RAIDR: Retention-Aware Intelligent DRAM Refresh

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SAFARI Carnegie Mellon University

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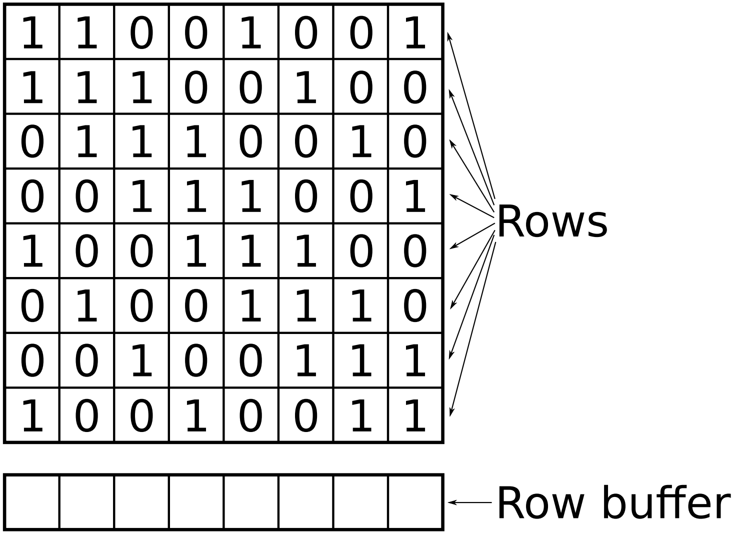
  - Group parts of DRAM into different bins depending on their required refresh rate
    - Use Bloom filters for scalable and efficient binning
  - Refresh each bin at the minimum rate needed
- RAIDR reduces refreshes significantly with low overhead in the memory controller

Outline

- Executive Summary
- Background & Motivation
- Key Observation & Our Mechanism: RAIDR
- Evaluation
- Conclusion

DRAM Refresh



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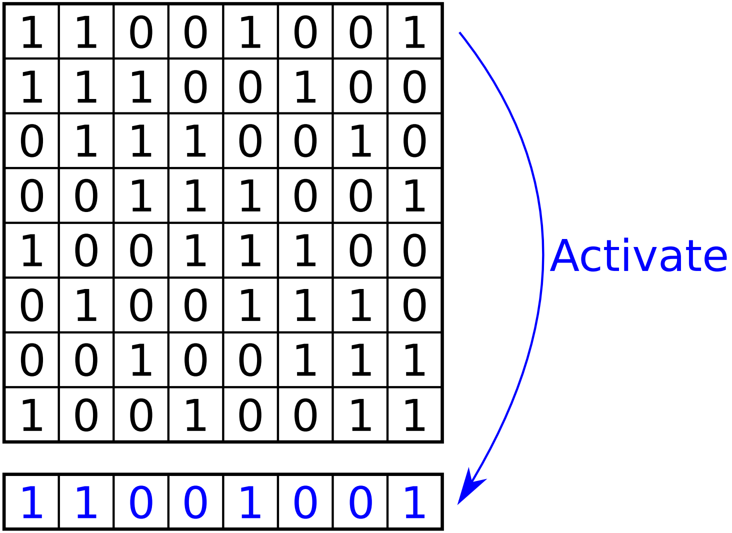

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1	0	0	1	1	1	0	0
0	1	0	0	1	1	1	0
0	0	1	0	0	1	1	1
1	0	0	1	0	0	1	1

1	1	0	0	1	0	0	1

DRAM Refresh

1	1	0	0	1	0	0	1
1	1	1	0	0	1	0	0
0	1	1	1	0	0	1	0
0	0	1	1	1	0	0	1
1	0	0	1	1	1	0	0
0	1	0	0	1	1	1	0
0	0	1	0	0	1	1	1
1	0	0	1	0	0	1	1

1	1	0	0	1	0	0	1

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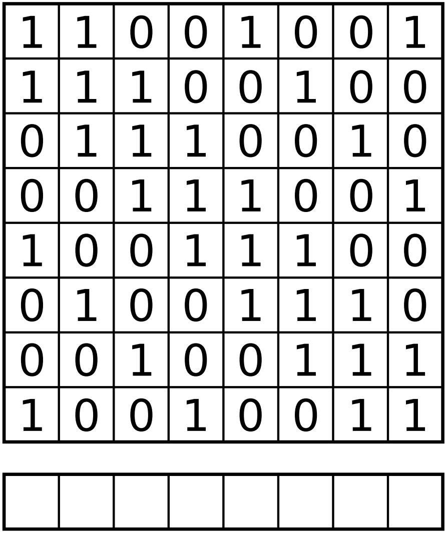

1	1	0	0	1	0	0	1
1	1	1	0	0	1	0	0
0	1	1	1	0	0	1	0
0	0	1	1	1	0	0	1
1	0	0	1	1	1	0	0
0	1	0	0	1	1	1	0
0	0	1	0	0	1	1	1
1	0	0	1	0	0	1	1

Precharge

DRAM Refresh

1	1	0	0	1	0	0	1
1	1	1	0	0	1	0	0
0	1	1	1	0	0	1	0
0	0	1	1	1	0	0	1
1	0	0	1	1	1	0	0
0	1	0	0	1	1	1	0
0	0	1	0	0	1	1	1
1	0	0	1	0	0	1	1

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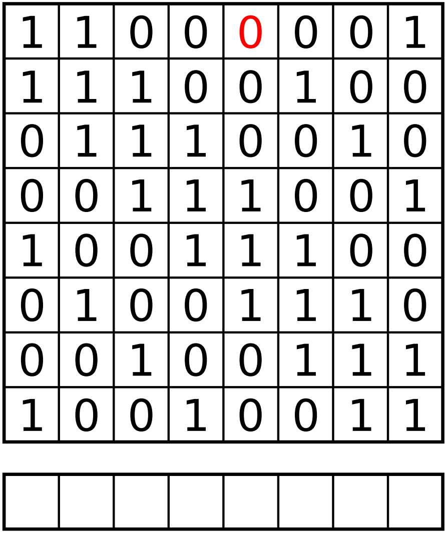

1	1	0	0	0	0	0	1
1	1	1	0	0	1	0	0
0	1	1	1	0	0	1	0
0	0	1	1	1	0	0	1
1	0	0	1	1	1	0	0
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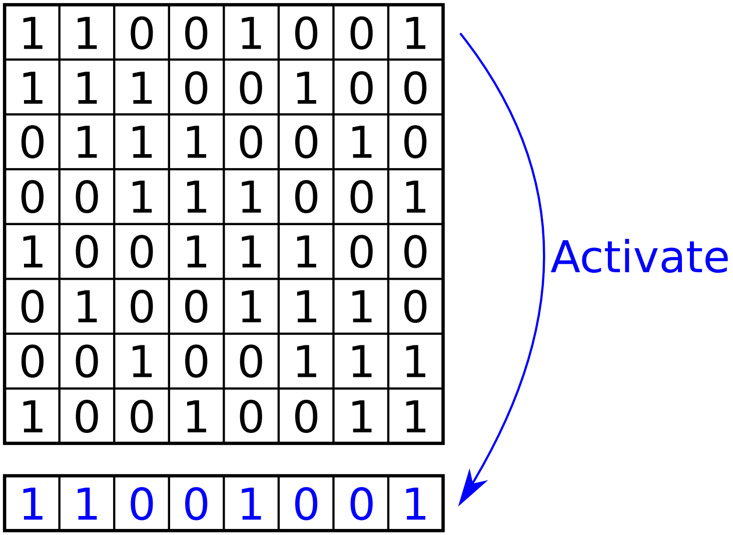

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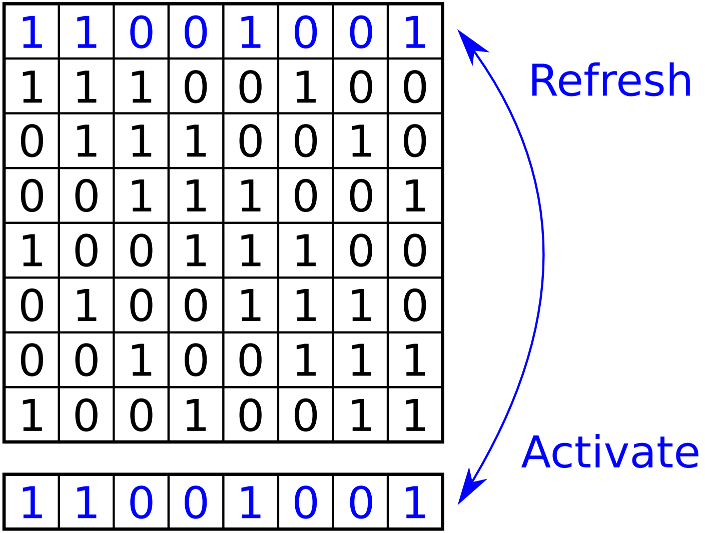
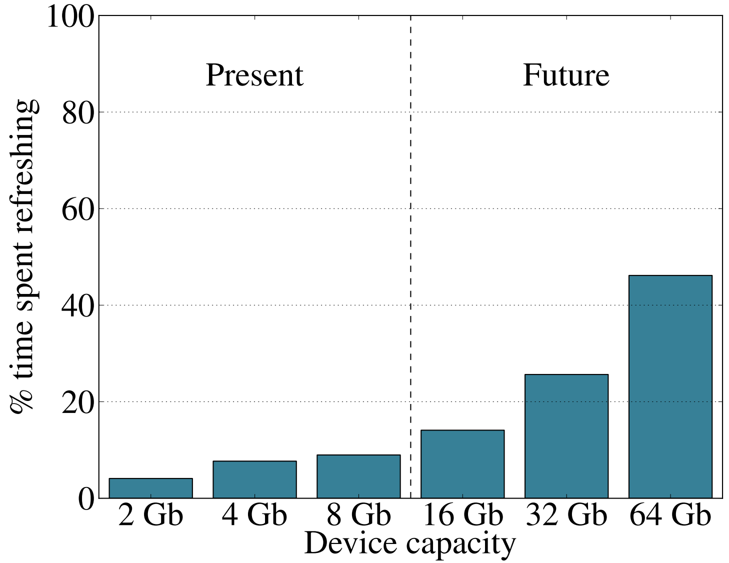


