RAMBleed: Reading Bits in Memory Without Accessing Them

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Motivation

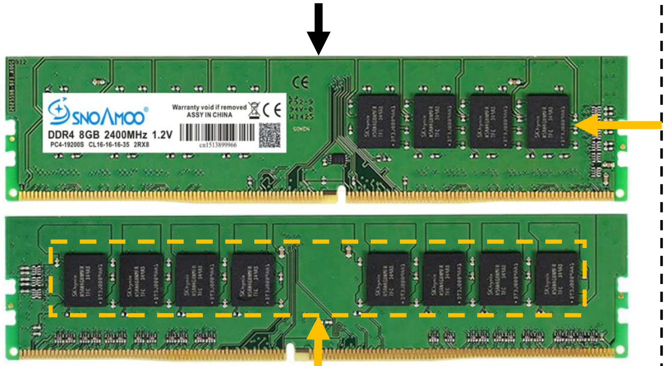
- Rowhammer has previously only been demonstrated as a threat to DRAM integrity.
- Flipping the roles of attacker and victim make it possible to use Rowhammer as a read channel.
- ECC RAM can be exploited as a timing channel.

Threat Model

- Attacker runs unprivileged software on same OS and victim program.
- OS maintains isolation between attacker and victim programs.
- Attacker cannot exploit microarchitectural side channel leakage from victim.
- The machine is vulnerable to Rowhammer, but programs can only access their own private memory.
- Attacker can trigger the victim to perform allocation of secret data.

