ZebRAM: Comprehensive and Compatible Software Protection against Rowhammer Attacks

Radhesh Krishnan Konoth, Marco Oliverio, Andrei Tatar, Dennis Andriesse, Herbert Bos, Cristiano Giuffrida and Kaveh Razavi

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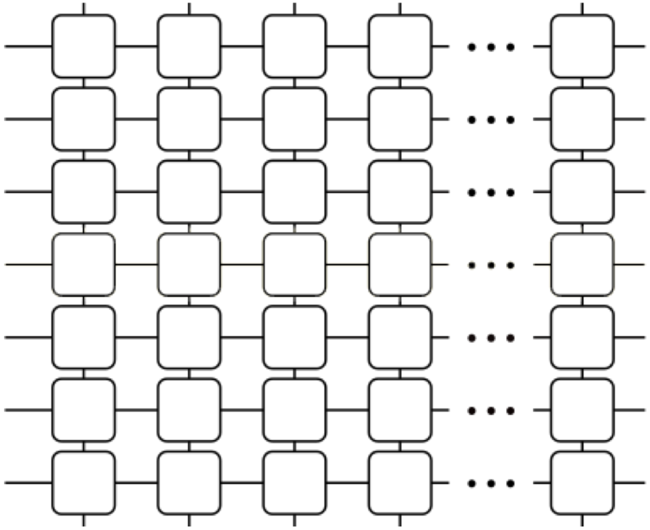
  - … to defend against this hardware bug.

Rowhammer bug



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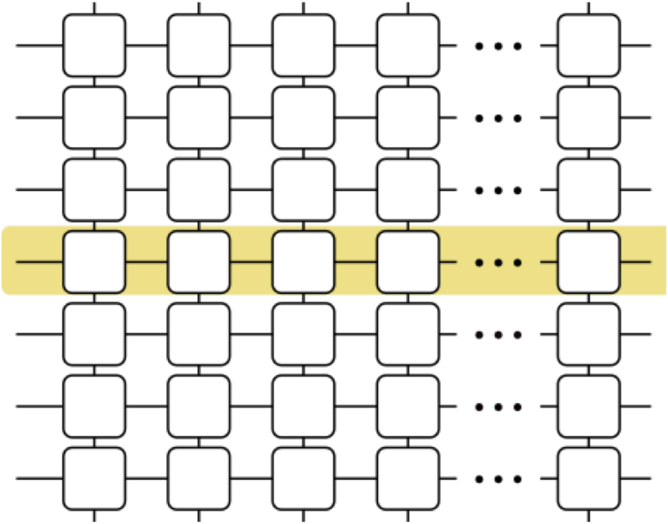

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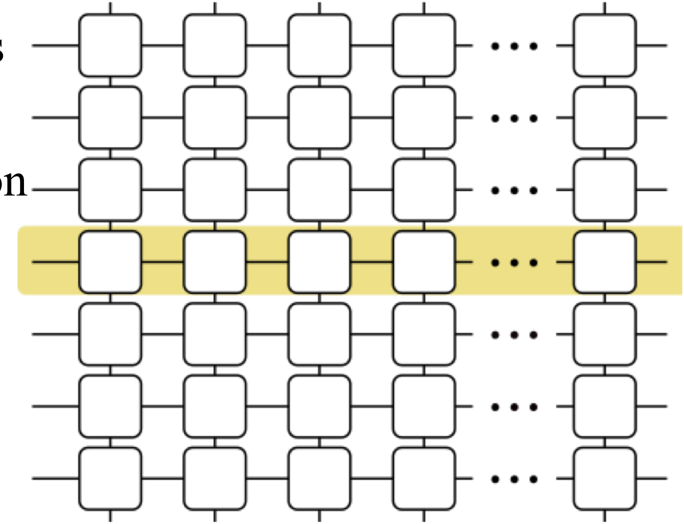

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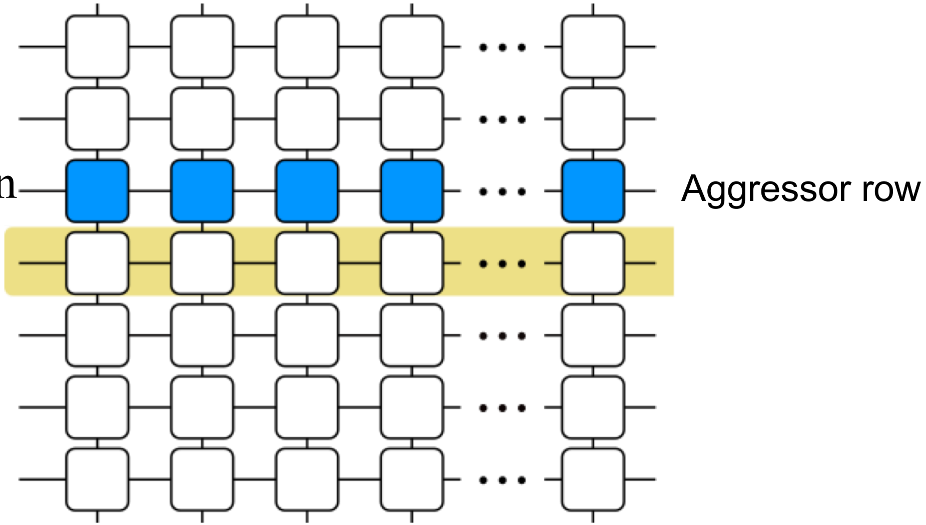

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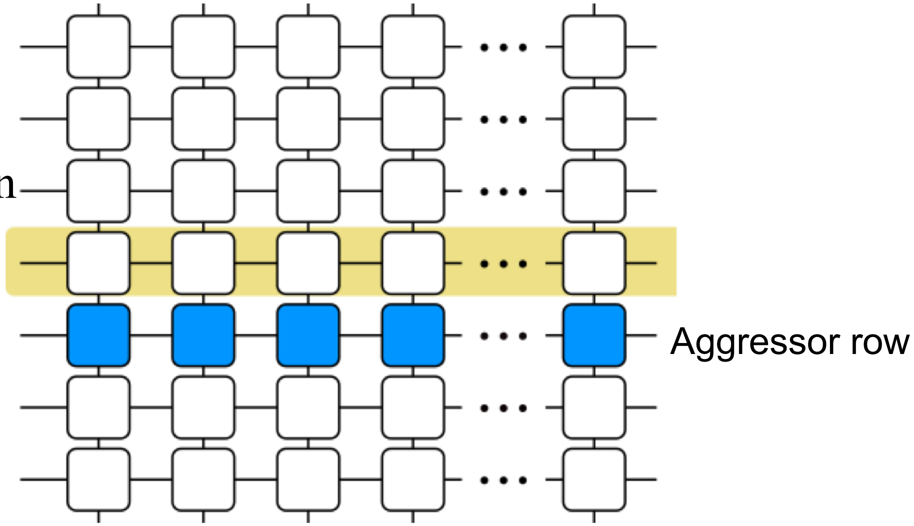

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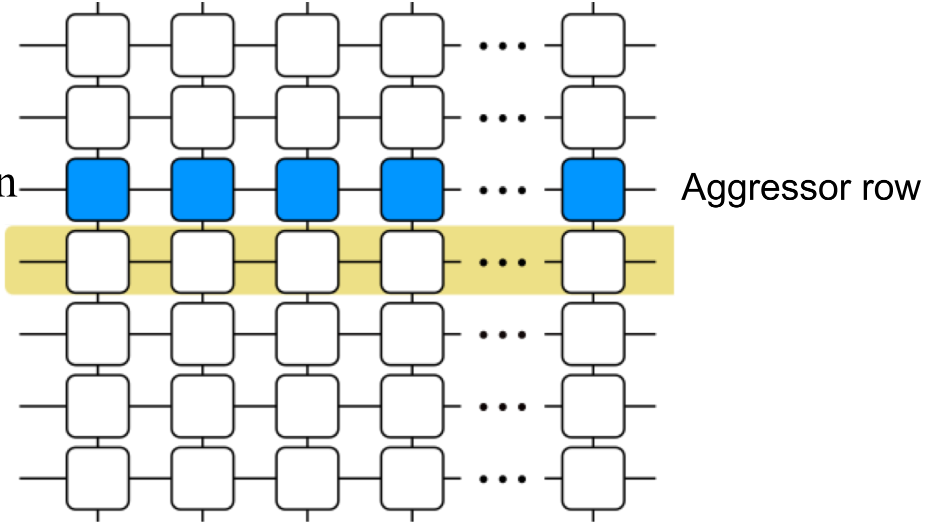

