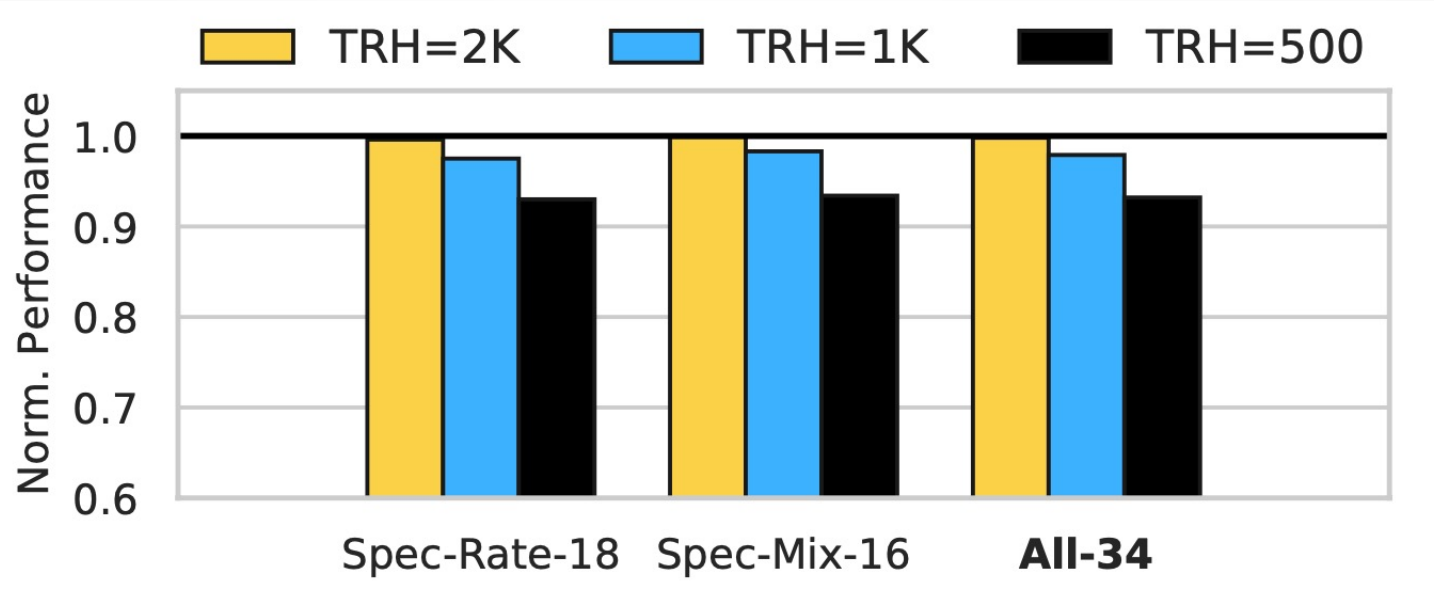
ROW MIGRATION WITH SRAM-BASED COPY BUFFER



AQUA WITH MEMORY-MAPPED TABLES



SENSITIVITY TO ROWHAMMER THRESHOLD

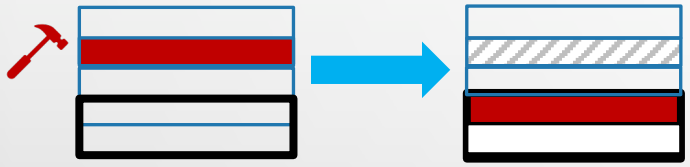


OVERHEADS OF CROW

Copy-Rows	DRAM Overhead	Aggressors	T_{RH} Tolerated
8 (default)	1.6%	4	340K
32	6.3%	16	85K
128	25%	64	21.3K
512	100%	256	5.3K

SIZING THE QUARANTINE REGION

Security via Isolation



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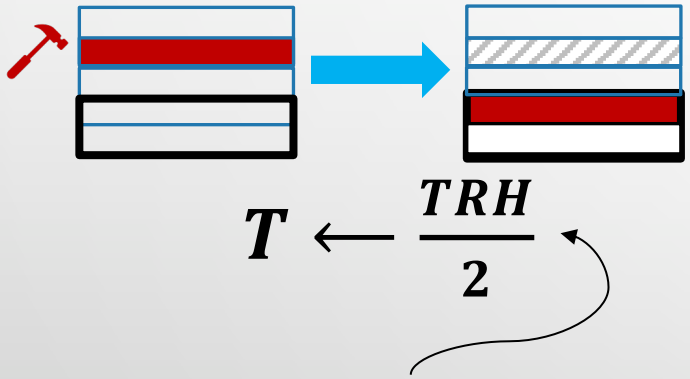

$$T \leftarrow \frac{TRH}{2}$$

Due to tracker inefficiency

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Quarantine Region

$$QR\_size \geq Max\_Rows$$

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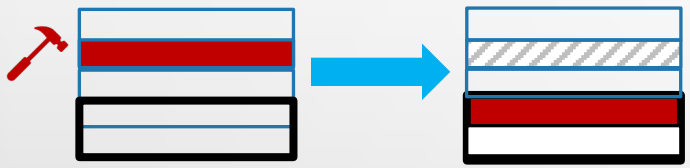