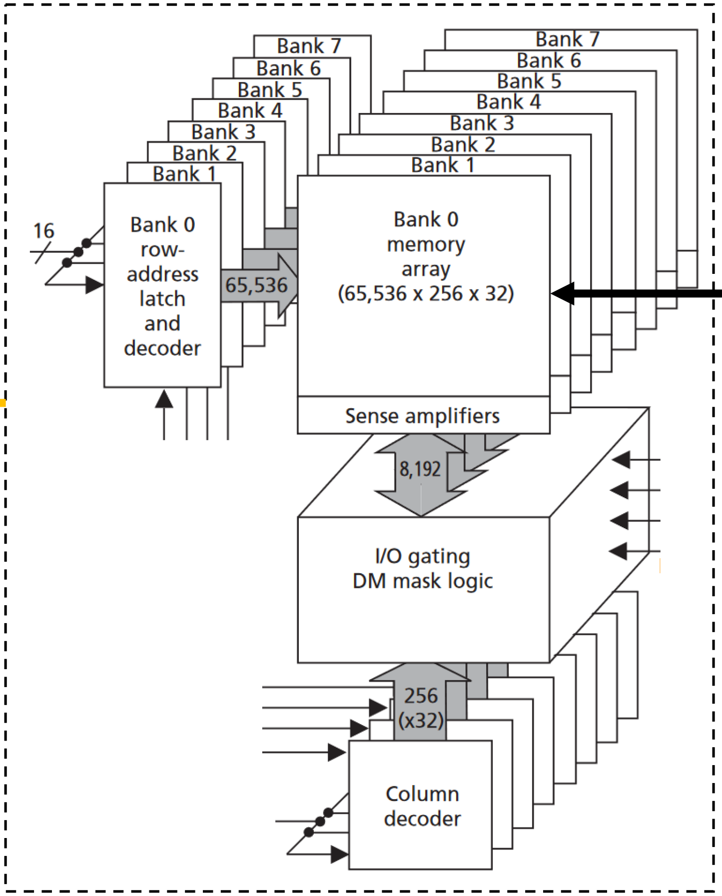
Background – DRAM Configuration

DIMM

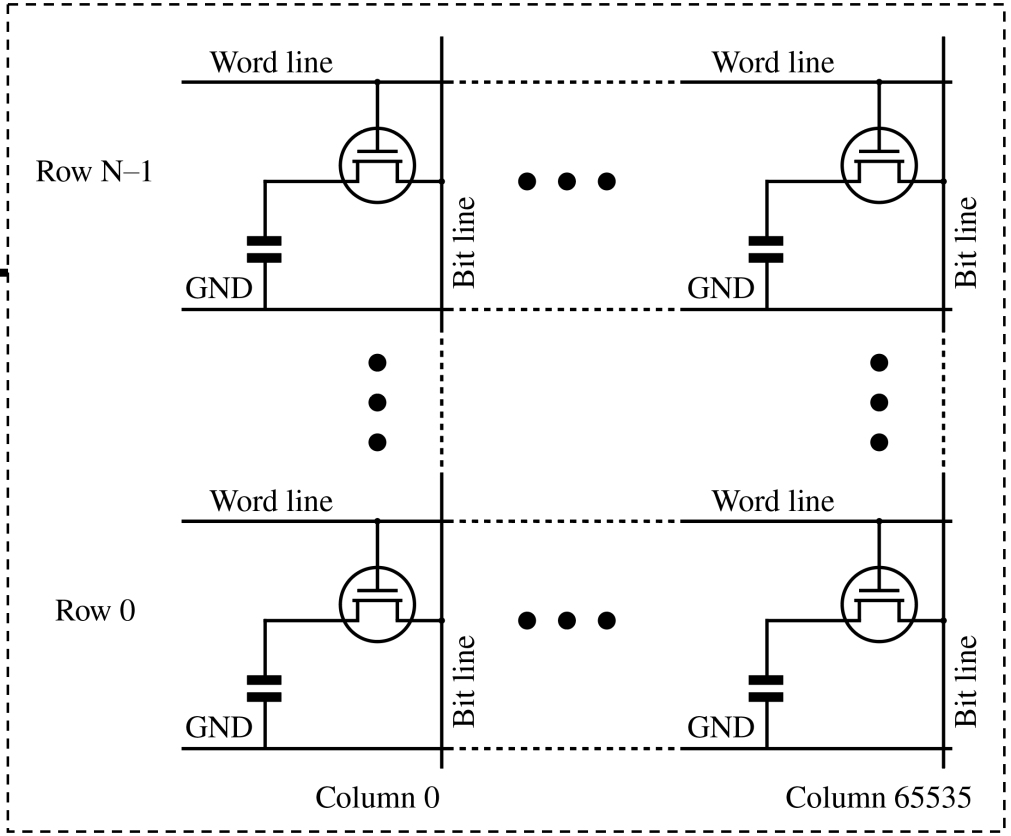


Rank

Chip

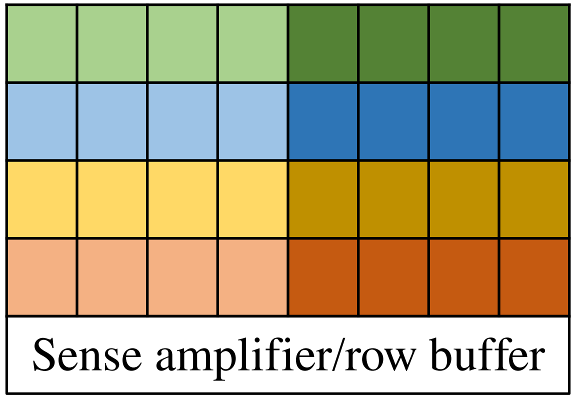


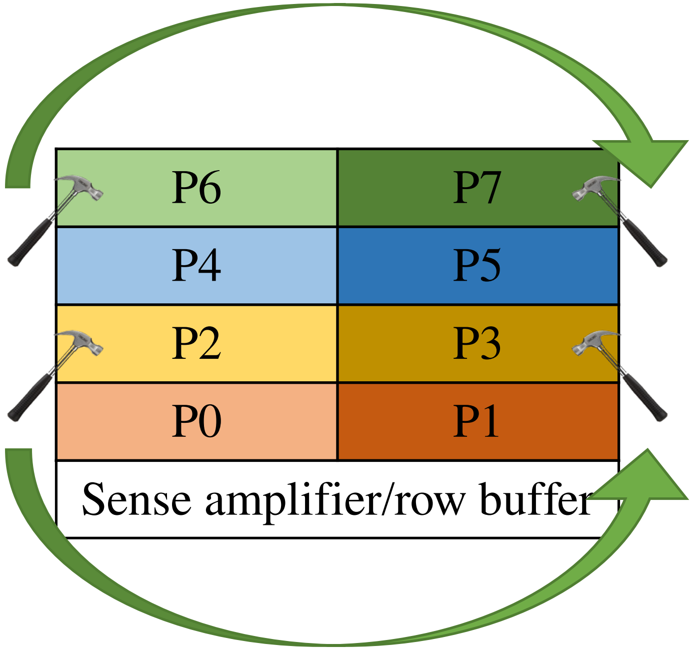
Bank



Background – DRAM Configuration

- DRAM cells are accessed at the granularity of the entire row
- Two pages exist in one row.
- Hammering one page will automatically cause the other page on the same row to be hammered.





Bit Flips

- The three adjacent bits in a column can be represented by x-y-z.
- 0-1-0 and 1-0-1 are stripe patterns and are likely to flip.
- 0-0-0 and 1-1-1 are uniform patterns and aren't likely to flip.
- 1-1-0, 1-0-0, 0-1-1, and 0-0-1 are neither and the outcome is unknown.

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

↓

1	1	0	0	0	0	1	1
1	1	0	0	?	?	?	?
1	1	0	0	1	1	0	0

Overall Technique

- Allocate a consecutive block of DRAM and check for cell susceptible to Rowhammer.
- Strategically deallocate memory to trick the victim into placing a secret value in the rows above and below an attacker controlled sampling page.