DRAM Refresh

1	1	0	0	1	0	0	1
1	1	1	0	0	1	0	0
0	1	1	1	0	0	1	0
0	0	1	1	1	0	0	1
1	0	0	1	1	1	0	0
0	1	0	0	1	1	1	0
0	0	1	0	0	1	1	1
1	0	0	1	0	0	1	1

Precharge

Refresh Overhead: Performance



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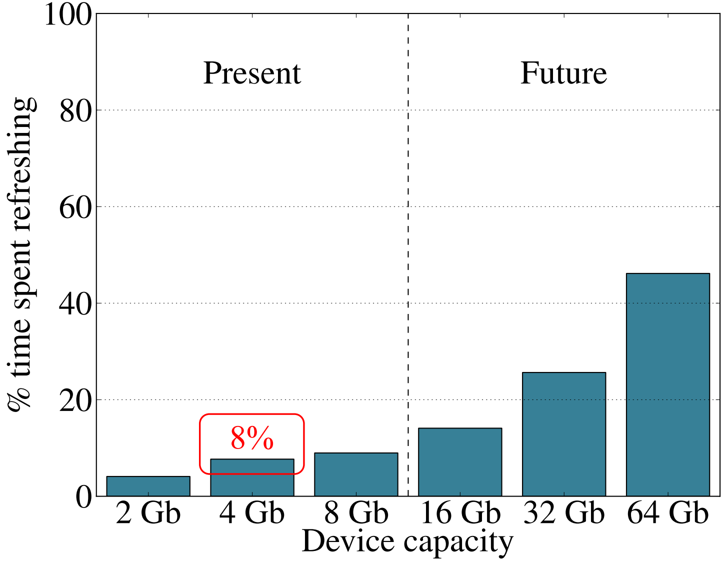

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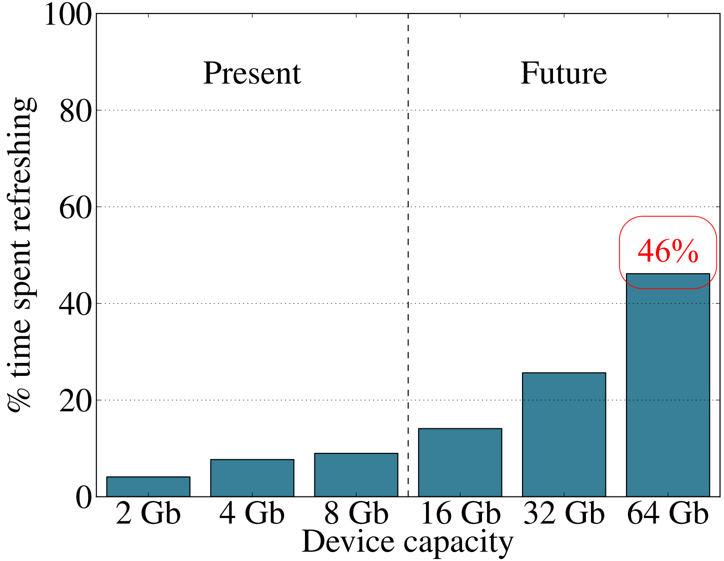

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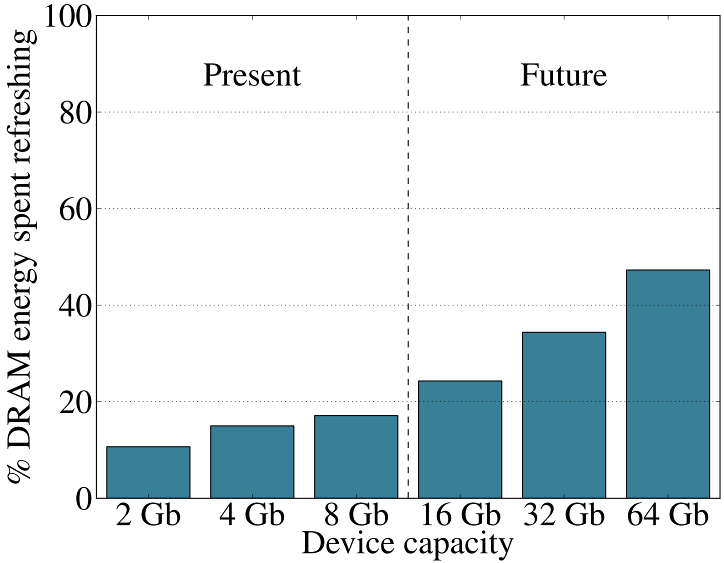

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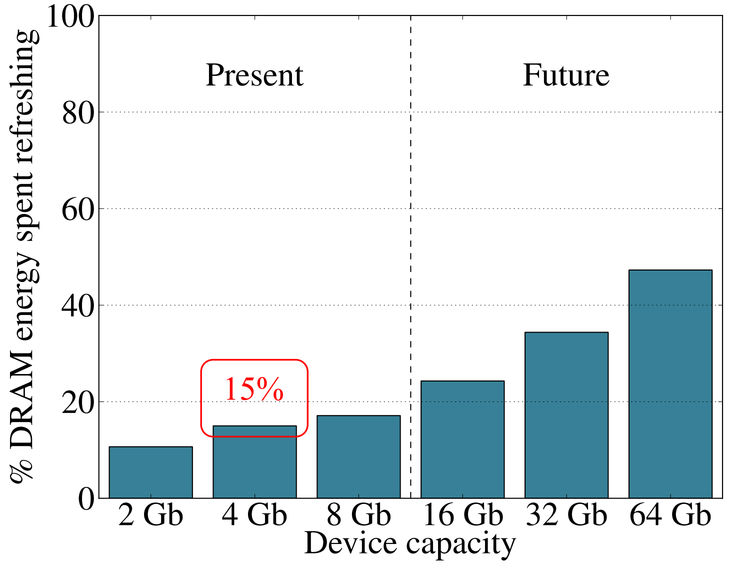

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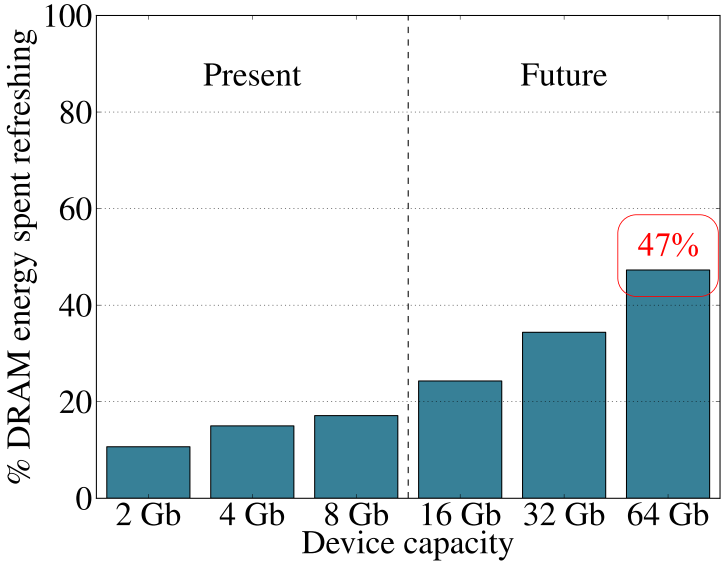

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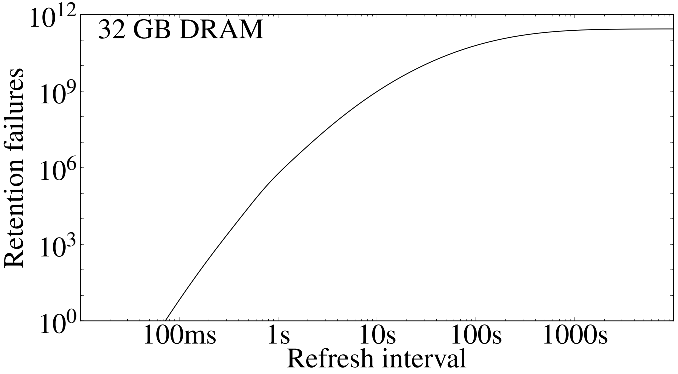
Key Observation and Idea