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$$QR\_size \geq Max\_Rows$$

$$Max\_Rows \propto \frac{1}{\mathrm{T},\ time\_to\_move}$$

Time spent performing row migration

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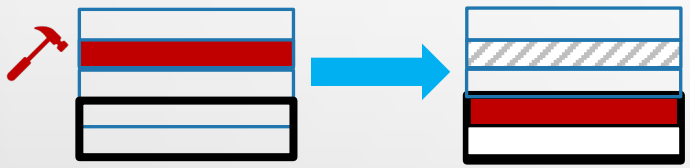

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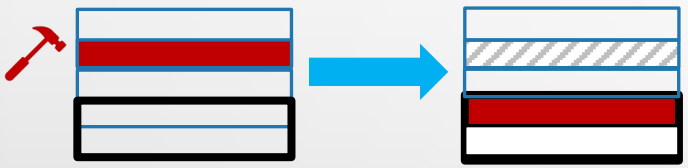

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Time spent performing row migration

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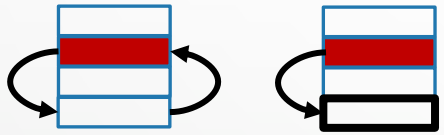
125	1.8%

Reserving 1-2% of DRAM for the quarantine region is sufficient to prevent Rowhammer

ROW MIGRATIONS

ROW MIGRATIONS

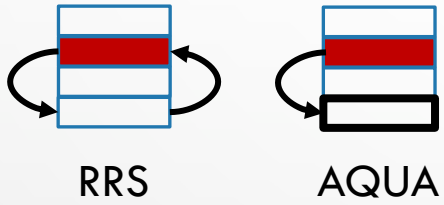
$$Row\text{-}Migrations \propto \frac{Row\text{—}Migrations}{Mitigation}$$



RRS AQUA

ROW MIGRATIONS

$$Row\text{-}Migrations \propto \frac{Row-Migrations}{Mitigation} \times \frac{Mitigations}{Rows-to-mitigate}$$



$$T_{RRS} \leftarrow \frac{T_{RH}}{6}$$

$$T_{AQUA} \leftarrow \frac{T_{RH}}{2}$$

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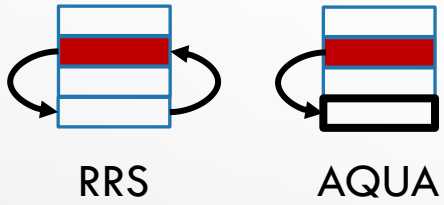

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Workload	Rows with ACT-166+	Rows with ACT-500+
Average	1,665 (2.4X)	694

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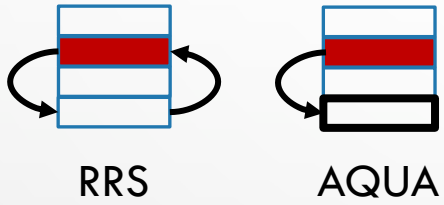

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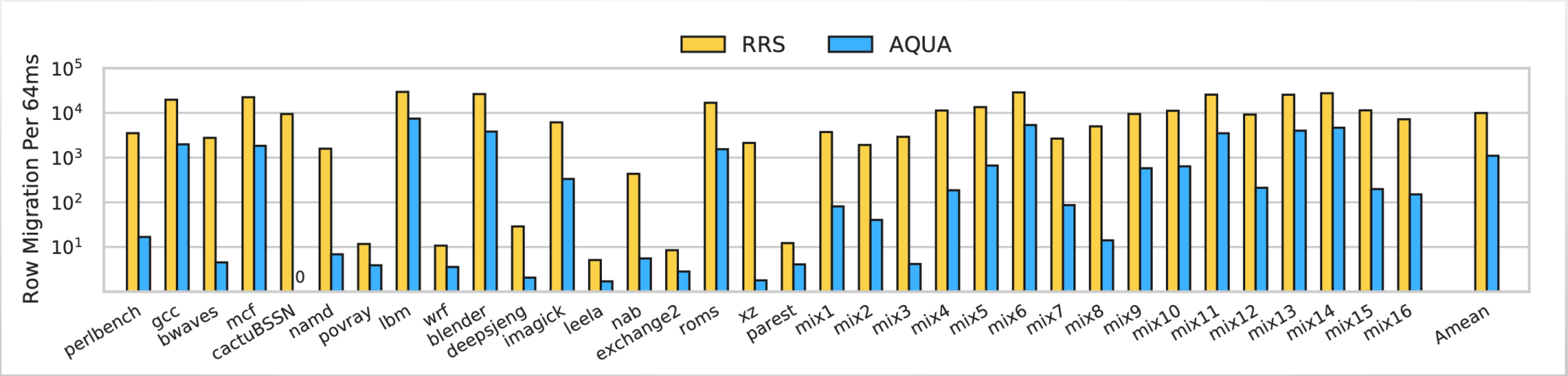
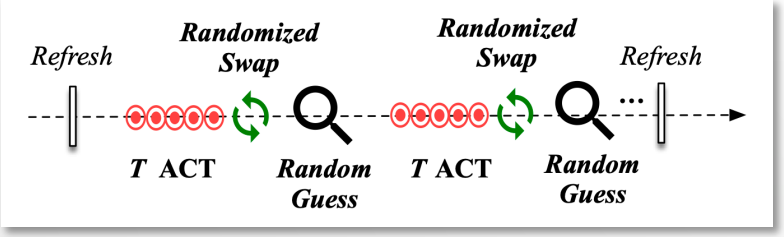