- Access the other pages on the same rows as the secrets to leak the data into the middle attacker row.
- Combine bits recovered by placing the secret in various locations in the allocated DRAM block.
- Use math to recover all missing components of the RSA key.

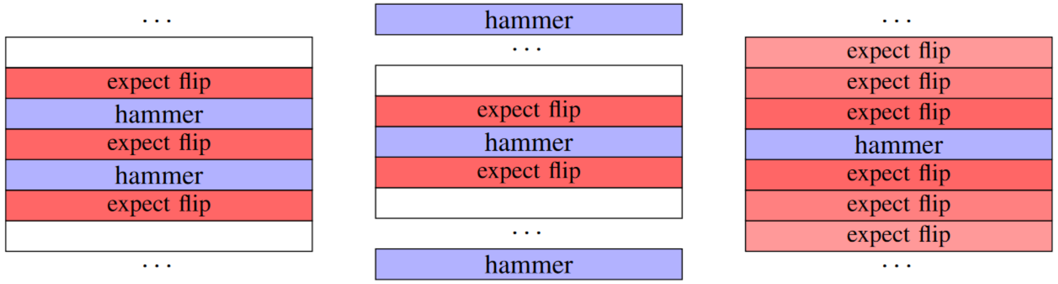
Row Activation Page	Secret
Unused	Sampling Page
Row Activation Page	Secret

Thoughts?

Strengths/Weaknesses

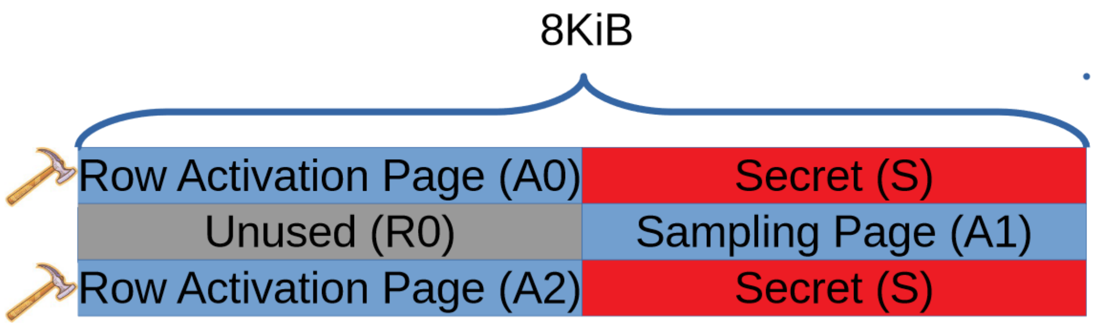
- Strengths
  - Novel usage of Rowhammer to convert from a write to a read channel.
  - Works on Ubuntu Linux in standard configuration (no huge pages, page map access, memory deduplication).
  - Clever circumventions of ECC, memory scrambling, and physical address unalignment.
  - New mechanism (Frame Feng Shui) used to place victim pages at desired locations.
- Weaknesses
  - Capability to recover random data is not shown.
  - Relies heavily on *a priori* knowledge (key location, allocation patterns).
  - Technique seems much easier to mitigate than authors indicate.
  - A detailed study of the DRAM templating is not provided.