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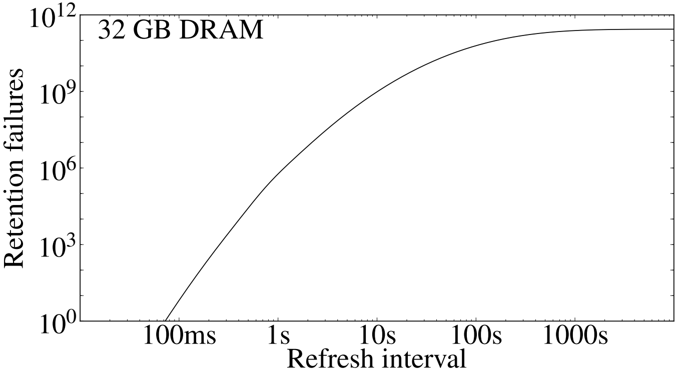

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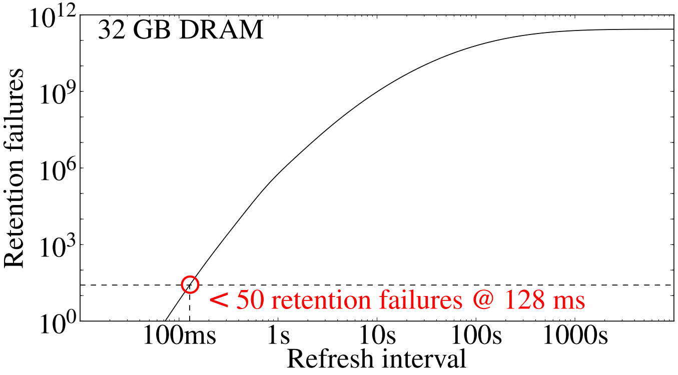

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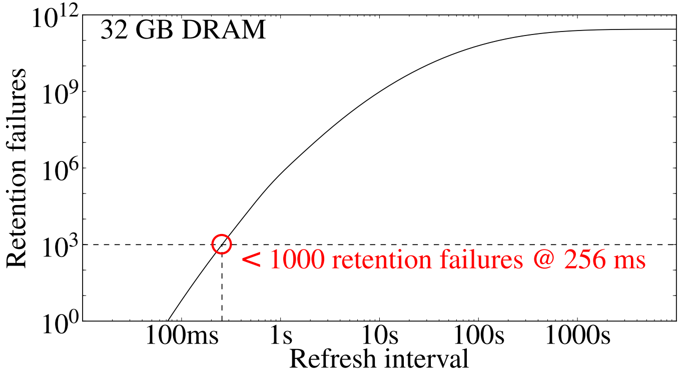

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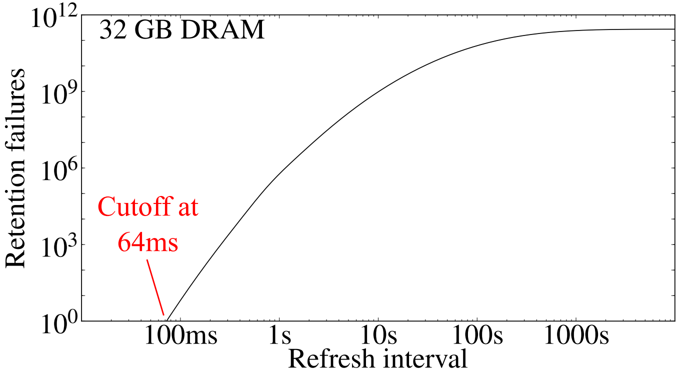

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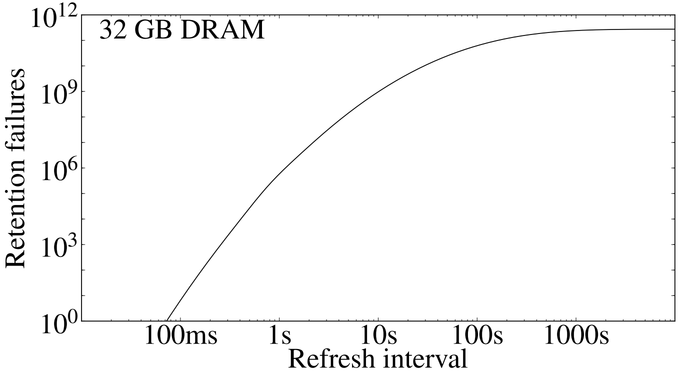

- Key observation: Most cells can be refreshed infrequently without losing data [Kim+, EDL '09]
- Problem: All cells are refreshed at the same worst-case rate
- Key idea: refresh rows containing weak cells more frequently; refresh other rows less frequently

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Initially	11111111...	11111111...	11111111...

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Initially	11111111...	11111111...	11111111...
After 64 ms	11111111...	11111111...	11111111...

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After 128 ms	11011111...	11111111...	11111111...

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	(64–128ms)		

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After 128 ms	11011111... (64–128ms)	11111111...	11111111...
After 256 ms		11111011...	11111111...

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Initially	11111111...	11111111...	11111111...
After 64 ms	11111111...	11111111...	11111111...
After 128 ms	11011111... (64–128ms)	11111111...	11111111...
After 256 ms		11111011... (128–256ms)	11111111... (>256ms)

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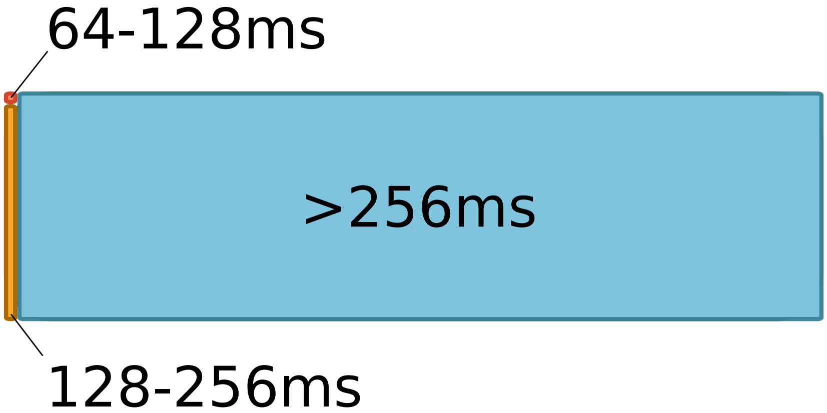

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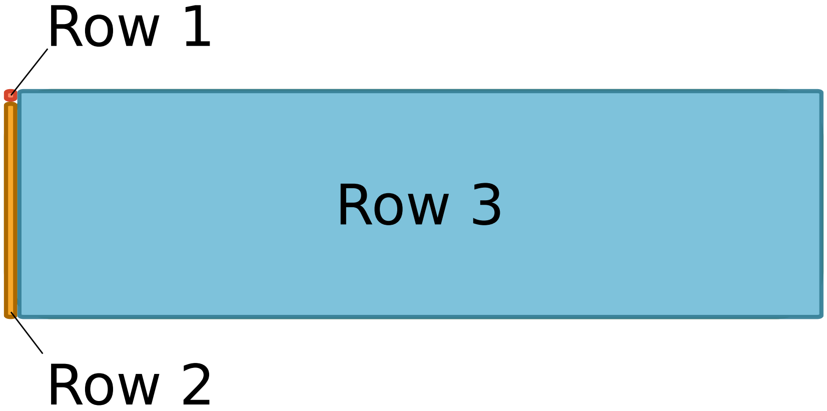

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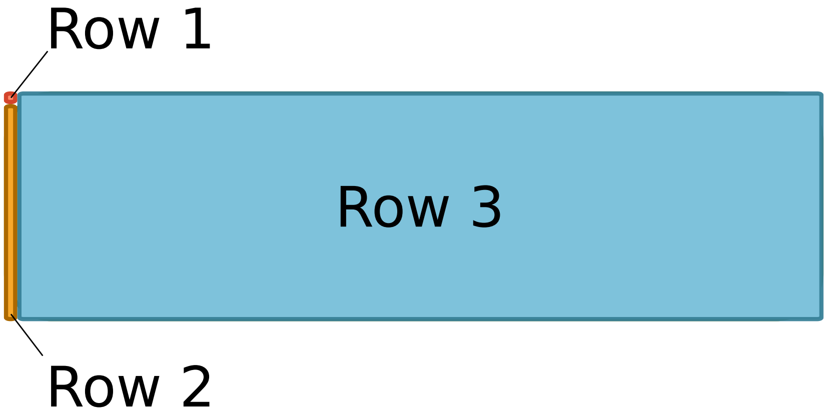
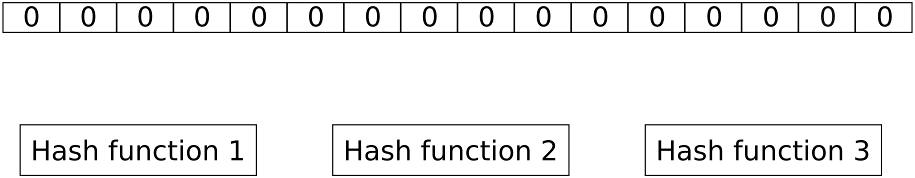


- Store bins using Bloom filters [Bloom, CACM ’70]

Storing Retention Time Bins Using Bloom Filters

Example with 64–128ms bin:



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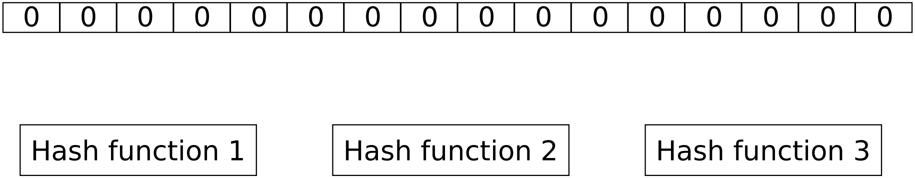

Insert Row 1

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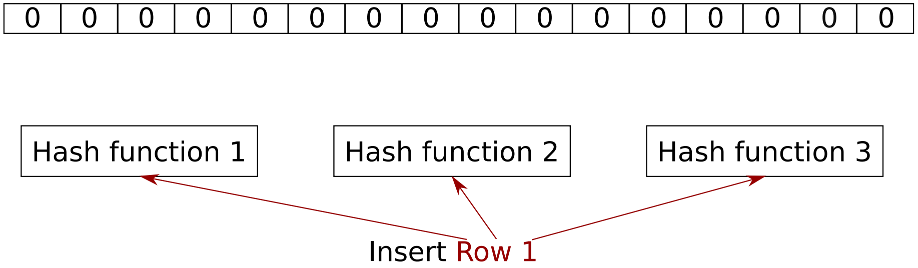

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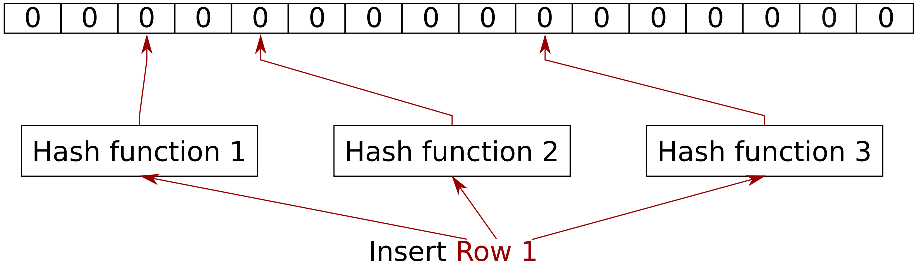

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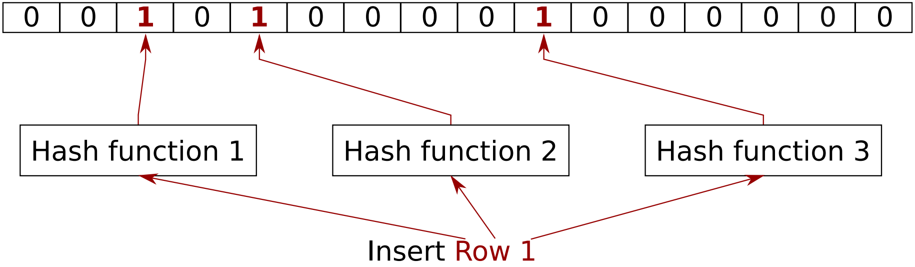

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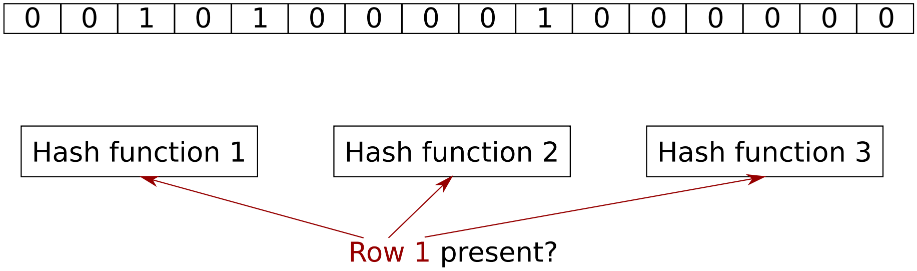

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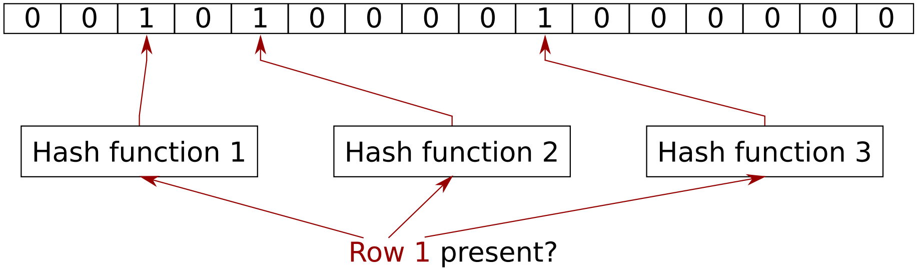

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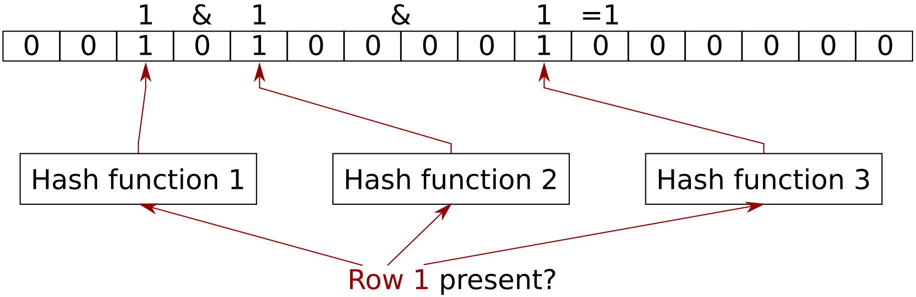

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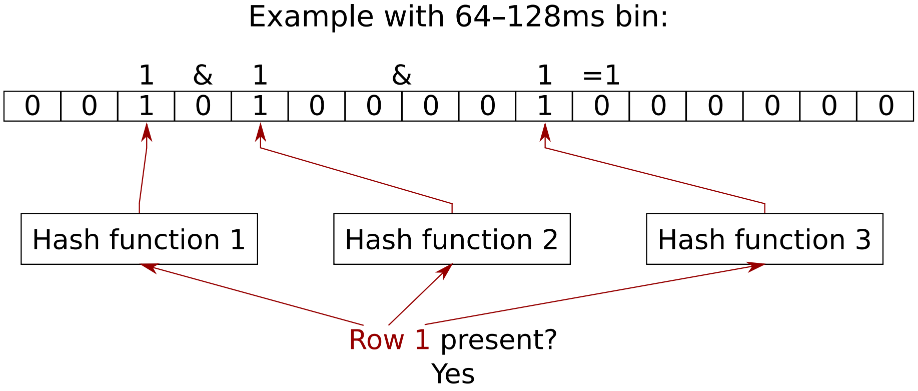

Storing Retention Time Bins Using Bloom Filters

Example with 64–128ms bin:

0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0

Hash function 1

Hash function 2

Hash function 3

Row 2 present?

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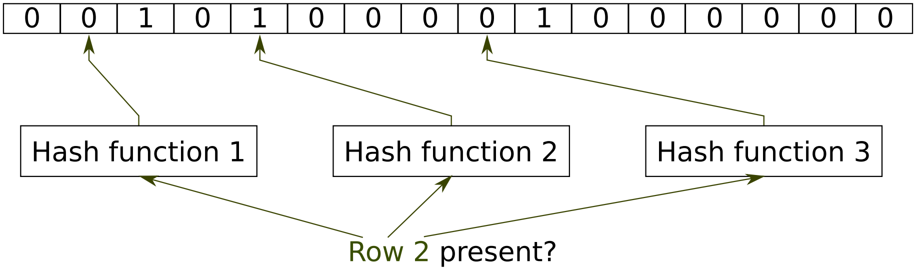

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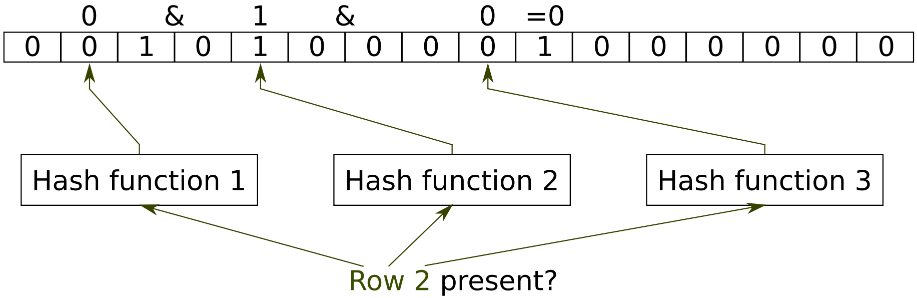

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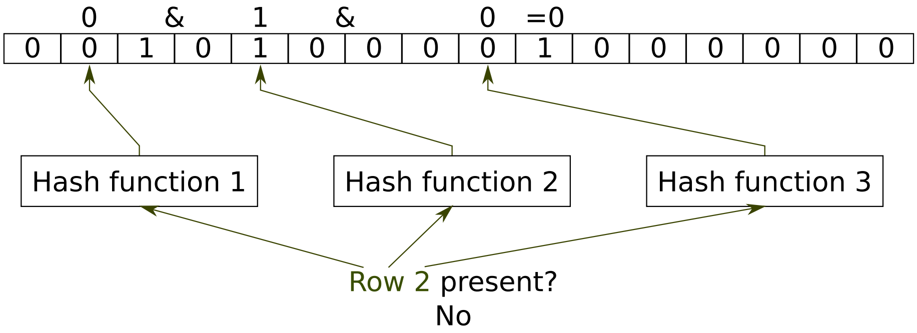