Row migrations reduce by 9X as less mitigations are performed

LIMITATIONS OF RANDOMIZED SWAPS

Security via Randomization



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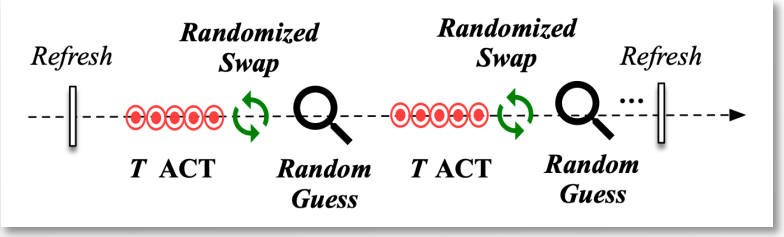
Security via Randomization



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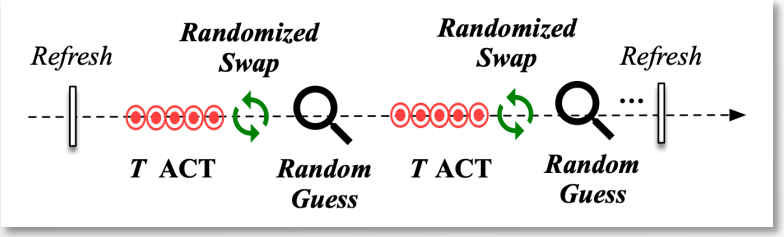
Current TRH

$$666 \leftarrow 4K$$

LIMITATIONS OF RANDOMIZED SWAPS

Security via Randomization



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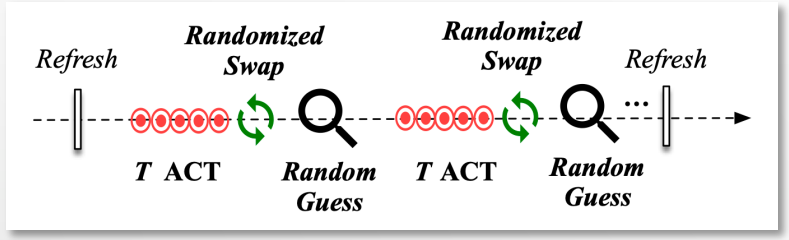
Our default TRH