DRAM Page Layout

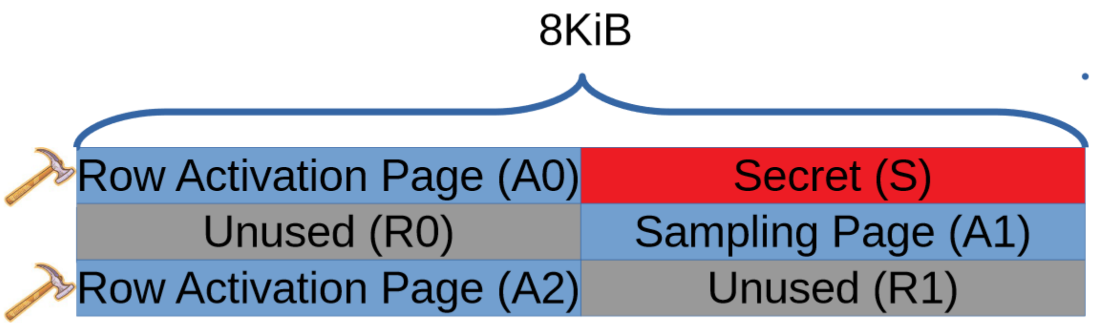


(a) Double-sided (b) Single-sided (c) One-location

- Double-sided Rowhammer is preferred to maximize the likelihood of a bit flip.
- The secret (S) is placed above and below the sampling page (A1) in the same rows as A0 and A2.
- Accessing A0 and A2 hammers data into A1 without accessing S.



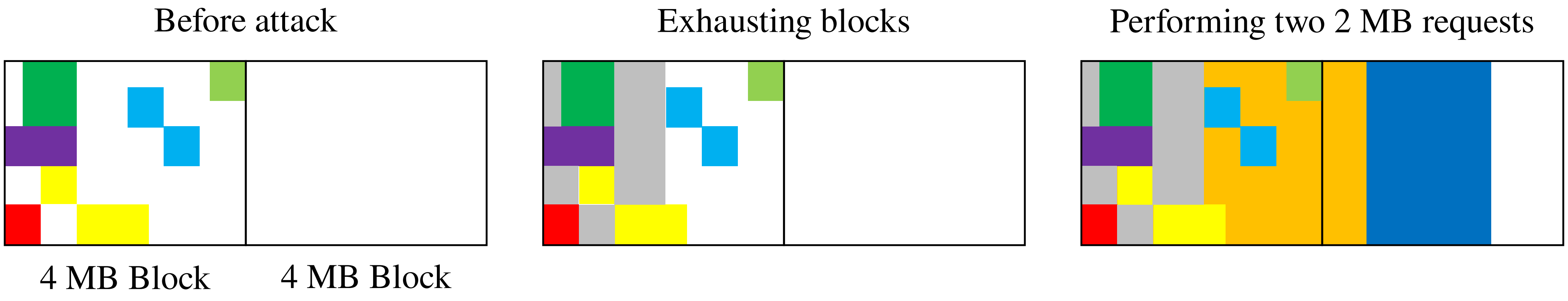
(a) Double-sided Rambleed. Here, the sampling page (A1) is sandwiched between two copies of S.



(b) Single-sided Rambleed. Here, the sampling page (A1) is neighbored by the secret-containing page (S) on a single side.