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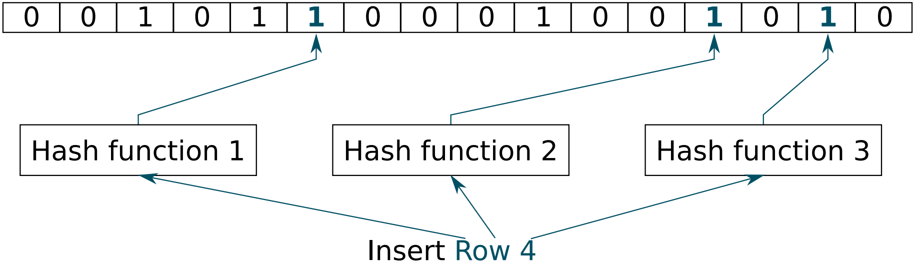

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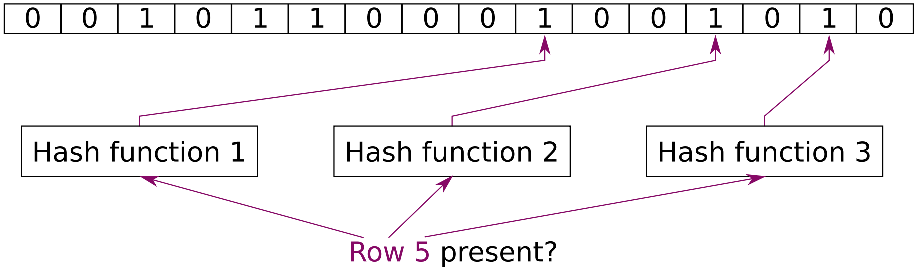

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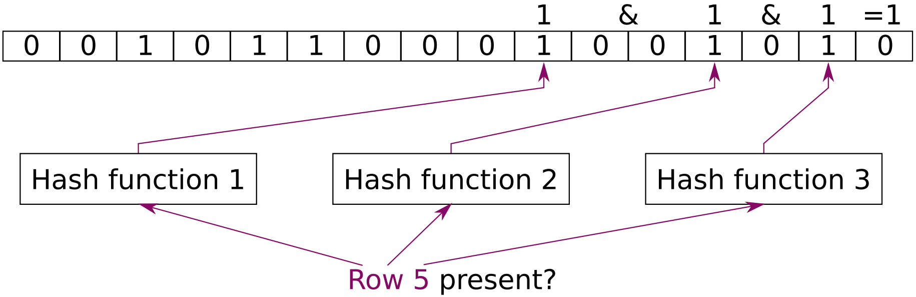

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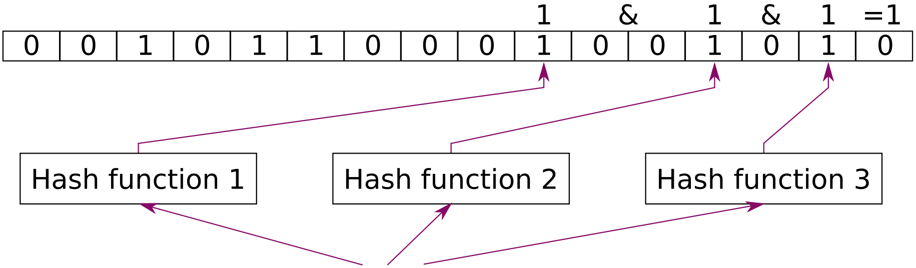

Row 5 present?
Yes (false positive)

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- No overflow: any number of rows may be inserted into a Bloom filter

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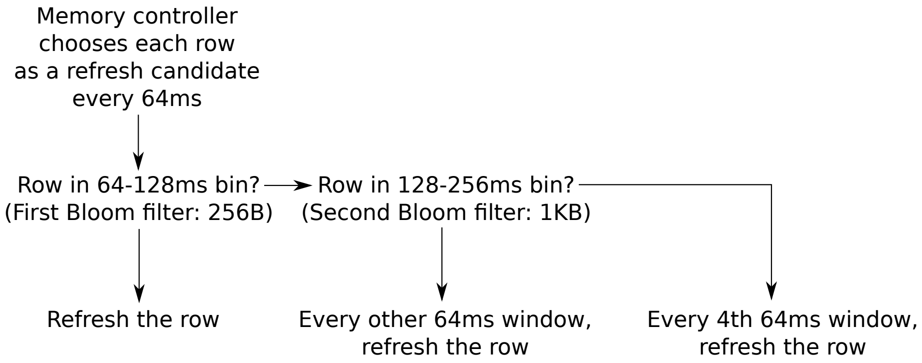
  - 1.25 KB storage overhead (2 Bloom filters) for 32 GB DRAM system

Retention-Aware Intelligent DRAM Refresh

1. Profiling
   - Determine each row’s retention time (how frequently each row needs to be refreshed to avoid losing data)
2. Binning
   - Group rows into different retention time bins based on their retention time
3. Refreshing
   - Refresh rows in different bins at different rates

③ Refreshing Rows at Different Rates


Memory controller chooses each row as a refresh candidate every 64ms
Row in 64-128ms bin? (First Bloom filter: 256B)
Row in 128-256ms bin? (Second Bloom filter: 1KB)
Refresh the row
Every other 64ms window, refresh the row
Every 4th 64ms window, refresh the row

Tolerating Temperature Variation: Refresh Rate Scaling

- Change in temperature causes retention time of all cells to change by a uniform and predictable factor

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- Implementation: counter with programmable period
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  - Higher temperature $\Rightarrow$ shorter period $\Rightarrow$ more frequent refreshes

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Methodology

- 8-core, 4 GHz, 512 KB 16-way private cache per core
- 32 GB DDR3 DRAM system (2 channels, 4 ranks/channel)
- 1.25 KB storage overhead for 2 Bloom filters
- Extended temperature range (85–95°C) characteristic of server environments
- SPEC CPU2006, TPC-C, TPC-H benchmarks in 8-core multiprogrammed workloads
  - Benchmarks categorized by memory intensity (LLC misses per 1000 instructions)
  - Workloads categorized by fraction of memory-intensive benchmarks
  - 32 workloads per category, 5 workload categories

Comparison Points

- Auto-refresh [DDR3, LPDDR2, . . .]:
  - Memory controller periodically sends auto-refresh commands
  - DRAM devices refresh many rows on each command
  - Baseline typical in modern systems
  - All rows refreshed at same rate

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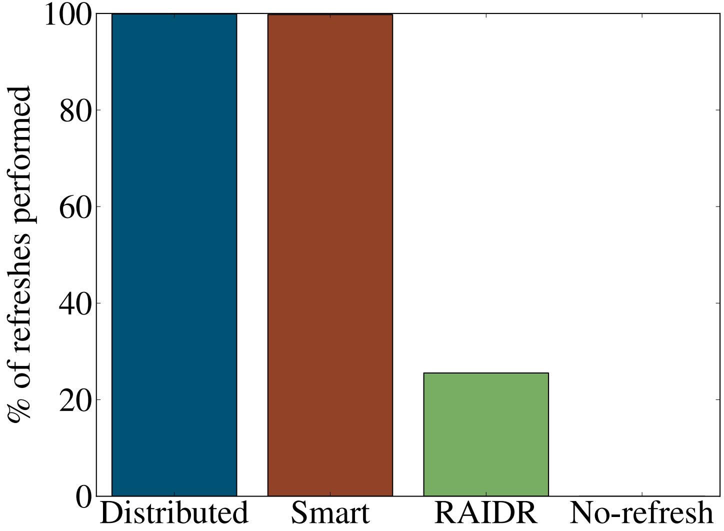
- No refresh (ideal)

Refresh Operations Performed (32 GB DRAM)



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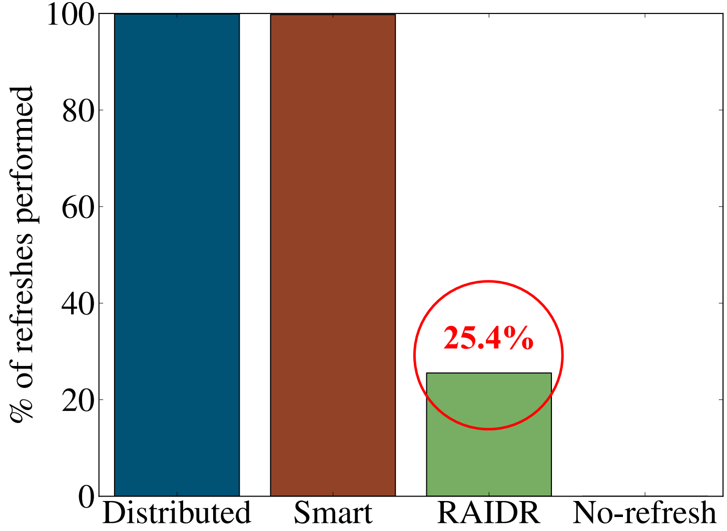
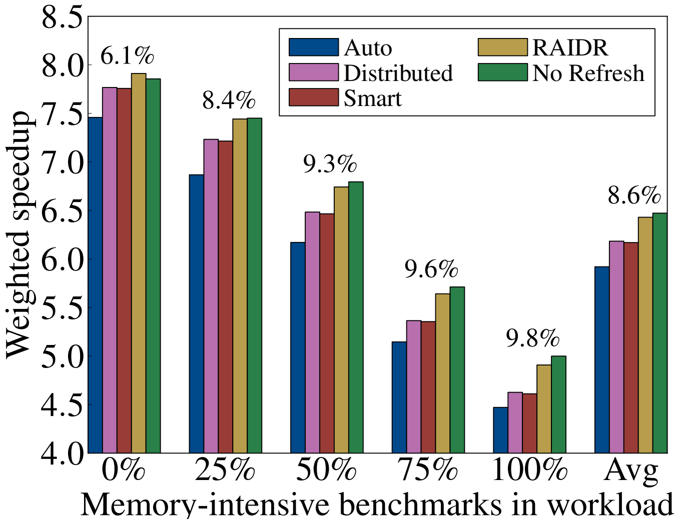