LIMITATIONS OF RANDOMIZED SWAPS

Security via Randomization



$$T \leftarrow \frac{TRH}{6}$$

$666 \leftarrow 4K$ Current TRH

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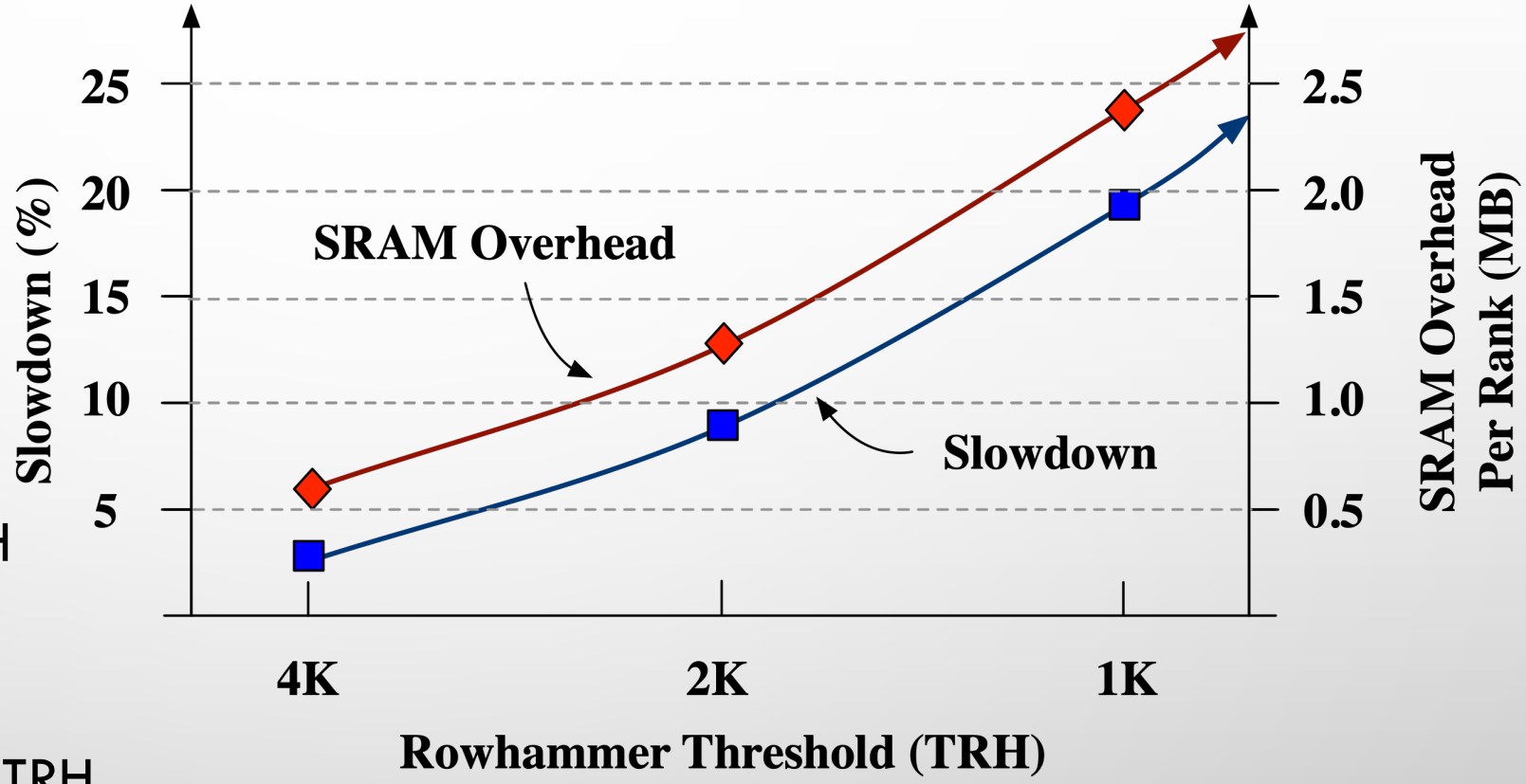


Our goal is to develop a scalable Rowhammer mitigation with low overheads

SPEC2017 ROW ACTIVATION CHARACTERISTICS

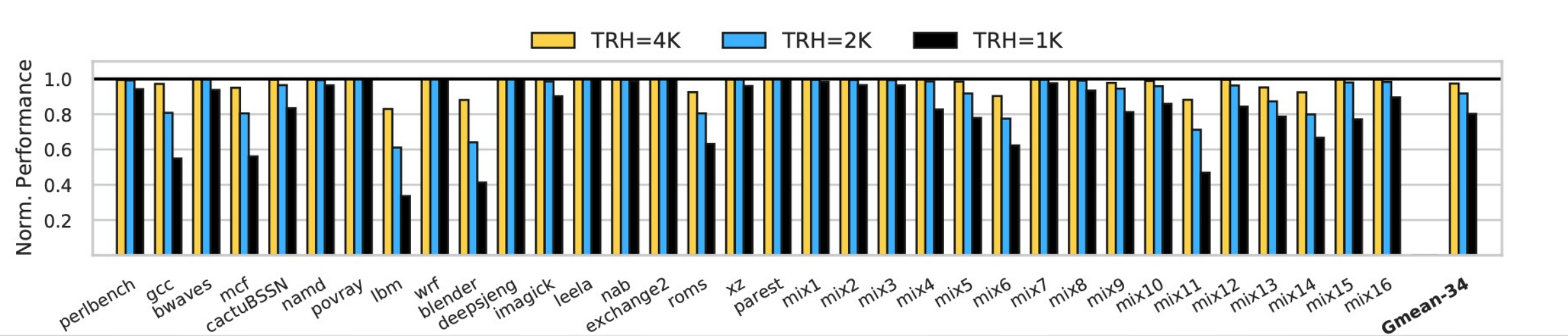
Workload	MPKI	Rows ACT-166+	Rows ACT-500+	Rows ACT-1K+
lbm	20.9	6794	5437	0
blender	14.8	6085	3021	572
gcc	6.32	4850	1836	111
mcf	7.02	4819	835	393
cactuBSSN	2.57	2515	0	0
roms	4.37	1150	191	11
xz	0.41	655	0	0
perlbench	0.74	0	0	0
bwaves	0.21	0	0	0
namd	0.38	0	0	0
povray	0.01	0	0	0
wrf	0.02	0	0	0
deepsjeng	0.25	0	0	0
imagick	0.27	0	0	0
leela	0.03	0	0	0
nab	0.54	0	0	0
exchange2	0.01	0	0	0
parest	0.1	0	0	0
Average	3.5	1665	694	57