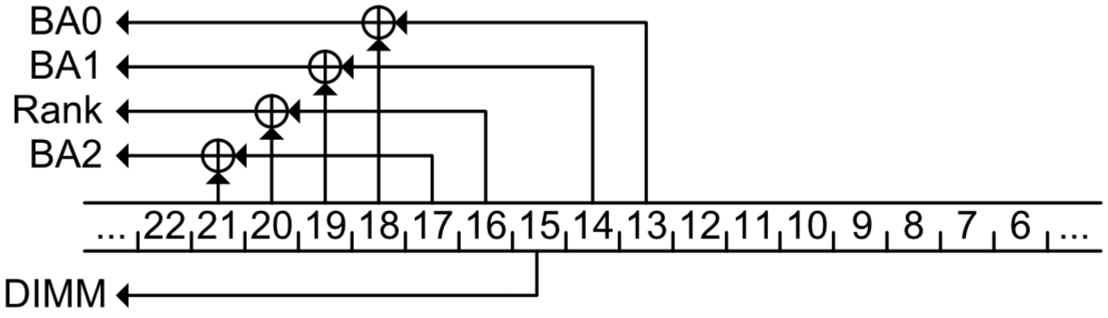
Memory Massaging – Obtain DRAM Block

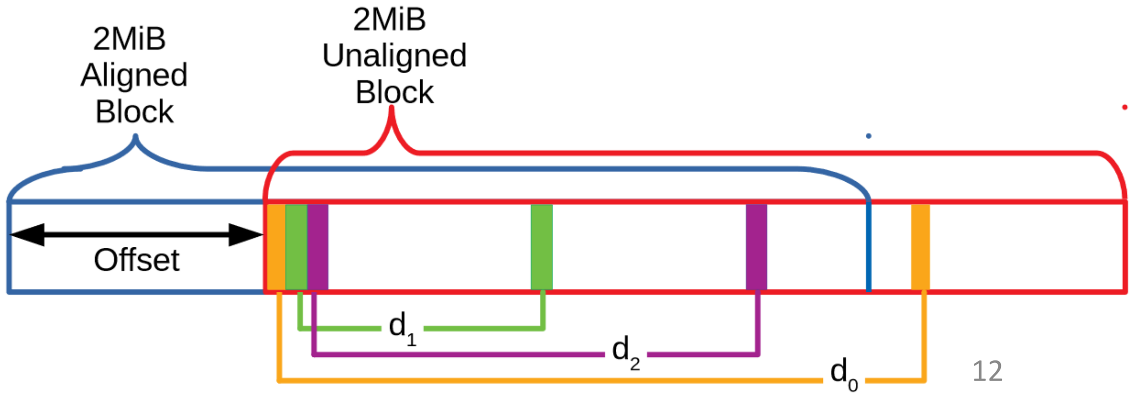
- Attack Linux buddy allocator
  - Exhaust small blocks with *mmap* and monitor available block sizes in kernel free lists until less than 2 MB of free space is available in blocks smaller than order 10 (4 MB).
  - Request two 2 MB blocks. A 4 MB block will be split and the second request will be physically consecutive memory.