Performance



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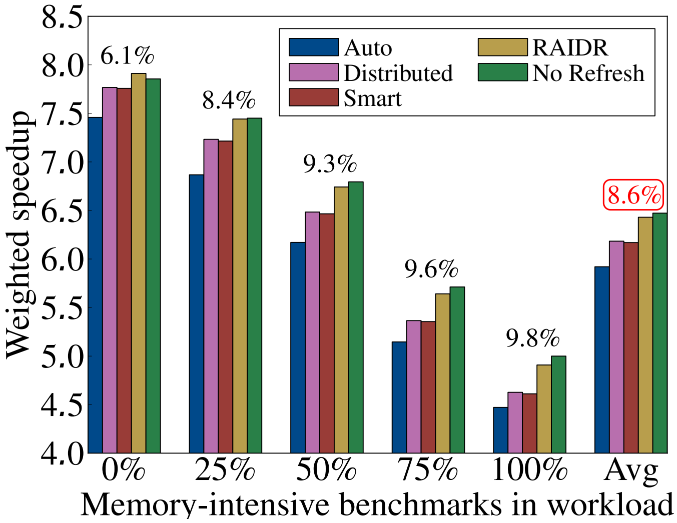

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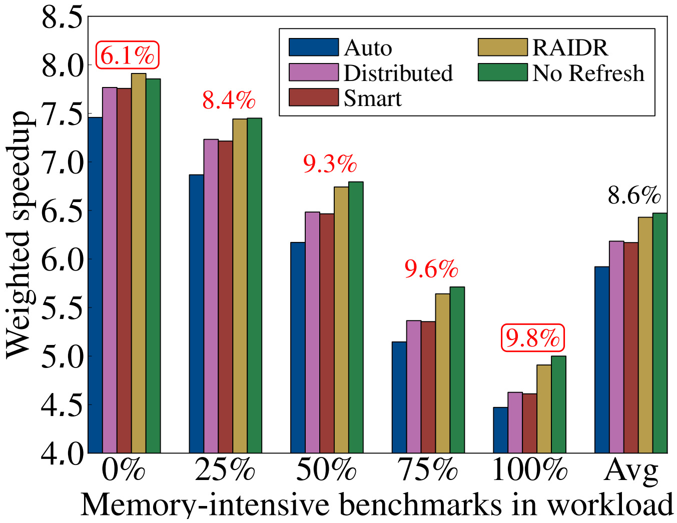
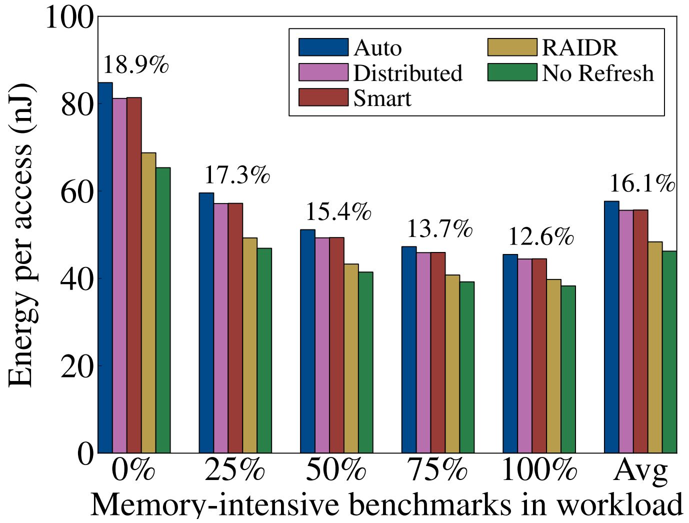


DRAM Energy Efficiency



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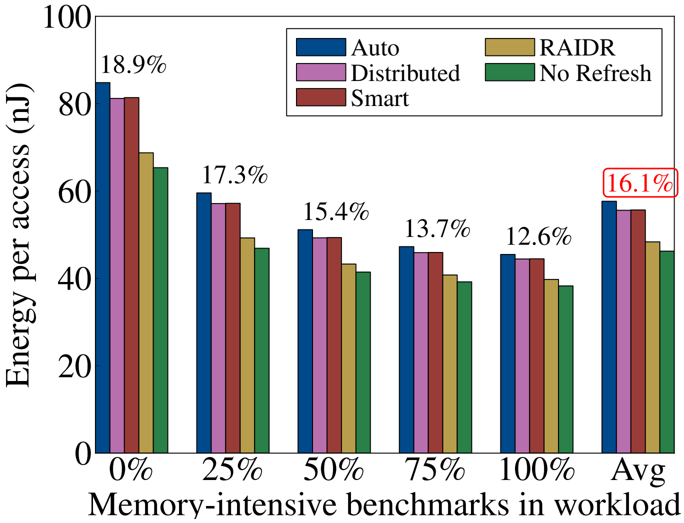

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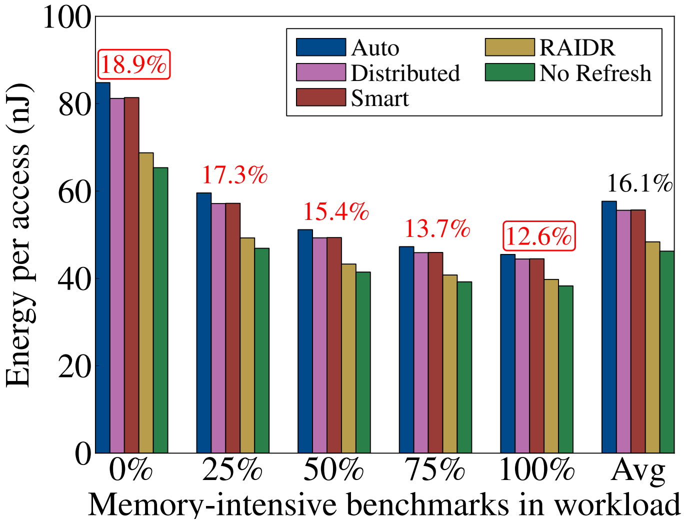
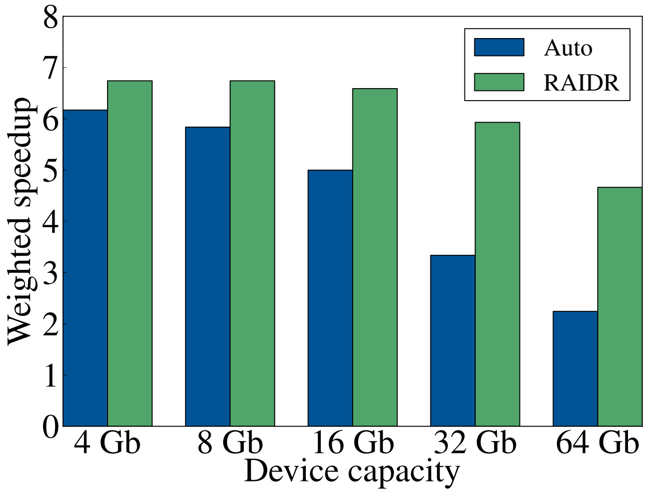


DRAM Device Capacity Scaling: Performance



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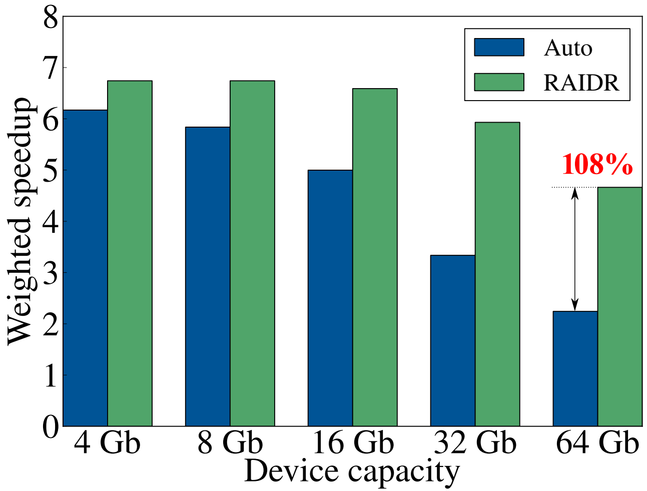