EXPERIMENTAL SETUP

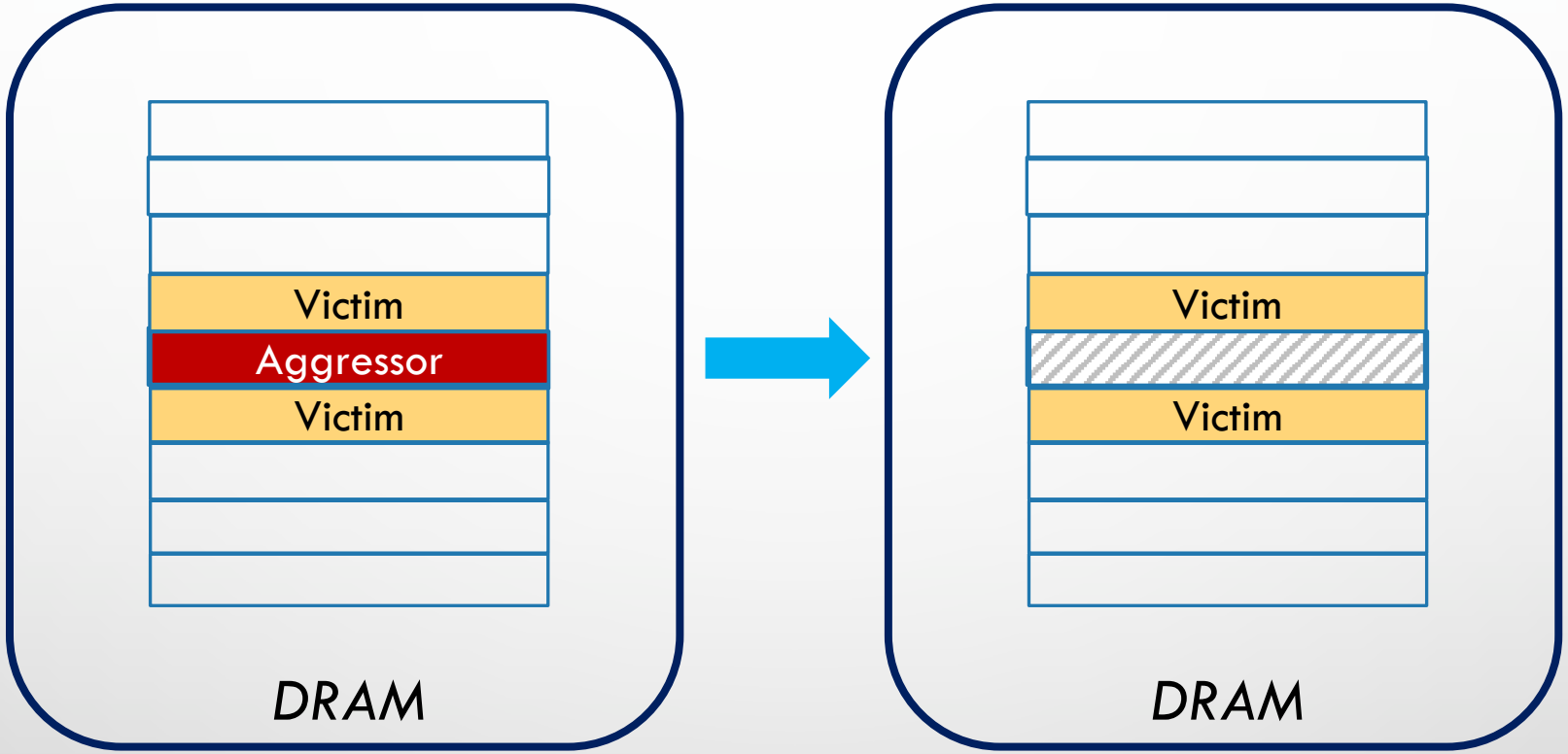
Out-of-Order Cores	4 cores at 3GHz
ROB size	192
Fetch and Retire width	8
Last Level Cache (Shared)	4MB, 16-Way, 64B lines
Memory size	16 GB – DDR4
Memory bus speed	1.2 GHz (2400 MT/s)
t_{RCD}-t_{CL}-t_{RP}-t_{RC}	14.2-14.2-14.2-45 ns
t_{CCD_S}, t_{CCD_L}	3.3 ns, 5 ns
Banks x Ranks x Channels	16×1×1
Rows per bank	128K
Size of row	8KB

- 18 SPEC2017 rate and 16 mixed workloads
- Fast-forward by 25 Bn instructions
- Simulate for 250 Mn instructions