Memory Massaging – Offsets and Templating

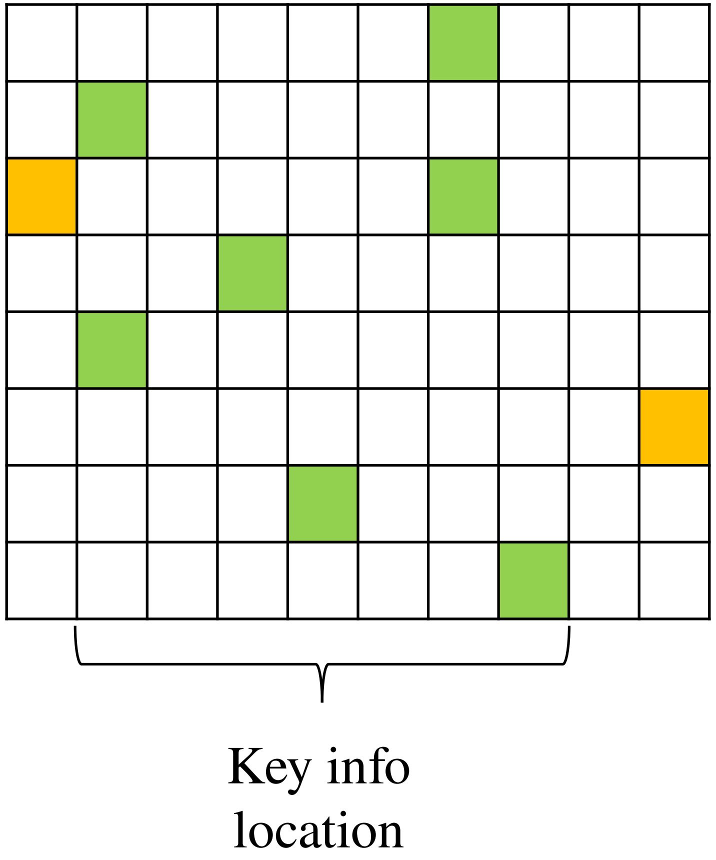
- Address differences between co-banked pages uniquely identifies unaligned block offset based on memory controller addressing design.
  - Address bits a_0 - a_{20} are known once the offset is known.
  - Timing channels are used to identify co-banked pages.
- Get a_{21} using $a^0_{17} \oplus a^0_{21} = a^1_{17} \oplus a^1_{21}$ on consecutive rows.
- Template by imposing 1-0-1 and 0-1-0 stripes in consecutive row and checking for bit flips.





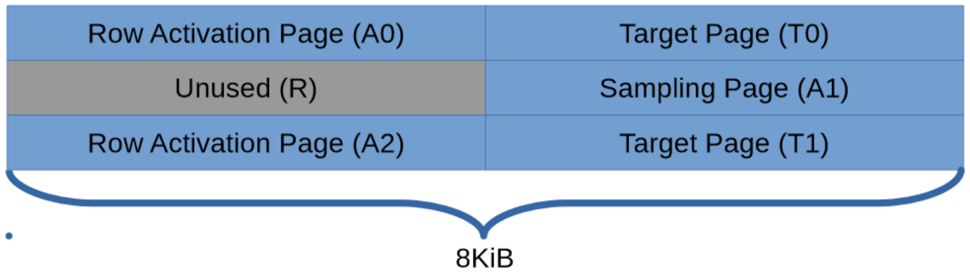
Key Extraction

- From templating, bits that flip in the same location as key data are considered useful (3/16).
- Bit flips occurring at the same offset in multiple rows are redundant and not useful (4/15).
- Out of 84K recovered bit flips, 4.2K will provide useful information for key extraction.
- Can achieve 3-4 bit/second.