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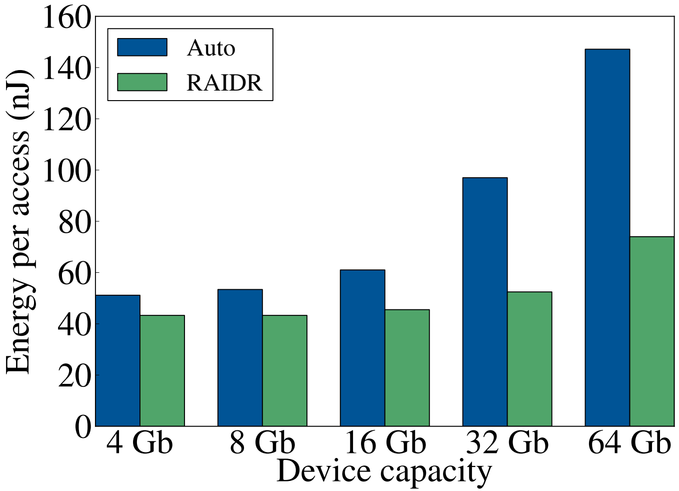

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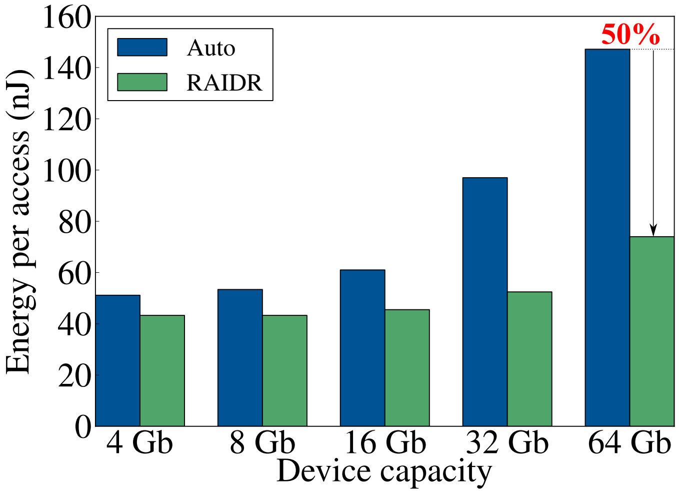

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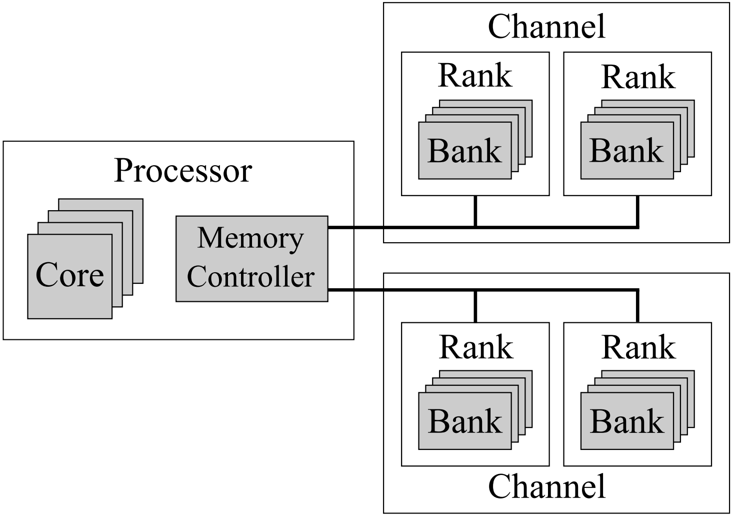
RAIDR:
Retention-Aware Intelligent DRAM Refresh

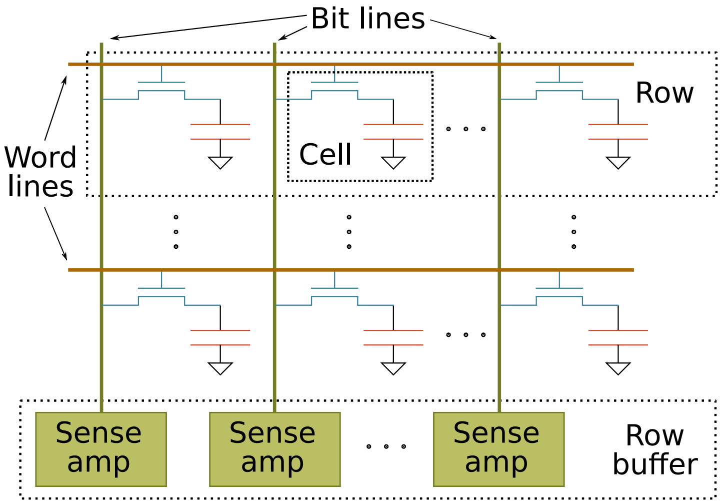
Jamie Liu   Ben Jaiyen   Richard Veras   Onur Mutlu

SAFARI   Carnegie Mellon University

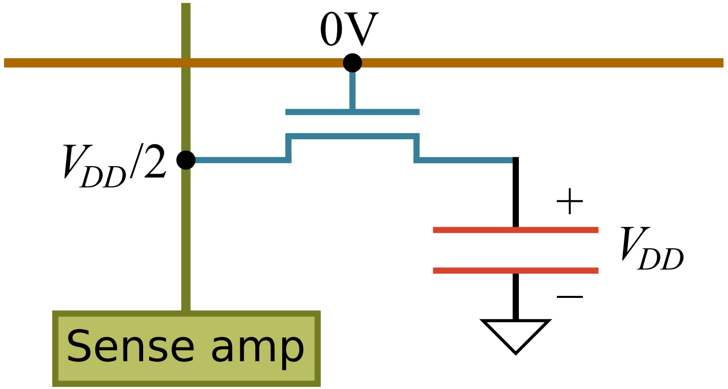
DRAM Hierarchy



DRAM Array Organization



DRAM Activation



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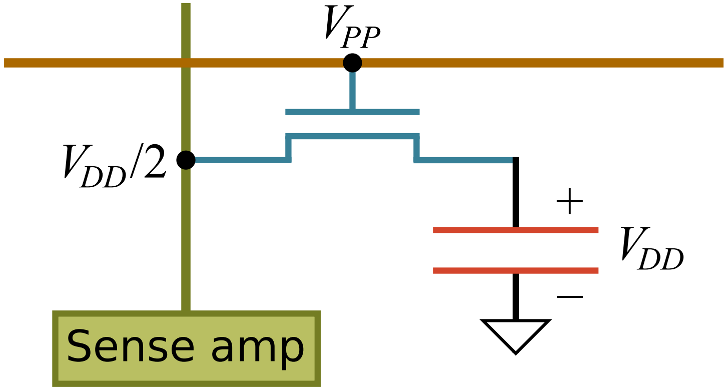

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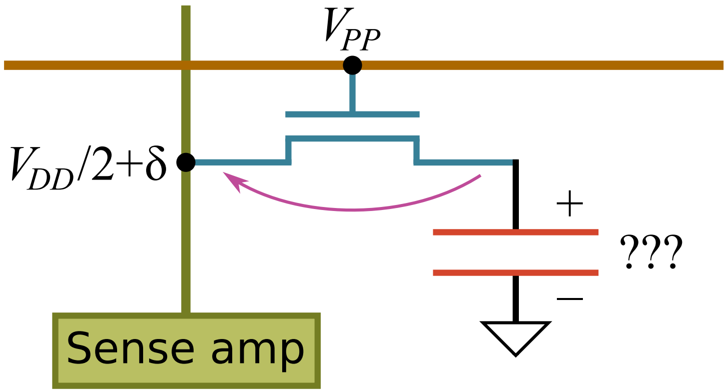

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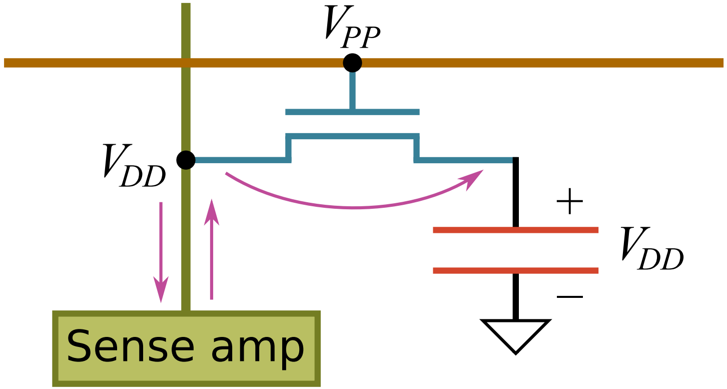
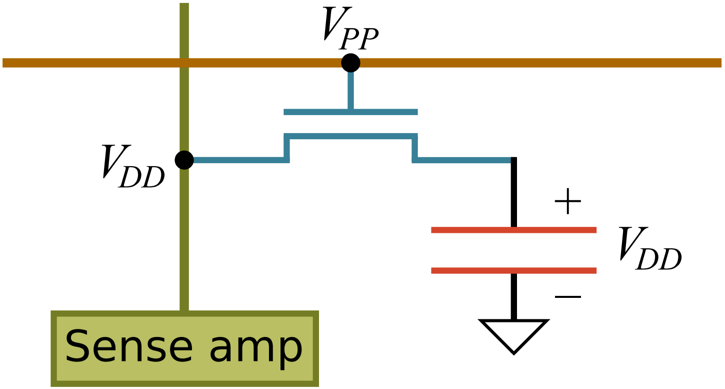