PERFORMANCE DEGRADATION OF RRS



AQUA: QUARANTINING AGGRESSORS



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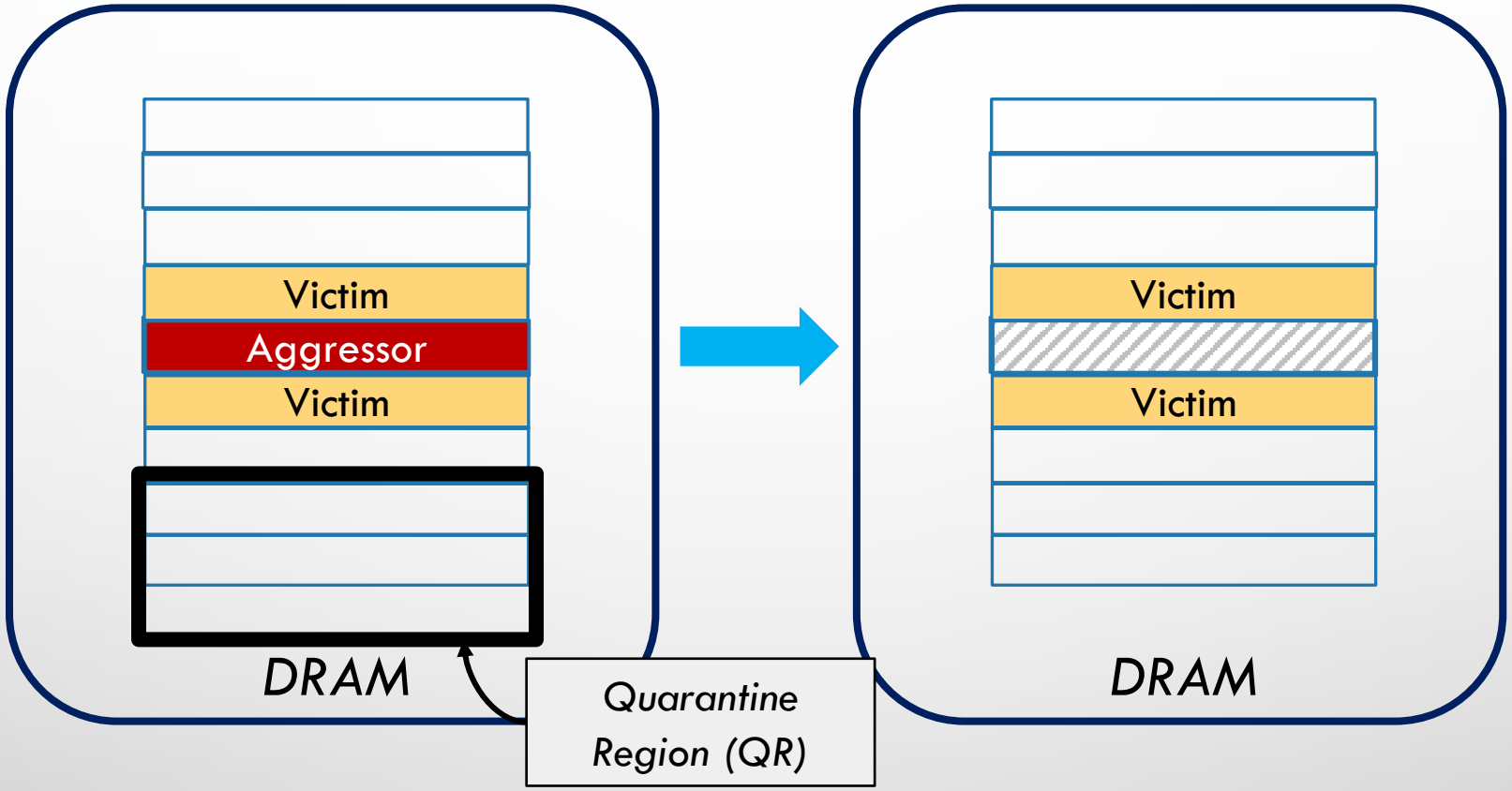