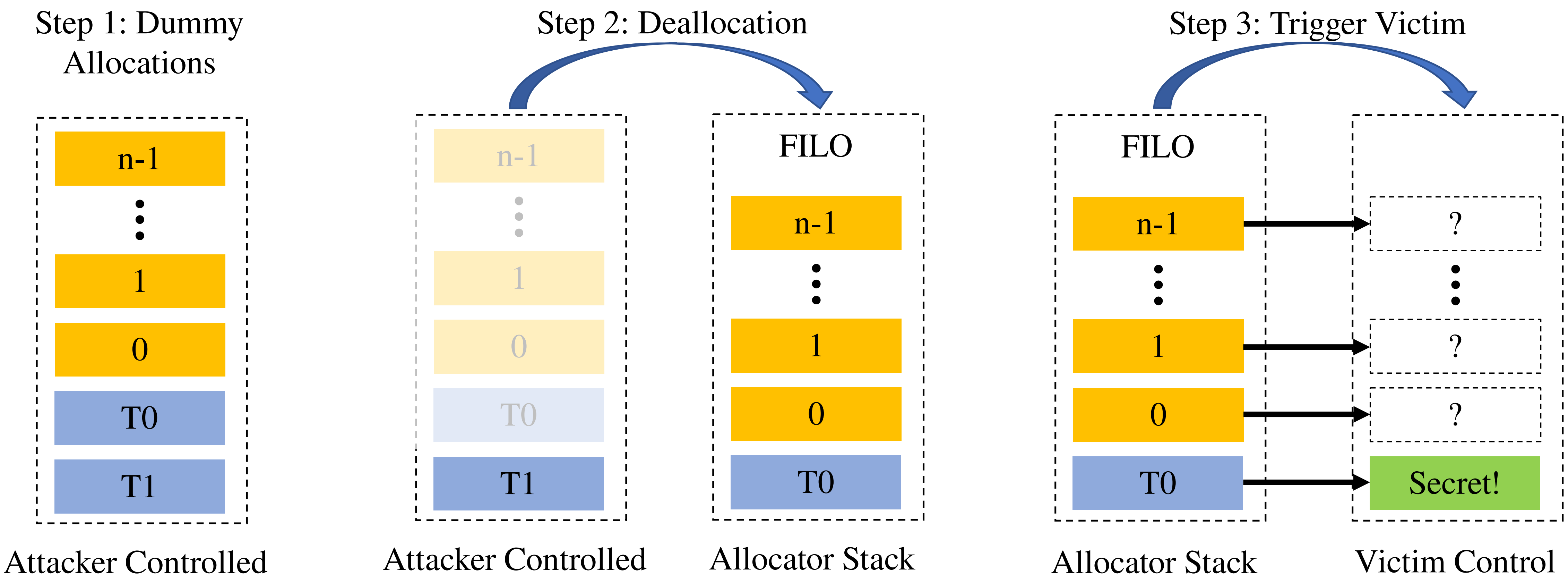


Type	Read Accuracy Percents		
	Overall	*False Positive*	*False Negative*
Double-sided	90%	5%	15%
Single-sided	74%	19%	29%

Frame Fung Shui

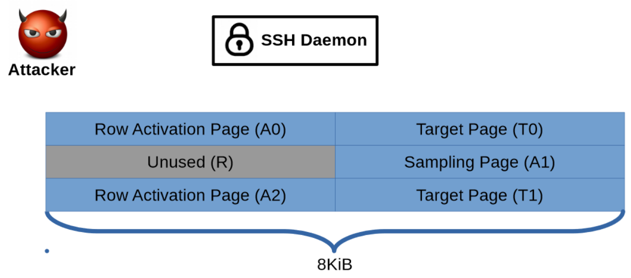


- Given a know victim DRAM allocation pattern, devise a situation such that the victim places the secret in T0 or T1.

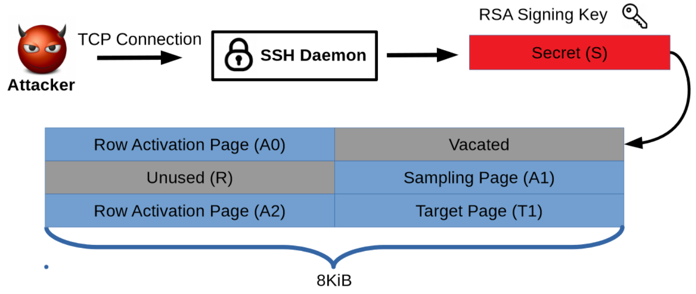


SSH Attack

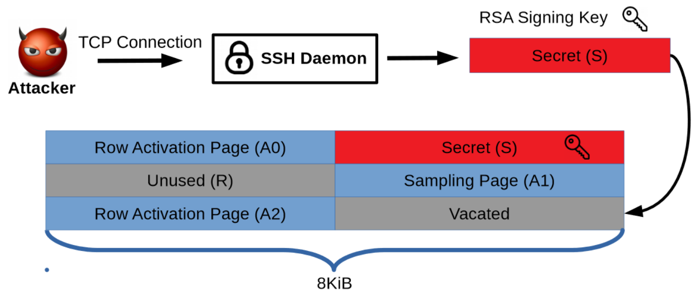
- 4,200 bits (68%) recovered at 0.31 bits/second and 82% accuracy. (~4 hours)
- Full key was successfully recovered with Heninger-Shacham algorithm.