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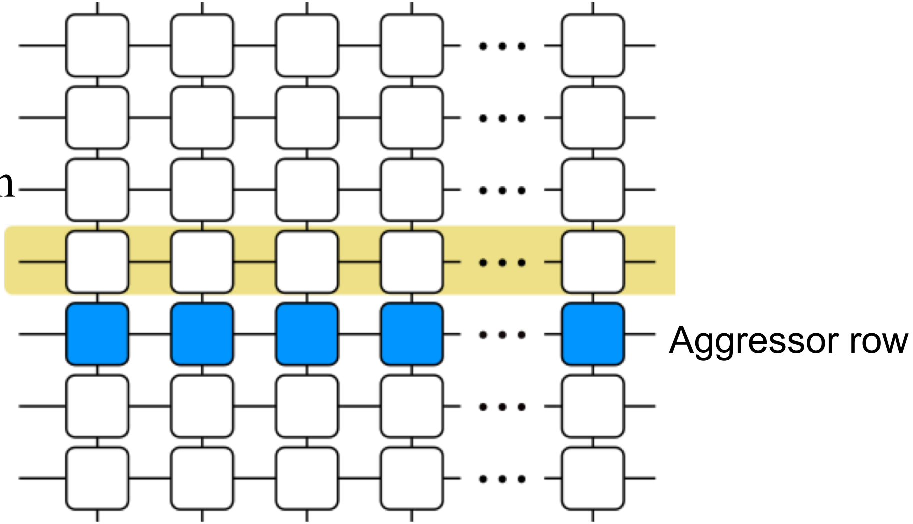

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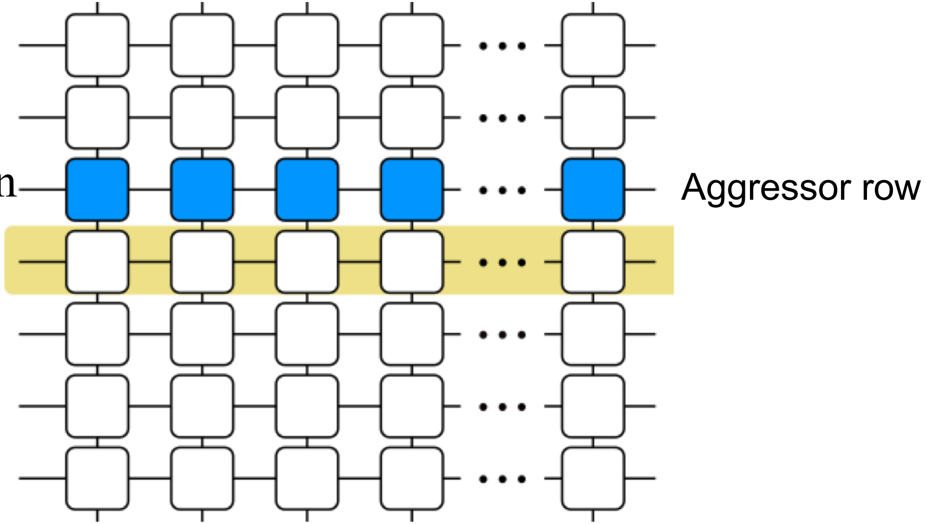

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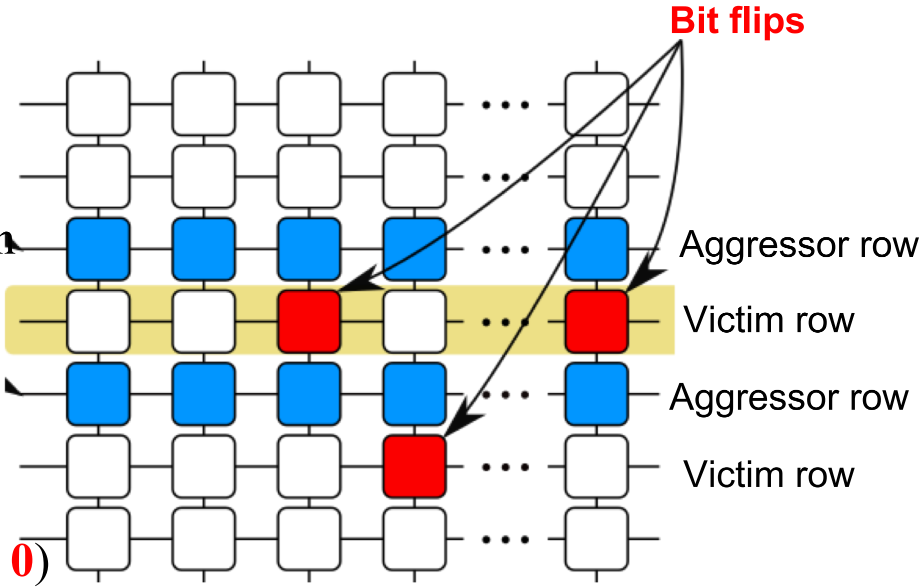

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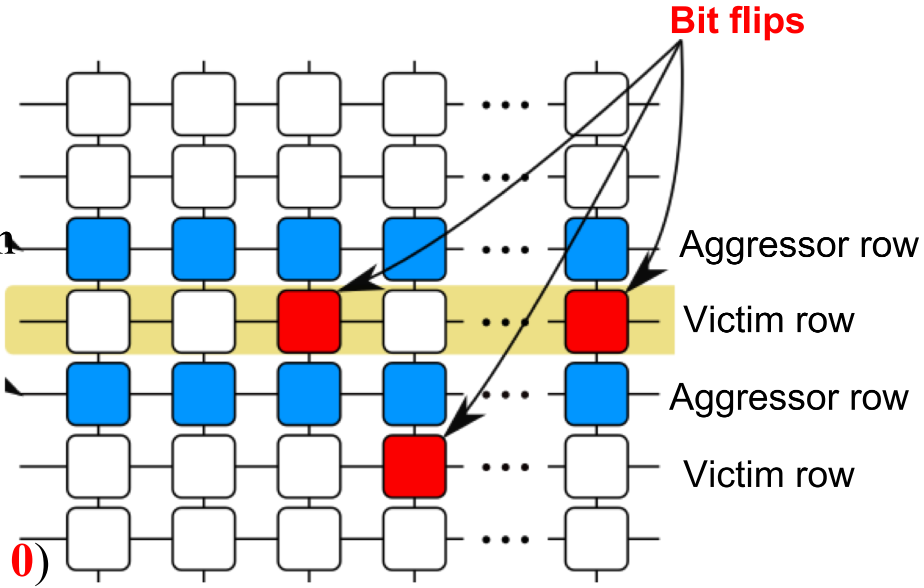

How is this a security problem?

An attacker can flips a bit in:

- Cryptographic key, page table entry in kernel e.t.c.
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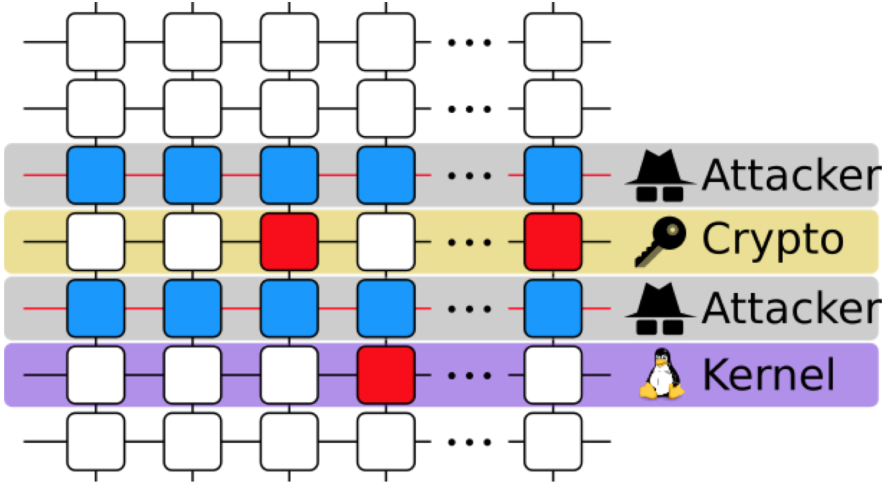

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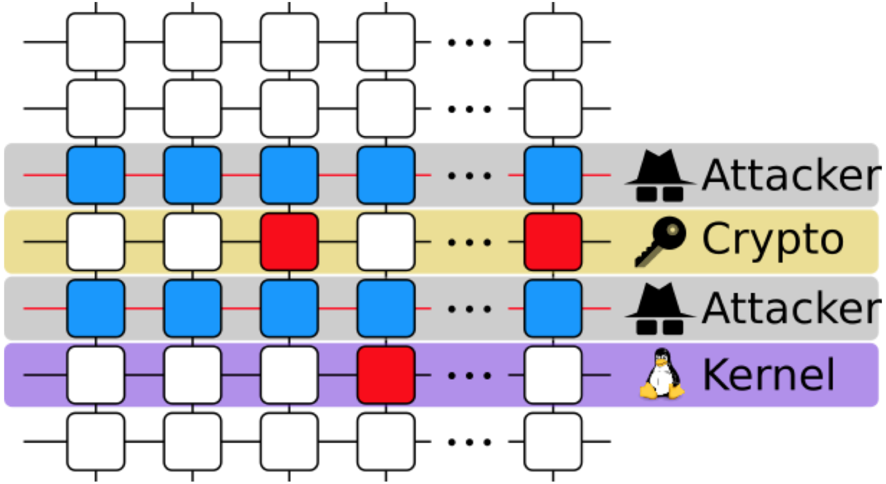