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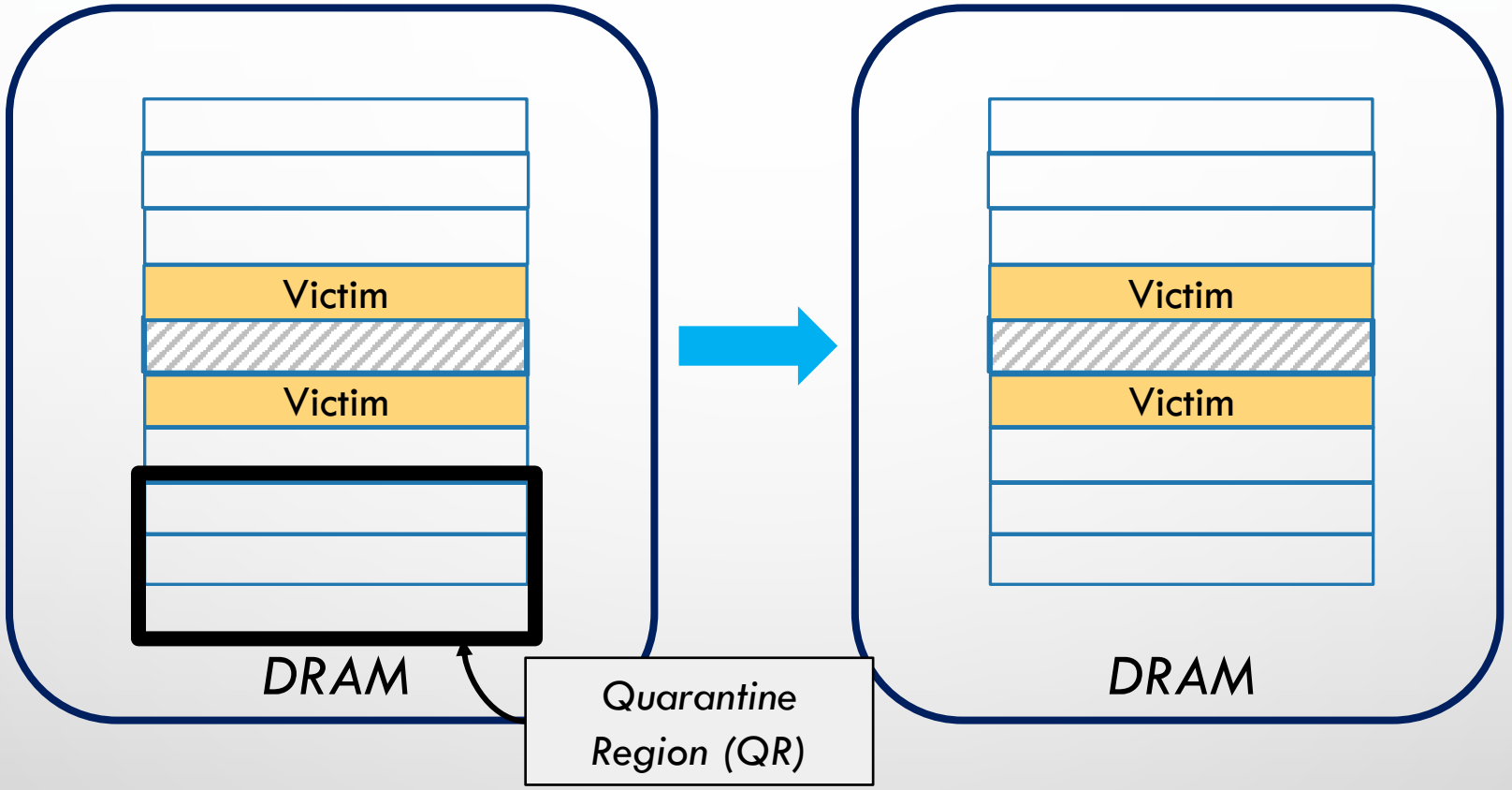

Security via Isolation: AQUA moves rows to a dedicated memory region

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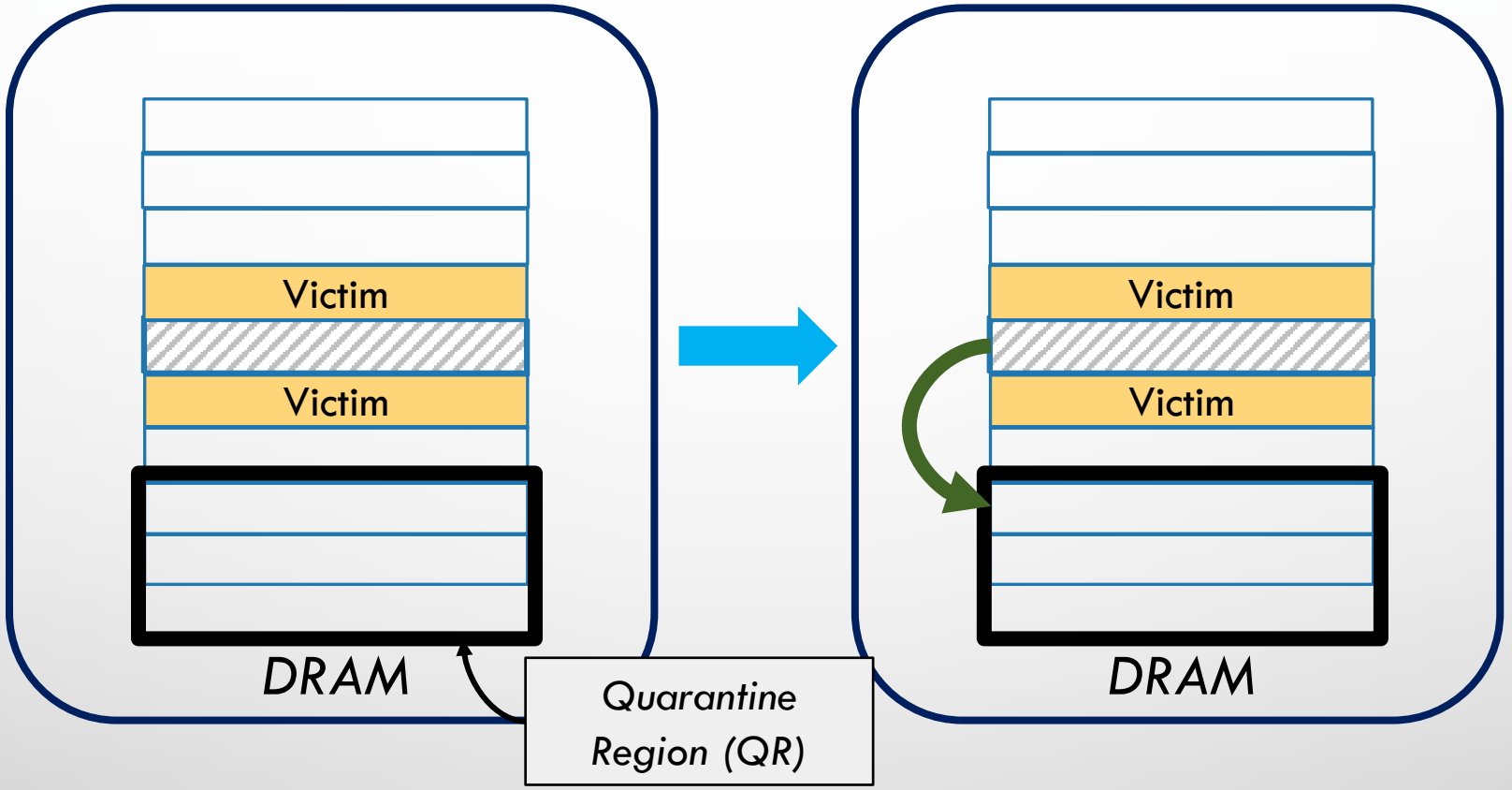