DRAM Precharge



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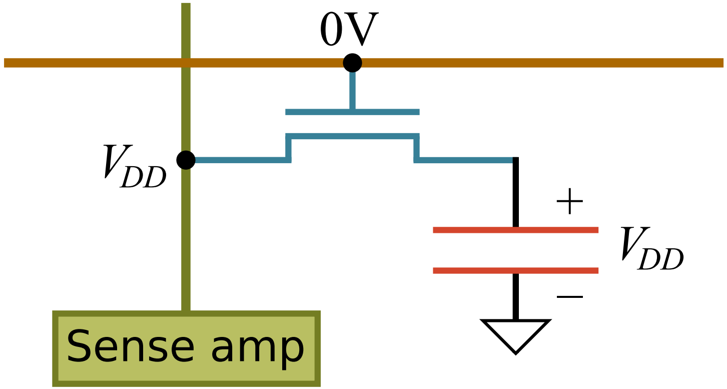

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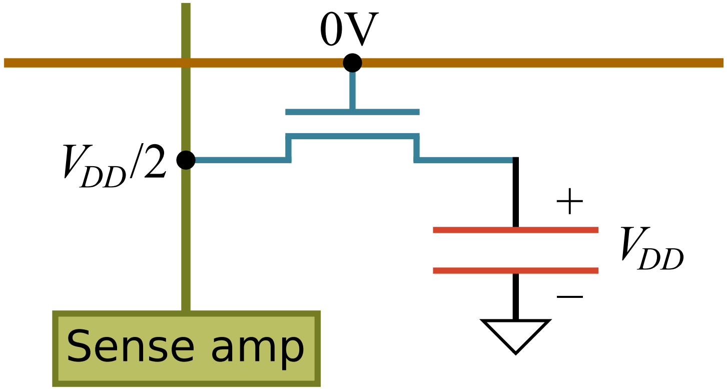
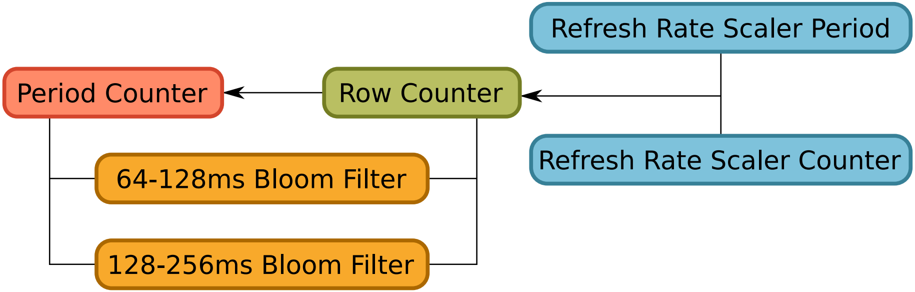
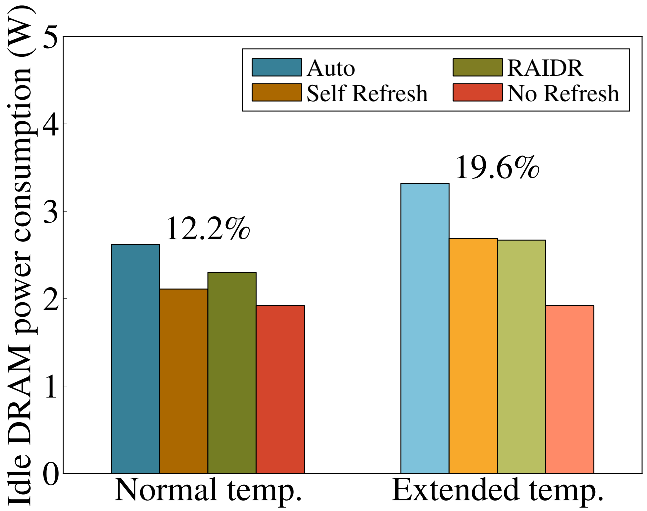


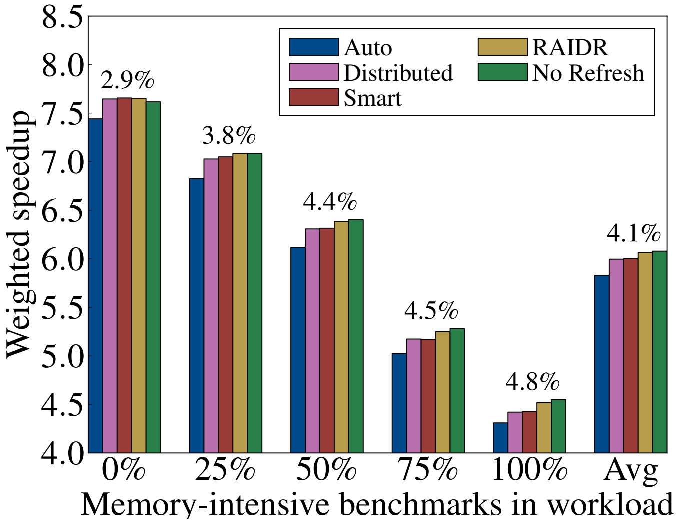
RAIDR Components



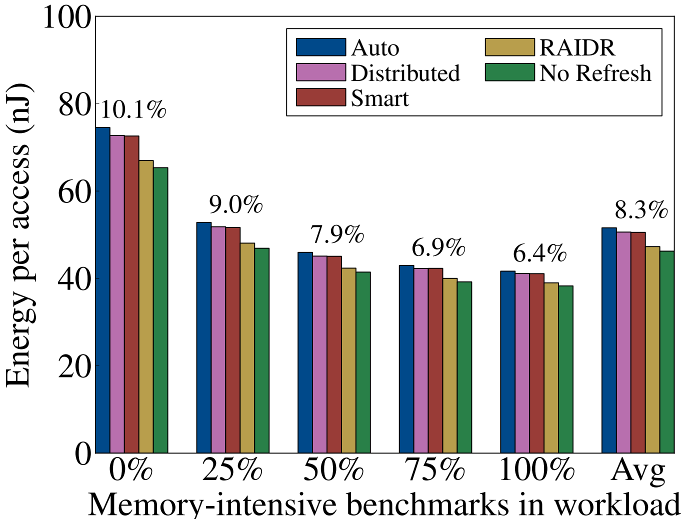
Idle Power Consumption



Performance: 85°C



Energy: 85°C

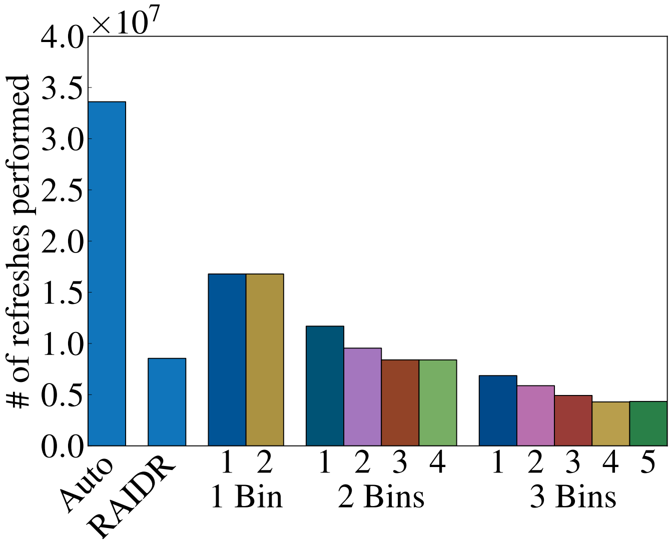


100
80
60
40
20
0
Energy per access (nJ)
Auto
Distributed
Smart
RAIDR
No Refresh
10.1%
9.0%
7.9%
6.9%
6.4%
8.3%
0%
25%
50%
75%
100%
Avg
Memory-intensive benchmarks in workload

RAIDR Default Configuration

- 64–128 ms bin: 256 B Bloom filter, 10 hash functions; 28 rows in bin, false positive probability $1.16 \cdot 10^{-9}$
- 128–256 ms bin: 1 KB Bloom filter, 6 hash functions; 978 rows in bin, false positive probability 0.0179

Refresh Reduction vs. RAIDR Configuration



RAIDR Configurations

Key	Description	Storage Overhead
Auto	Auto-refresh	N/A
RAIDR	Default RAIDR: 2 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$)	1.25 KB
1 bin (1)	1 bin (64–128 ms, $m = 512$)	64 B
1 bin (2)	1 bin (64–128 ms, $m = 1024$)	128 B
2 bins (1)	2 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 2048$)	512 B
2 bins (2)	2 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 4096$)	768 B
2 bins (3)	2 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 16384$)	2.25 KB
2 bins (4)	2 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 32768$)	4.25 KB
3 bins (1)	3 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$; 256–512 ms, $m = 32768$)	5.25 KB
3 bins (2)	3 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$; 256–512 ms, $m = 65536$)	9.25 KB
3 bins (3)	3 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$; 256–512 ms, $m = 131072$)	17.25 KB
3 bins (4)	3 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$; 256–512 ms, $m = 262144$)	33.25 KB
3 bins (5)	3 bins (64–128 ms, $m = 2048$; 128–256 ms, $m = 8192$; 256–512 ms, $m = 524288$)	65.25 KB