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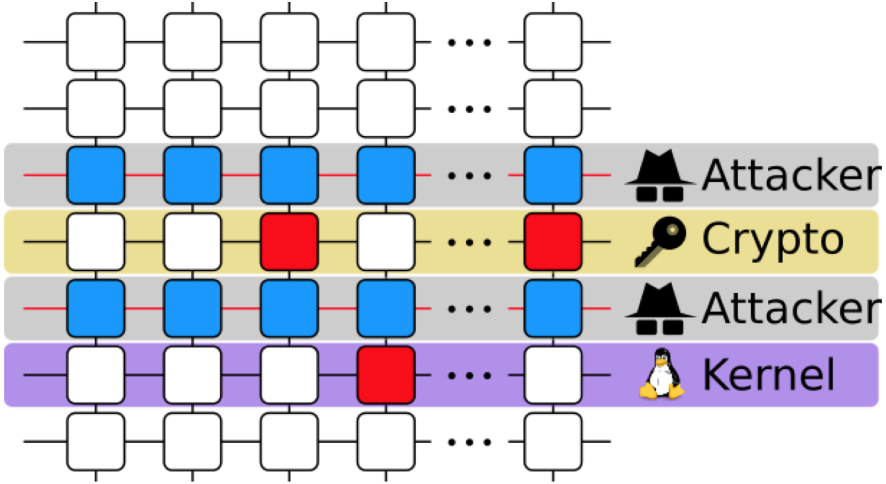

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1. Attacker should able to read **very fast**
2. Can flip a bit on its **neighboring** row

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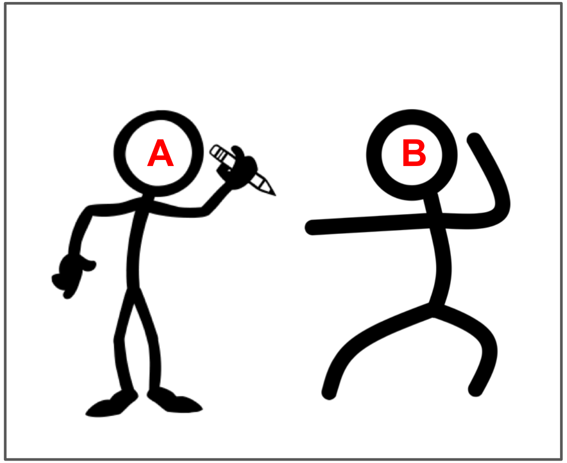

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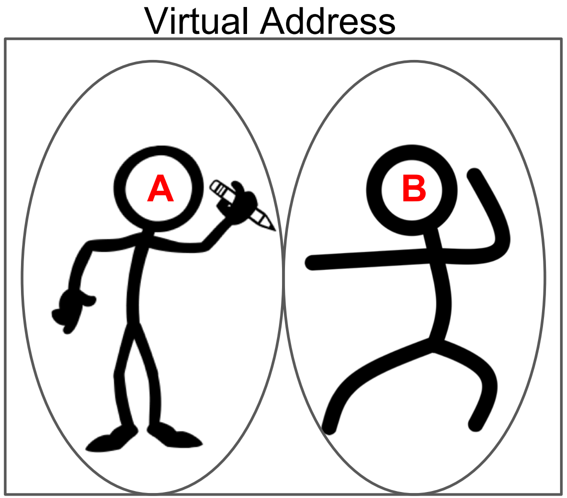
To protect a process *A* from writing to process *B*'s memory:

- ➢ We isolate them using virtual address space



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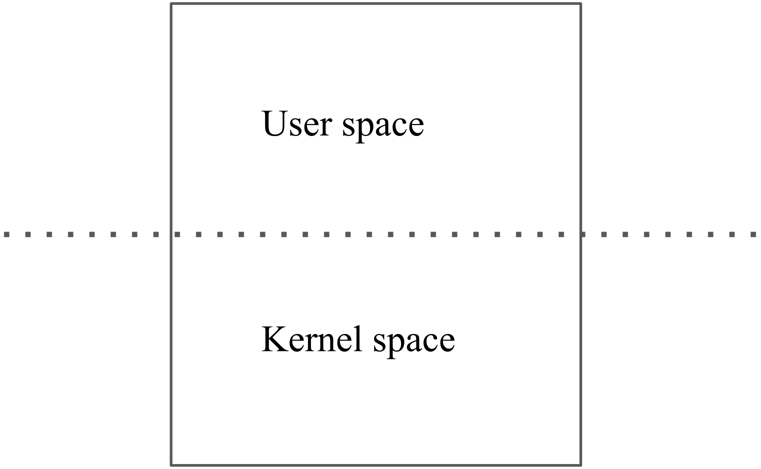

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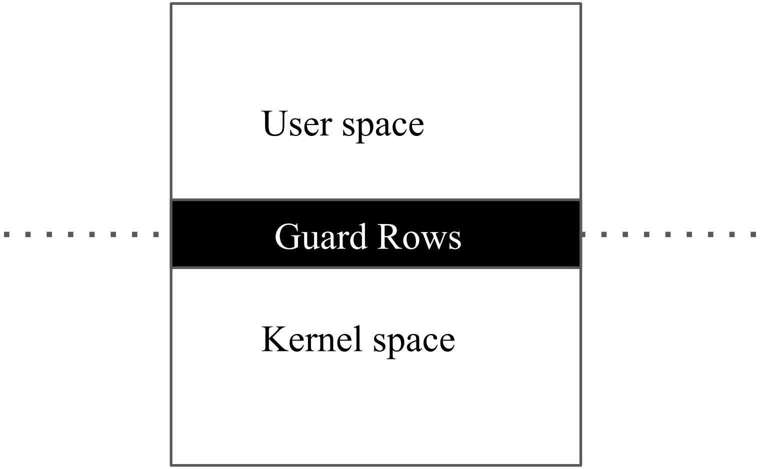

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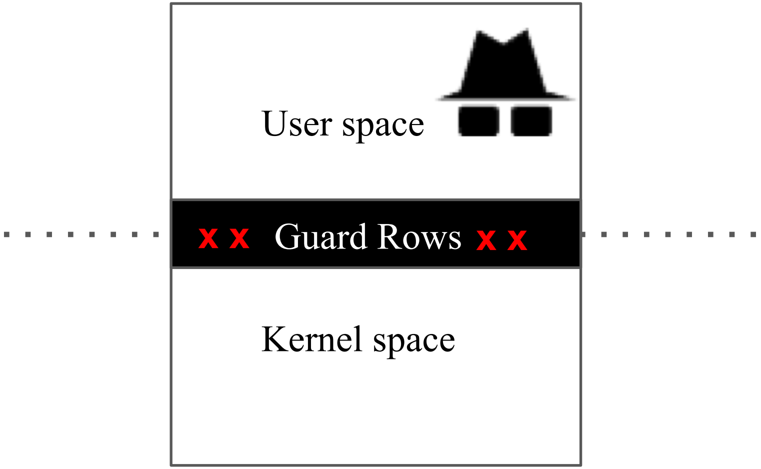

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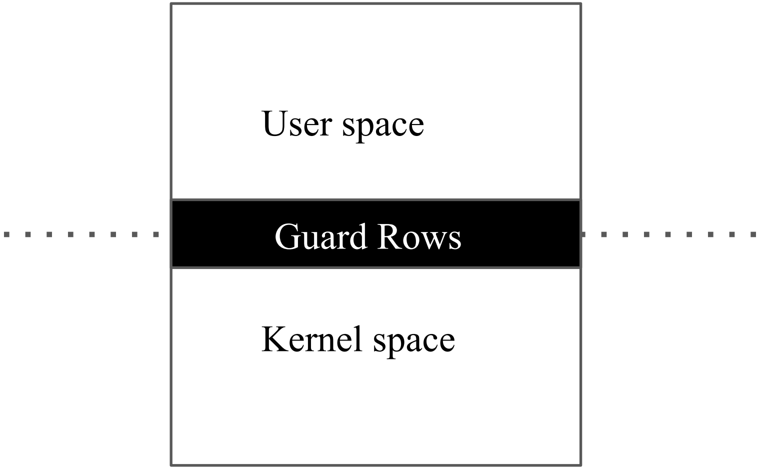