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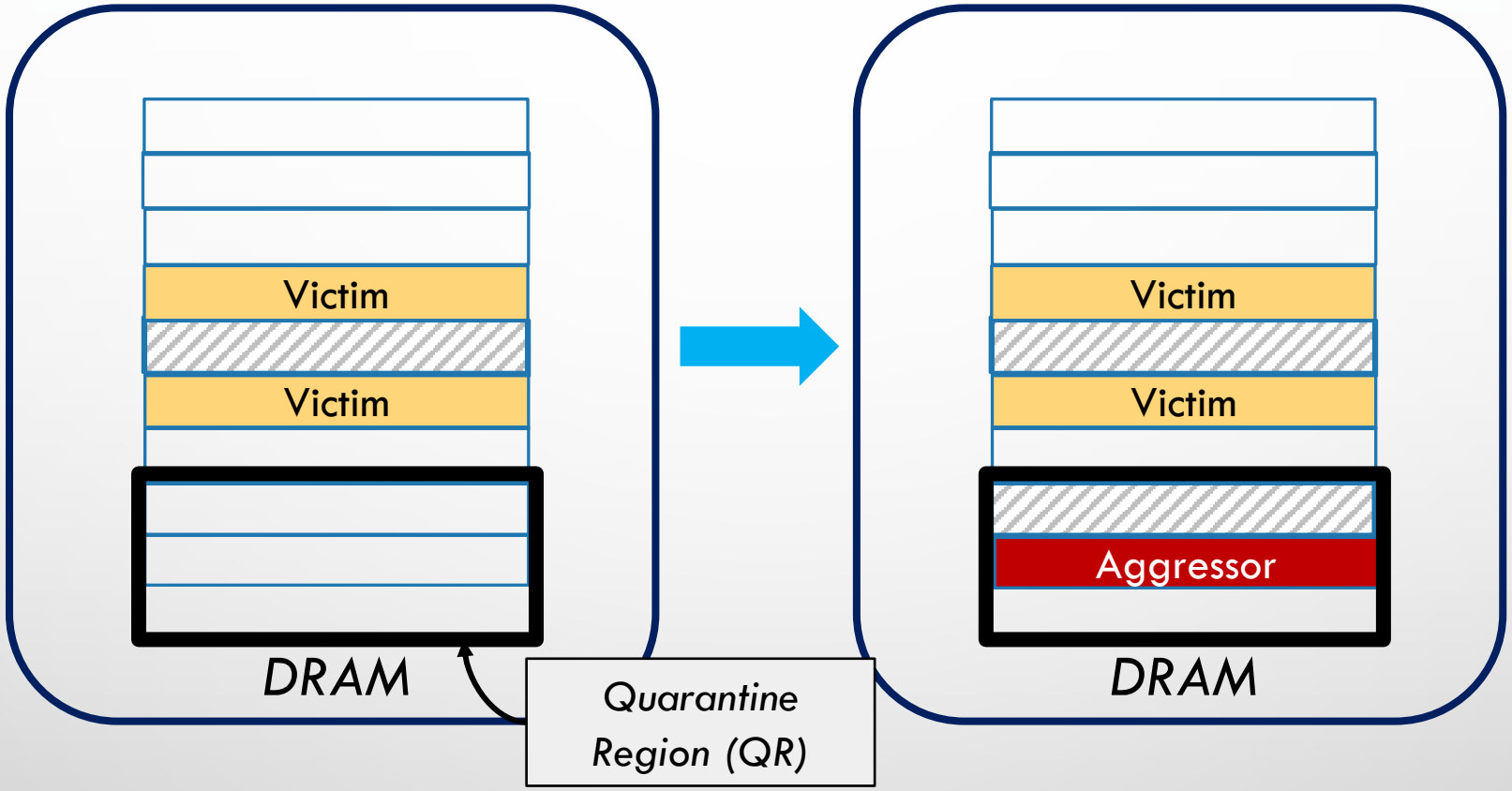

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