MAD: Memory Allocation meets Software Diversity

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Why are we here?

- no present defense prevents TRRespass-style attacks.
Anatomy of Rowhammer attacks

Rowhammer attacks often proceed in three stages:

- **Reconnaissance stage:** Where are bit flips?
- ** Templating/Massaging stage:** Construct vulnerable configuration.
- **Coerce third party to put sensitive target information into expected location.**
Anatomy of Rowhammer attacks

Recon- & Massaging mostly two strategies:

- Sparse-Allocation Massaging
- Dense-Allocation Massaging

Memory spraying: combination of both strategies.
Anatomy of Rowhammer attacks

**Sparse-Allocation Massaging:**
Attacker allocates as little memory as possible.
(e.g., Phys Feng Shui, Memory Chasing)
Anatomy of Rowhammer attacks

Dense-Allocation Massaging:
Attacker allocates and holds on to as much memory as possible.
(e.g., Flip Feng Shui)
Defending Massaging Techniques

Sparse-Allocation Massaging

An attack cannot succeed, is deterred significantly, if it never obtains any new blocks.
Defending Massaging Techniques

Dense-Allocation Massaging

Attack is essentially brute-force, co-opting specific operating system behavior.
Software Diversity?

- Predominate use against code-reuse attacks.
- Seems an unlikely candidate, primarily due to lack of entropy.
  - A 16 GB system only manages 4 million 4KB pages.
How does MAD address low-enropy problem?

MAD combines two novel spatial diversification techniques

• Horizontal Diversity
• Vertical Diversity

to increase block recycling
Overall MAD architecture
Internal MAD architecture
Internal MAD architecture
Internal MAD architecture

<table>
<thead>
<tr>
<th>Order 0 (2^0 = 4,\text{kb})</th>
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Internal MAD architecture

Order 1 ($2^1 = 8$ kb)
Internal MAD architecture

Order 2 ($2^2 = 16$ kb)
Internal MAD architecture

Order 3 \( (2^3 = 32 \text{ kb}) \)
MAD: Horizontal Diversity
MAD: Horizontal Diversity

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select a random page from allocation cache
MAD: Horizontal Diversity

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MAD: Horizontal Diversity

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select a random page from allocation cache

[Diagram showing allocation and free states]
MAD: Horizontal Diversity

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put page at a random position in shadow cache
MAD: Horizontal Diversity

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MAD: Horizontal Diversity

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put page at a random position in shadow cache
MAD: Horizontal Diversity

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put page at a random position in shadow cache

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MAD: Horizontal Diversity

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put page at a random position in shadow cache
MAD: Horizontal Diversity

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move pages from shadow cache back to the allocation cache
MAD: Horizontal Diversity

move pages from shadow cache
back
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Evaluation: Deterring Sparse Allocation Massaging
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In numbers:

• page "loss" ratio:
  ○ averaged over 1 billion allocs in 25k steps
    MAD: 0.3563
    No MAD: 1.4832
    Ratio: 4.16x
  ○ 16 GB: 77 billion vs 294 billion allocs

• Note plateau: 900m allocs **without** significant increase in unique physical blocks allocated.
Q: Could you not still exhaust all memory?

MAD: Detection of Dense Allocation Massaging

Q: Could you not still exhaust all memory?
A: long: wait a minute...
Dense Allocation Massaging Through Lens of MAD

alloc served from Allocation Caches until empty.
Dense Allocation Massaging Through Lens of MAD

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Dense Allocation Massaging Through Lens of MAD

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<td><img src="image" alt="Allocator Caches" /></td>
<td><img src="image" alt="Massaging Caches" /></td>
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Horizontal diversity moves pages from Shadow Caches to Allocation Caches.
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Dense Allocation Massaging Through Lens of MAD

<table>
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<th>Always empty</th>
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Now both caches are empty.
Need to refill from BA.
At a *higher* frequency!
Dense Allocation Massaging Through Lens of MAD

free puts blocks into Shadow Caches
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Dense Allocation Massaging Through Lens of MAD

*Horizontal diversity* moves pages from Shadow Caches to Allocation Caches.
Dense Allocation Massaging Through Lens of MAD

*Horizontal diversity* moves pages from Shadow Caches to Allocation Caches.
Dense Allocation Massaging Through Lens of MAD

\texttt{free} puts blocks into Shadow Caches
Dense Allocation Massaging Through Lens of MAD

free puts blocks into Shadow Caches
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### Dense Allocation Massaging Through Lens of MAD

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```free puts blocks into Shadow Caches```
Dense Allocation Massaging Through Lens of MAD

free puts blocks into Shadow Caches
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_free_ puts blocks
into Shadow Caches
Dense Allocation Massaging Through Lens of MAD

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free  puts blocks
into Shadow Caches
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Dense Allocation Massaging Through Lens of MAD

`free` puts blocks into Shadow Caches
Dense Allocation Massaging Through Lens of MAD

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\text{free puts blocks into Shadow Caches}
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\texttt{free} puts blocks into Shadow Caches
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free puts blocks into Shadow Caches
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```plaintext
free  puts blocks
into Shadow Caches
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Dense Allocation Massaging Through Lens of MAD

free puts blocks into Shadow Caches
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free  puts blocks
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free puts blocks into Shadow Caches
Dense Allocation Massaging Through Lens of MAD

Now both caches are full.
Dense Allocation Massaging Through Lens of MAD

Now both caches are full.
No space left for freed blocks.
Dense Allocation Massaging Through Lens of MAD

Now both caches are empty.
No space left for freed blocks.
Dense Allocation Massaging Through Lens of MAD

MAD effectively boosts signal from asymptomatic configurations.

Collecting more samples gives higher resolution picture.

- if attacker adapts, attack protracted significantly! (battle MAD recycling & detection monitoring)
Security Evaluation: Worst Case Analysis

• Assuming the attacker can place a vulnerable block into MAD’s caches, how many allocations are needed to obtain a vulnerable configuration.
## Obtaining Vulnerable Configuration

<table>
<thead>
<tr>
<th>LB</th>
<th>UB</th>
<th>Average</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>597,301</td>
<td>112,916</td>
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<tr>
<td>8</td>
<td>16</td>
<td>565,959</td>
<td>70,065</td>
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<tr>
<td>16</td>
<td>32</td>
<td>418,565</td>
<td>37,858</td>
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<tr>
<td>32</td>
<td>64</td>
<td>278,490</td>
<td>30,729</td>
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<tr>
<td>64</td>
<td>128</td>
<td>255,154</td>
<td>39,563</td>
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</table>

LB = lower bound;  
UB = upper bound;  
en-bloc allocation times 1024.
Contributions

• Generalization: First step towards a diversity-based defense against Rowhammer.

• Effectiveness: Horizontal + Vertical Diversity in low-entropy domains.
  ○ 16GB RAM ~4m blocks, brute force viable option
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
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<tbody>
<tr>
<td>Data 1</td>
<td>Data 2</td>
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<td>Data 4</td>
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**Notes:**
- Column 1 contains data points from source A.
- Column 2 contains data points from source B.
- Column 3 contains data points from source C.
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