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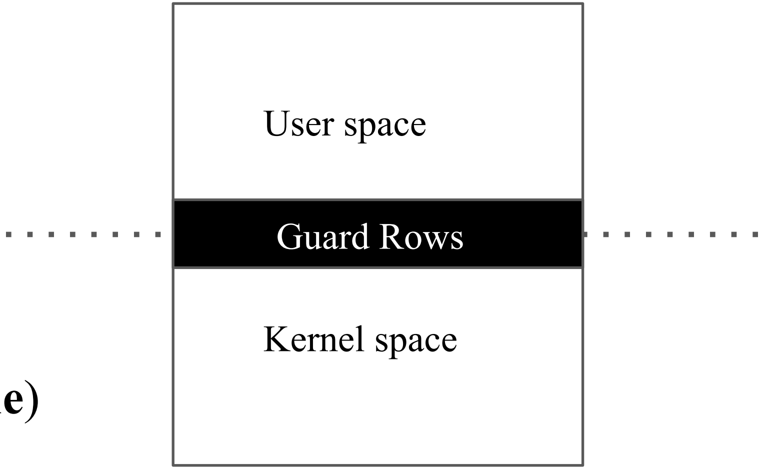
Limitation :

➢ Security domains share memory (**pagecache**) (Gruss et al. S&P'18)



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An application can use a custom memory allocator:

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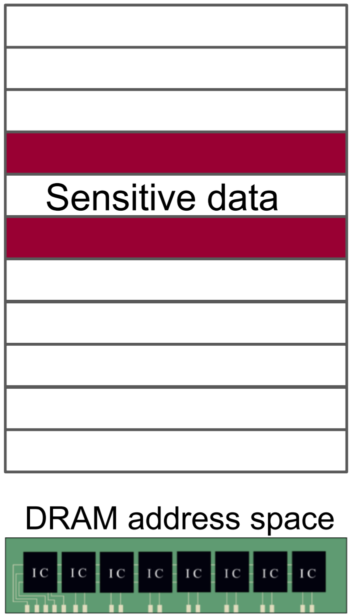

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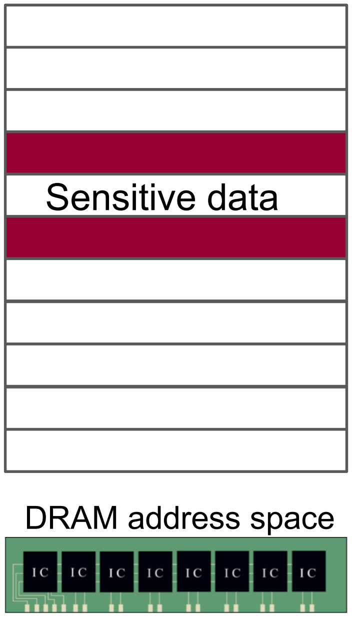

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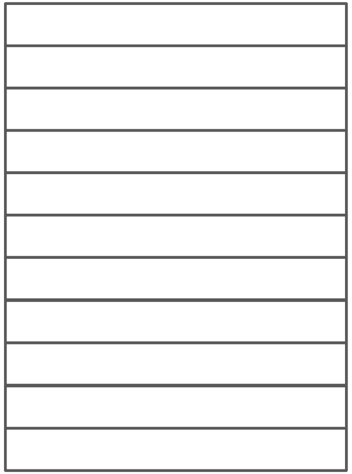
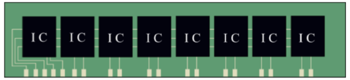


DRAM address space



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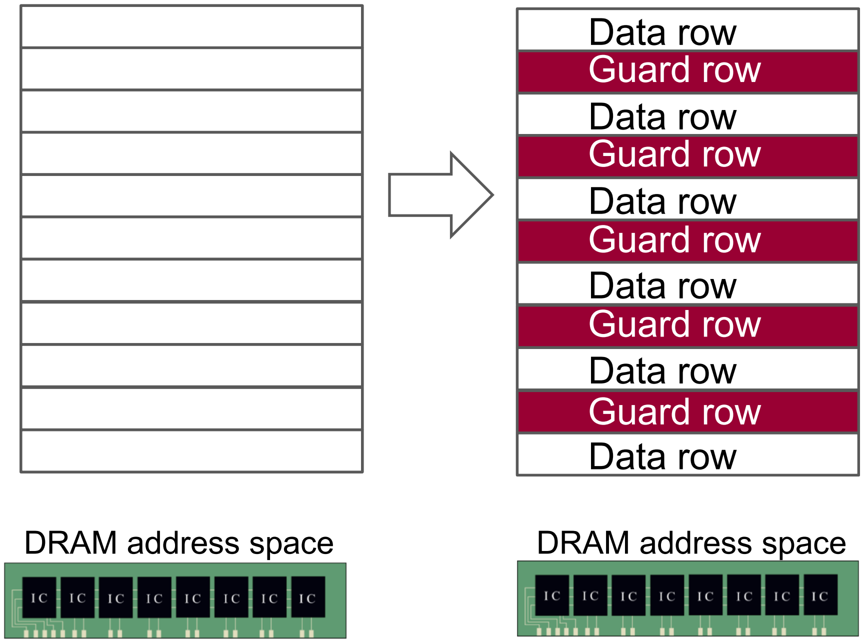

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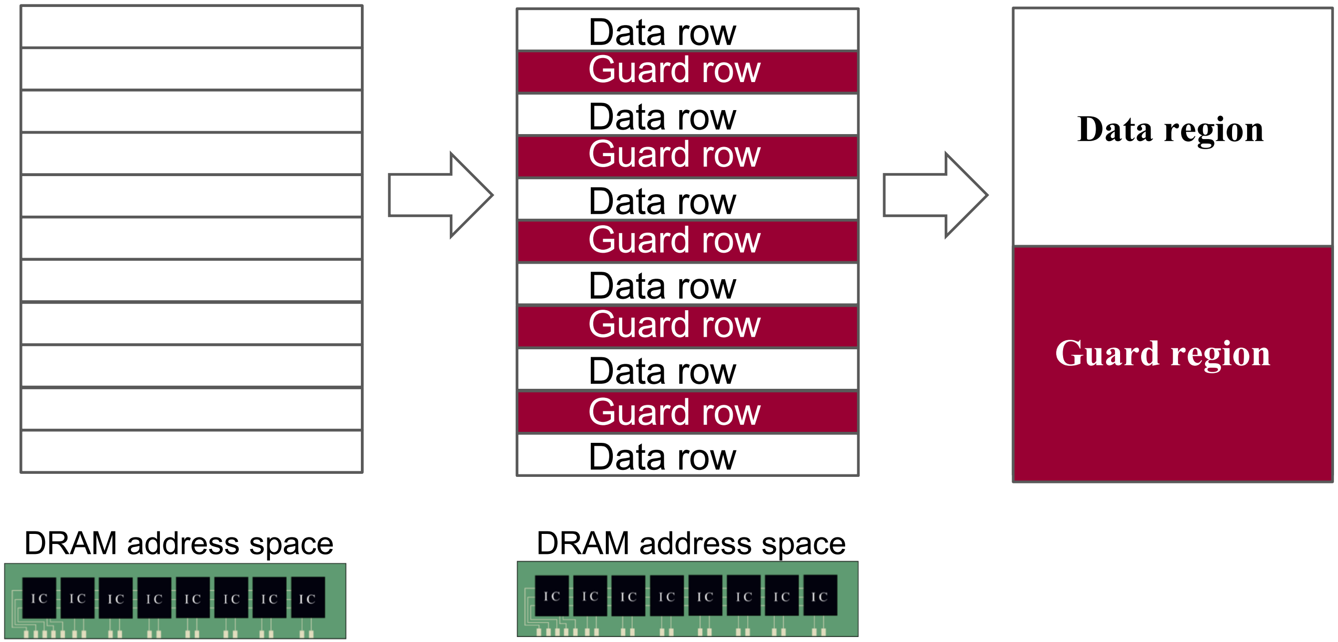