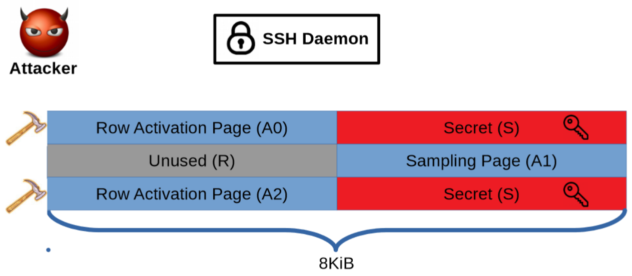
(a) The attacker initially owns both target pages T0 and T1.



(b) The attacker makes an SSH connection and performs Frame Feng Shui to land the secret S in the target page T0, which lies above the sampling page (A1).



(c) The attacker repeats the Frame Feng Shui process to land S in the target page T1, below the sampling page (A1).



(d) After achieving the double-sided RAMBleed position, the attacker now hammers the activation pages (A0 and A2) to induce flips in the sampling page (A1).

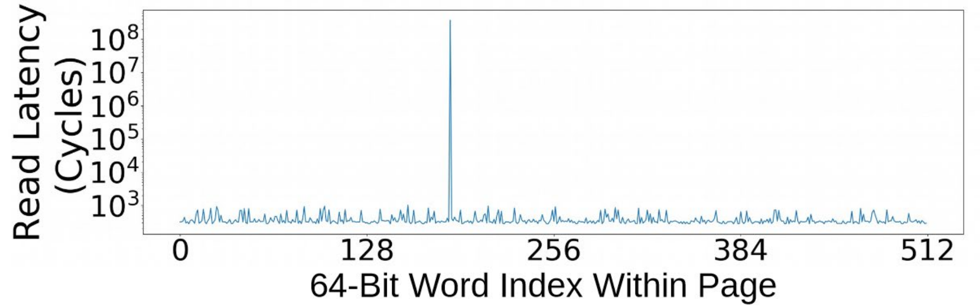
Type	Probability
Double-sided RAMBleed	68.89%
Single-sided RAMBleed	28.22%
Unable to place victim	2.39%

Poll Question

- Which countermeasure would provide the greatest difficulty in performing the RAMBleed attack?
  - PARA (Probabilistic Adjacent Row Activation)
  - Using ECC RAM.
  - Randomly changing key location within secret page (S) during SSH child spawn.
  - Using DDR4 instead of DDR3.
  - Memory scrambling.
  - Flushing key from memory when done.

ECC Modifications

- In ECC DRAM, the data and check bits are 64 and 8 bits respectively.
- During a read, if the memory controller detects
  - One errors: A large read latency is observed and the unflipped data is read out.
  - Two errors: The machine crashes
- Templating now works using a binary search in each 64 bit word and looking for increased read latency.



- Use increased read latency to ‘read’ the sampling page.
- Achieves 0.64 bits/second and 73% accuracy.

Mitigations

- Probabilistic Adjacent Row Activation (PARA)
  - Not widely adopted and probabilistic security.
- Targeted Row Refresh (TRR)
  - Some papers have induced Rowhammer bit flips even with TRR.
- More frequent refresh (from 64ms to 32 ms)
  - Some papers can flip bits even with this change; not practical for mobile use.
- Using ECC
  - This paper demonstrates how ECC can be used as a vulnerability.
- Memory Encryption
  - This works. Bit flips can cause SGX to halt due to failed integrity check.
- Flush keys from memory
  - Not practical for data that must be stored for long durations.
- Probabilistic memory allocator
  - Cannot defeat RAMBleed with probabilistic memory spraying techniques.
  - Attacker can use row-buffer timing side channel to detect correct configuration.

Discussion Questions

- Is it feasible to use ECC mechanisms which don’t have a discernable latency on correction events?
- How would the attacker handle random placement of the keys within the secret page? If the key were continuously moved?
- The attack's execution leaned heavily on the determinism of Linux's buddy allocator. Would it still be possible to pull off this exploit with a randomized memory allocator?
- This paper (along with other exploits we have discussed) demonstrate how dangerous it can be to share memory mappings/physical memory layouts with user space programs. Is there work demonstrating memory controller based randomized physical layouts?
- Can the ECC RAMBleed attack work if each 64 bit word has more than one bit flip?