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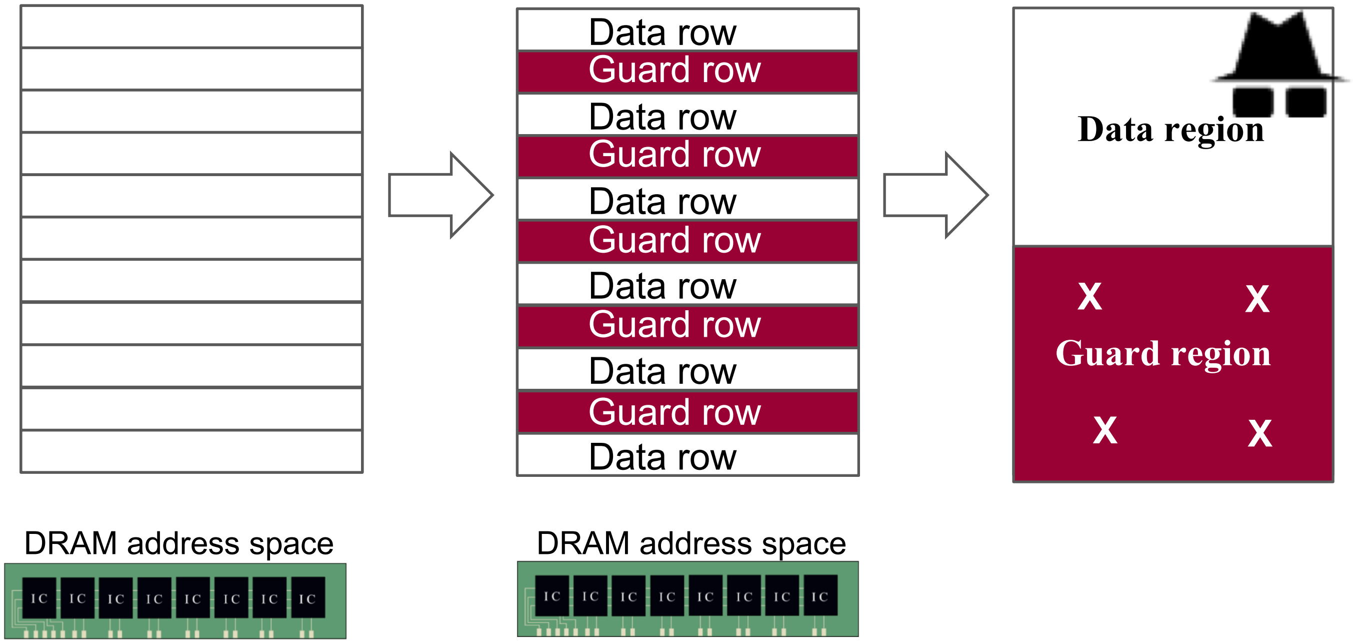

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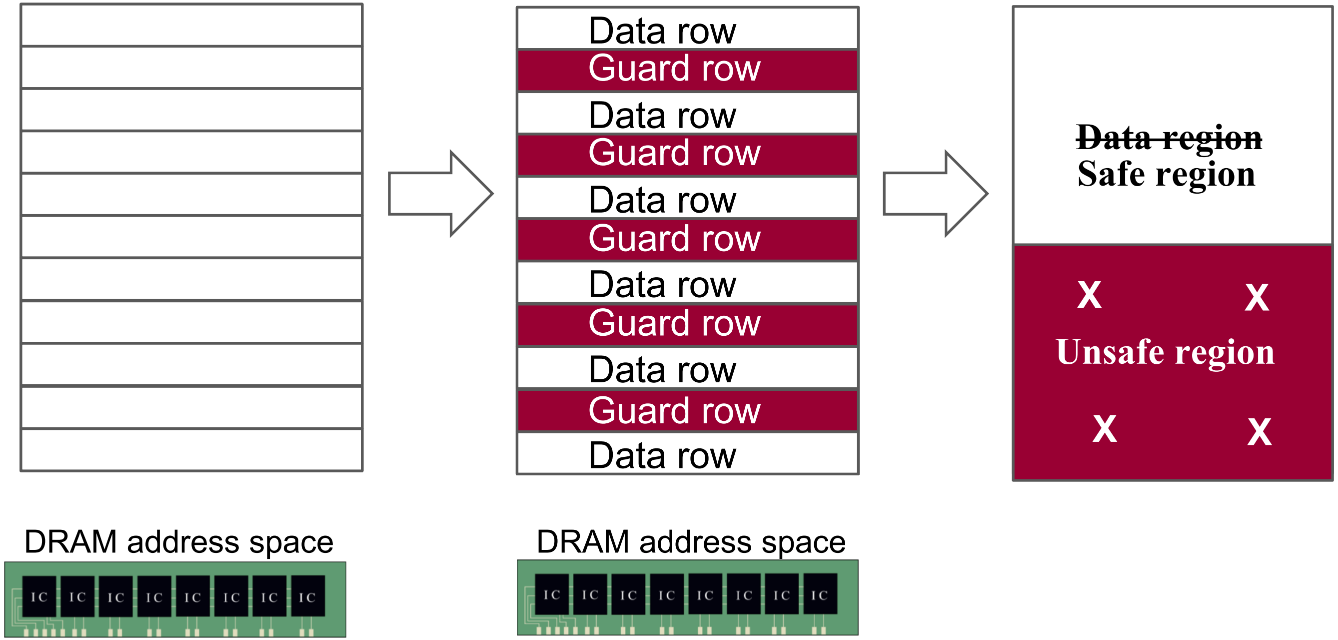

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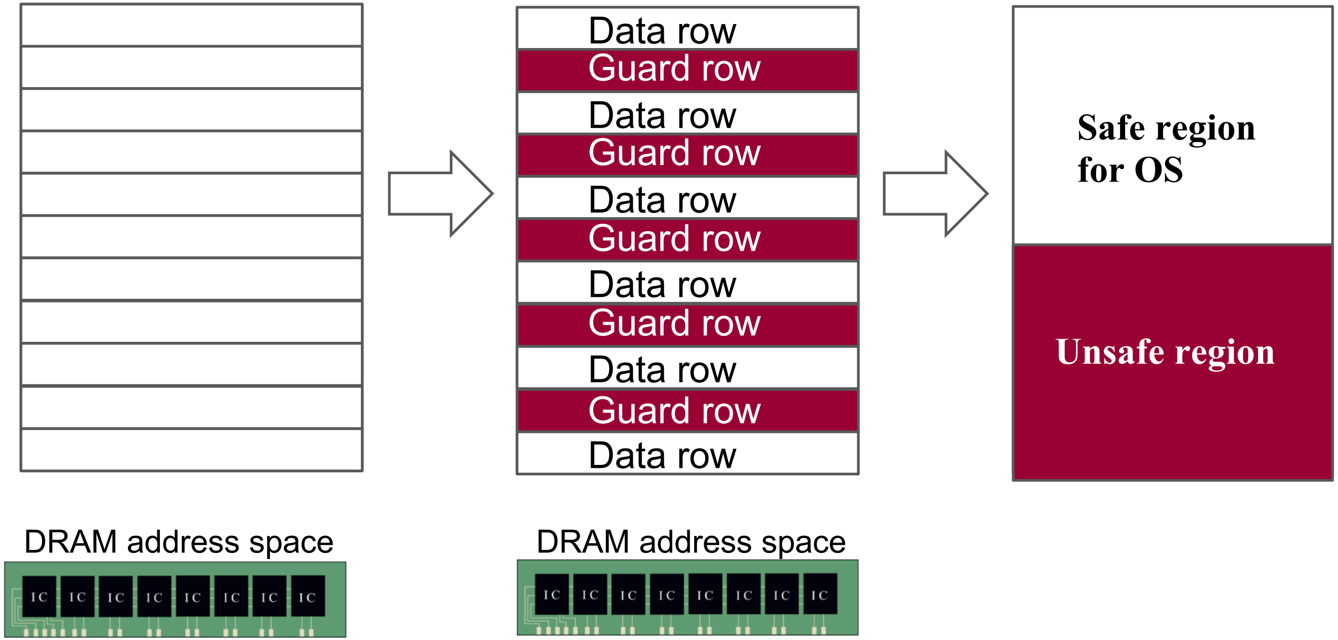

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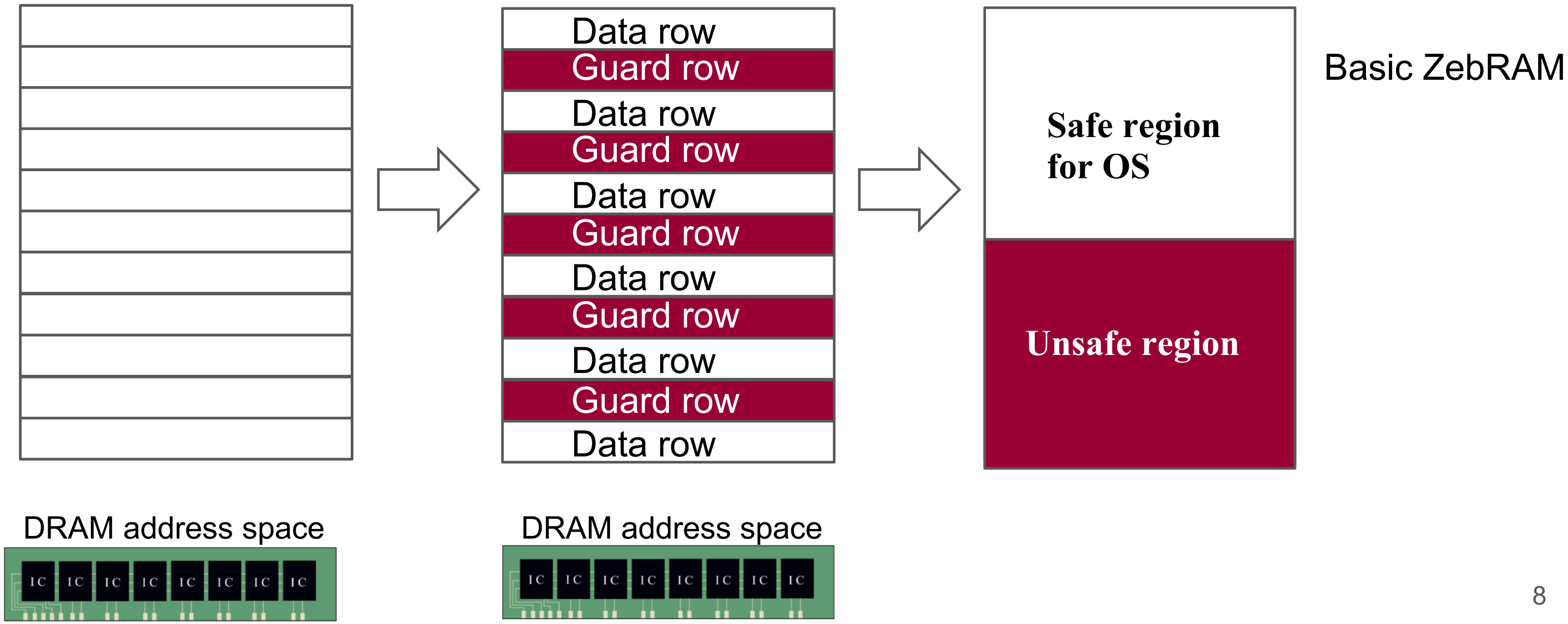
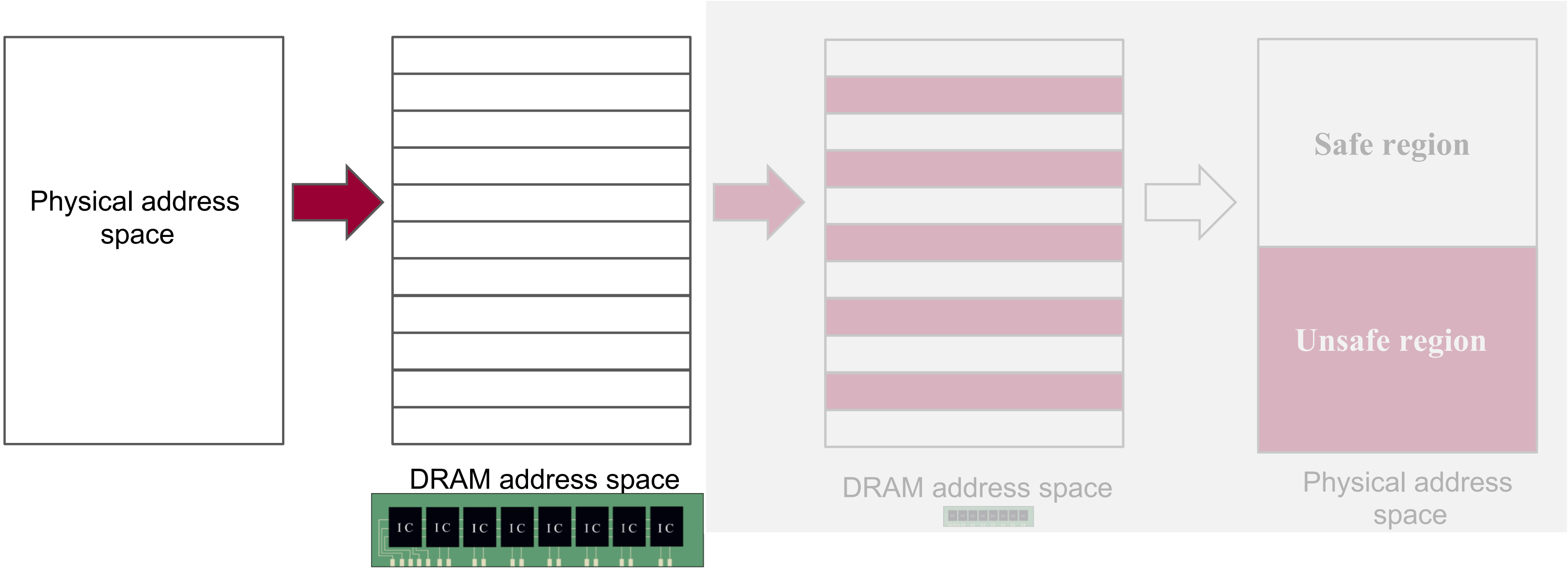


How do we achieve these?

ZebRAM Challenge 1

1. We want to isolate every row in DRAM using guard rows



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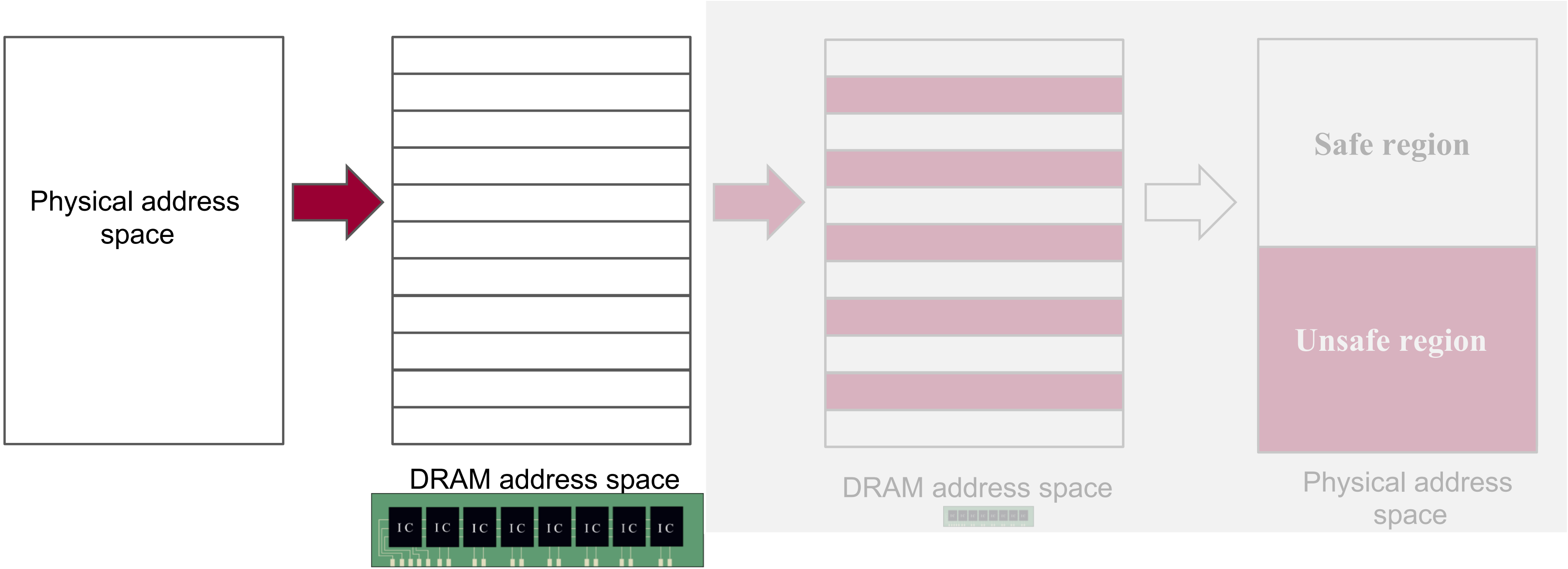
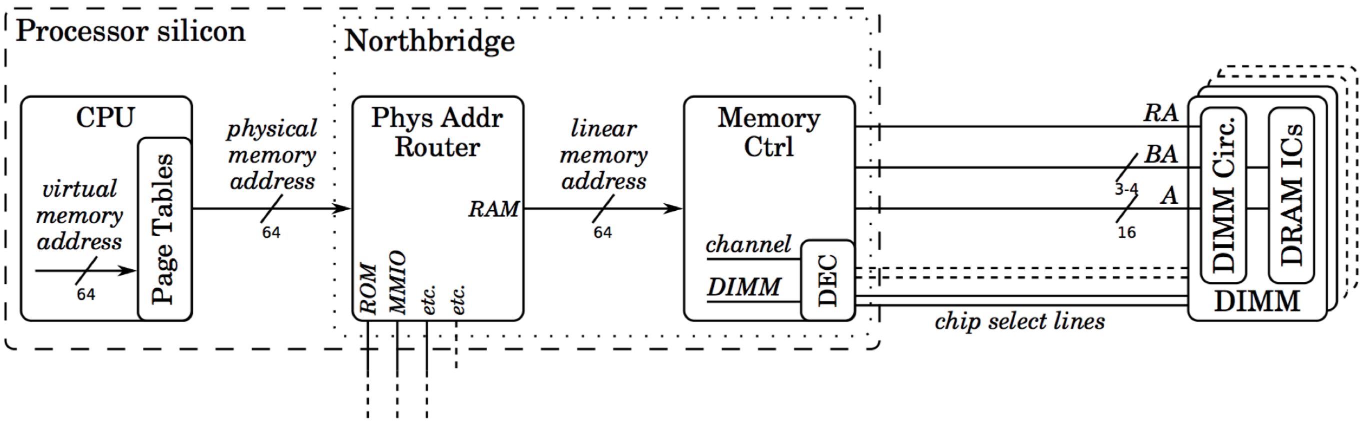
   - Map physical address to its location in DRAM (DRAM address)



Challenge 1 : Physical address to DRAM address

Virtual address to Physical address:



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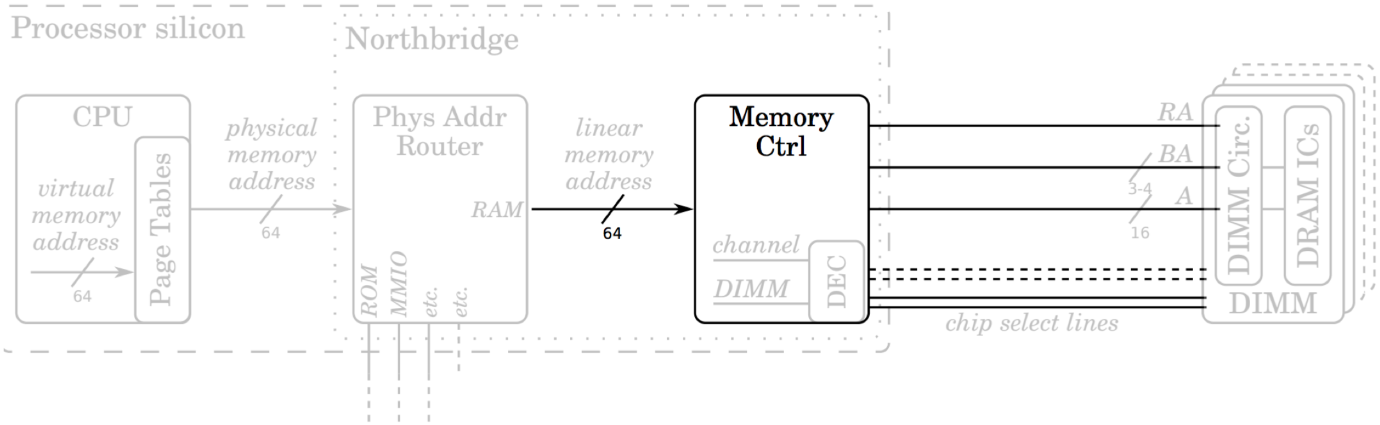

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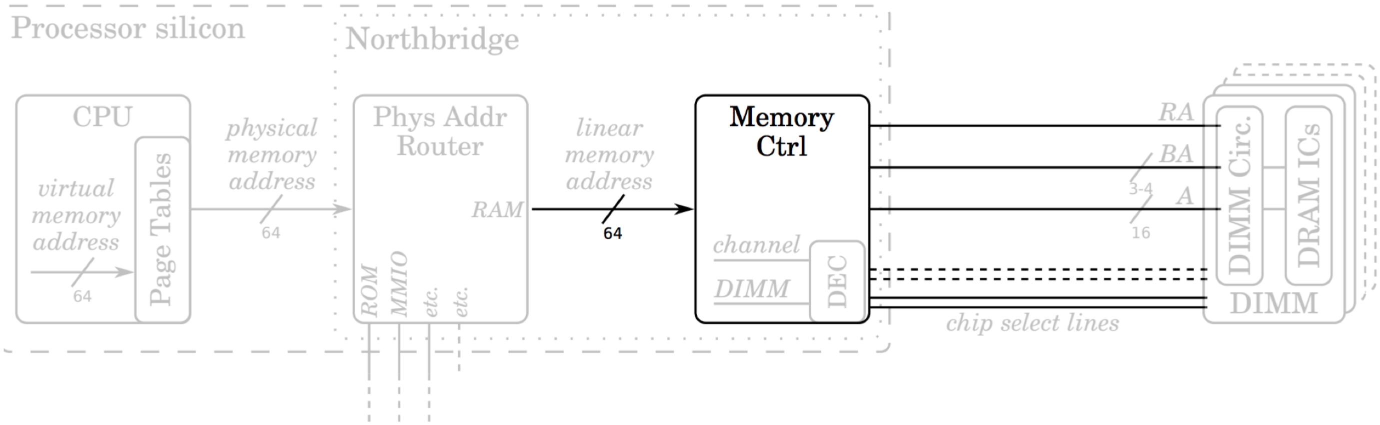

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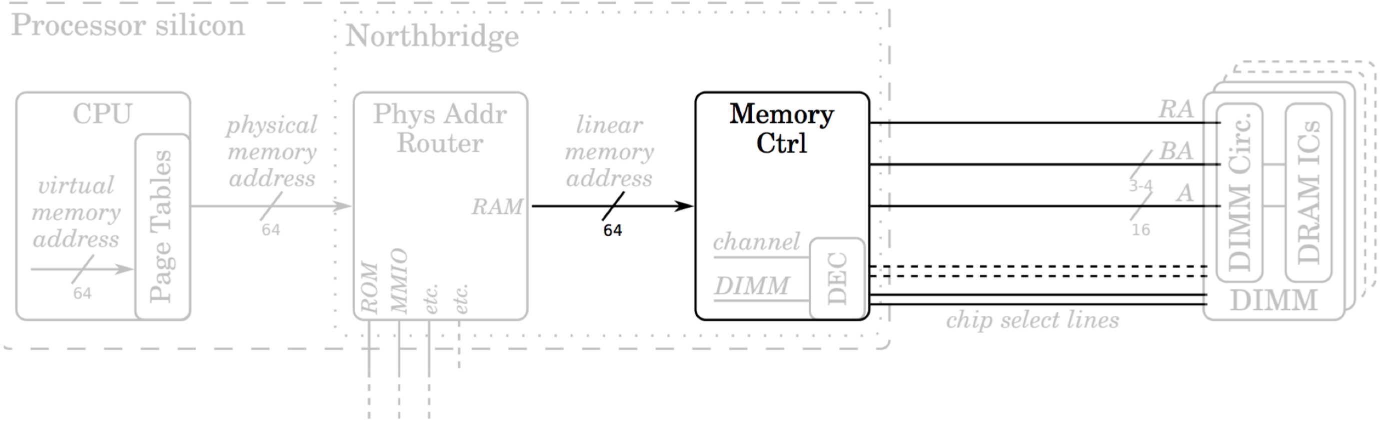

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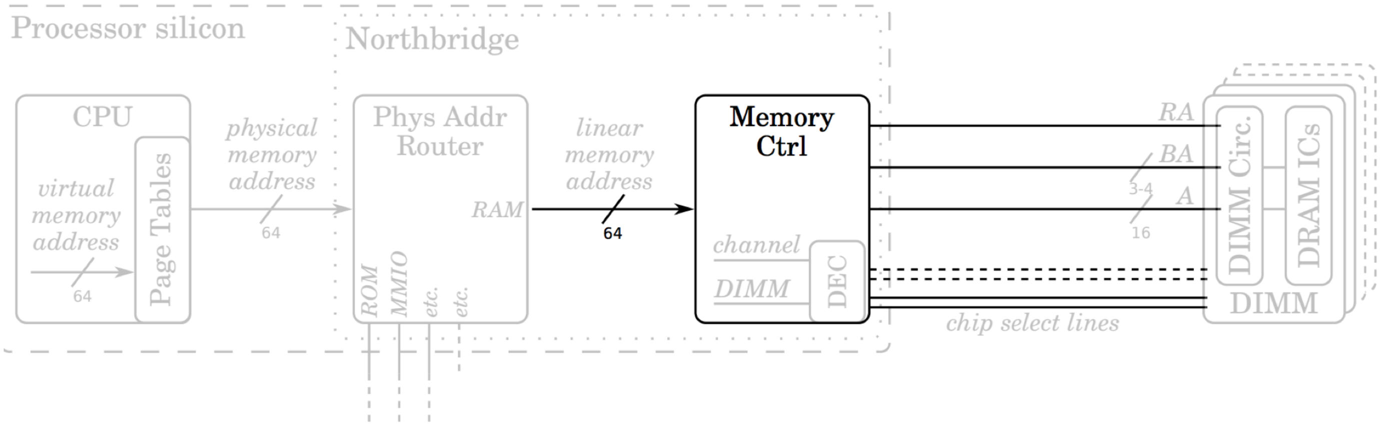

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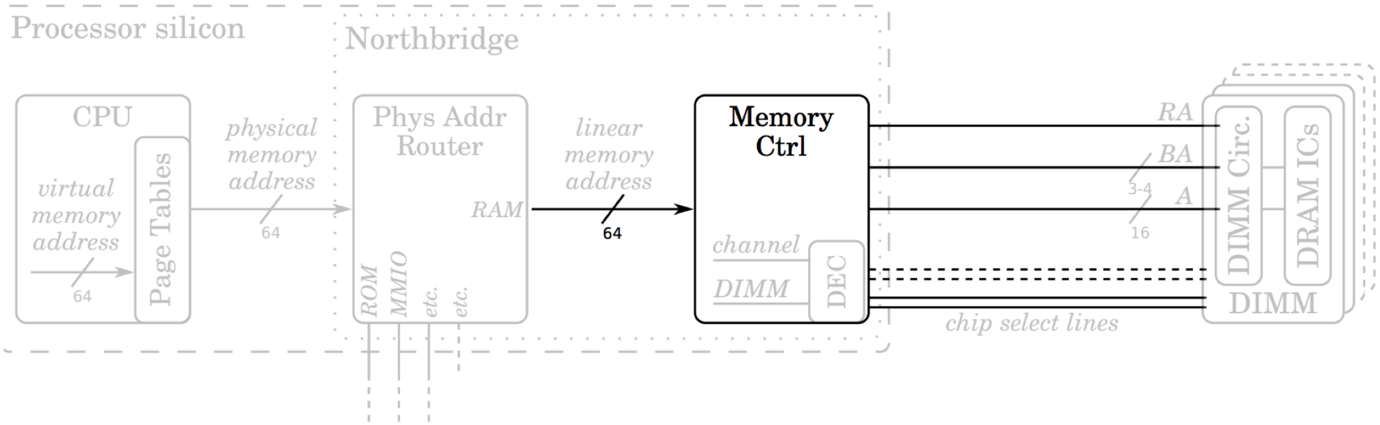

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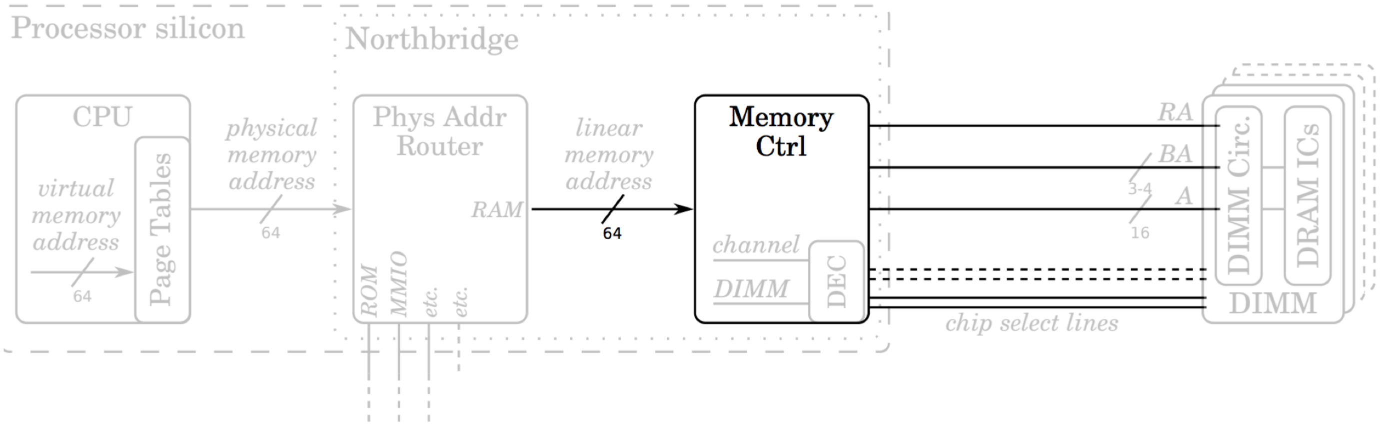

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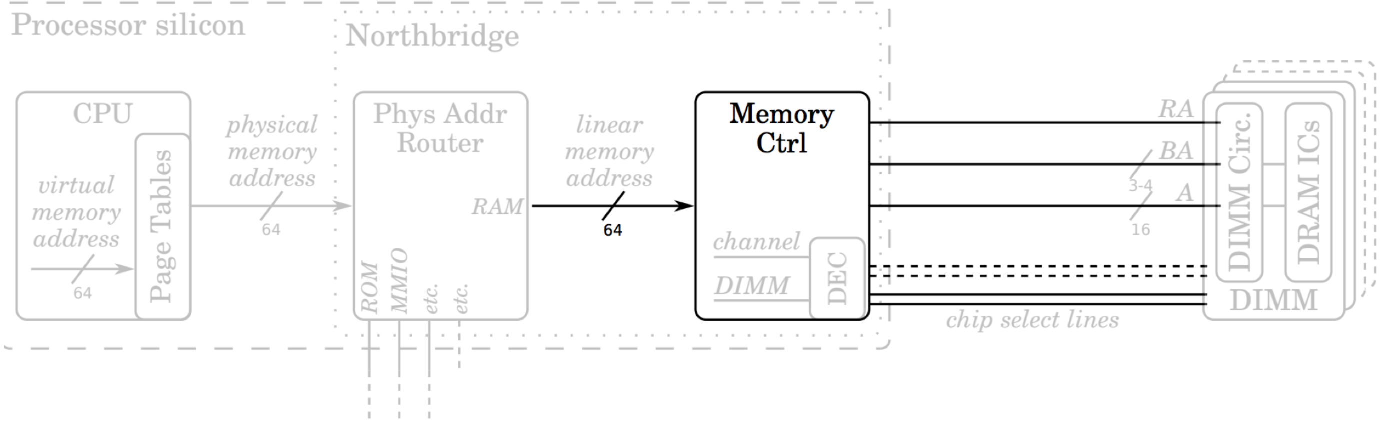

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- ➢ More reverse engineering

DRAM address translation library, **RAMSES**

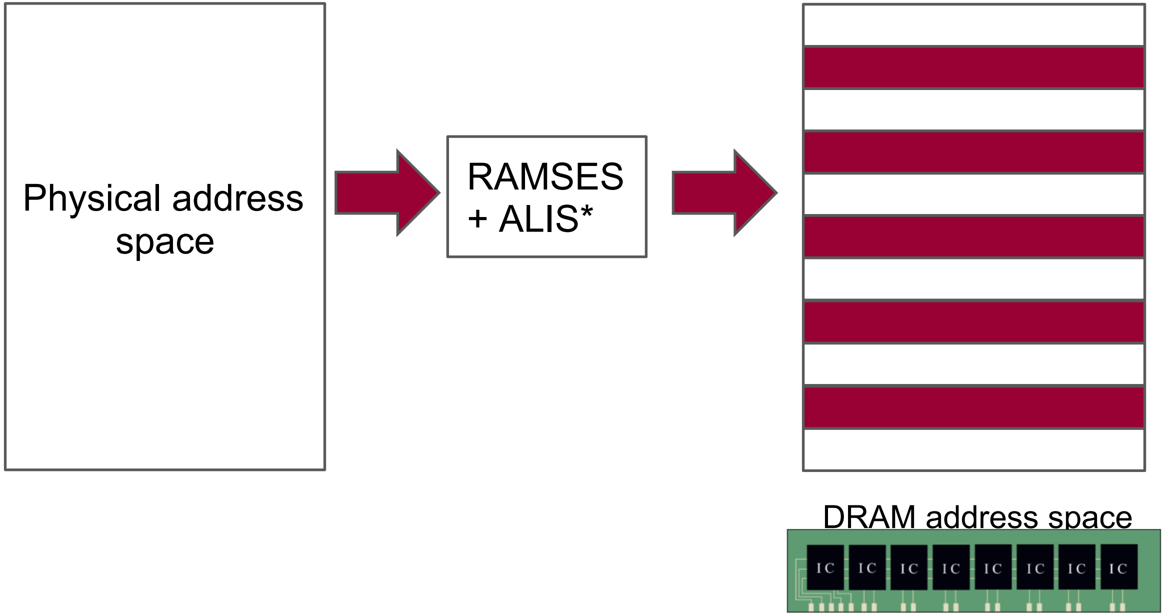
Memory allocator, **ALIS** (Tatar et al. ATC'18)

For ZebRAM, we extended ALIS…

...to allocate memory in zebra pattern.

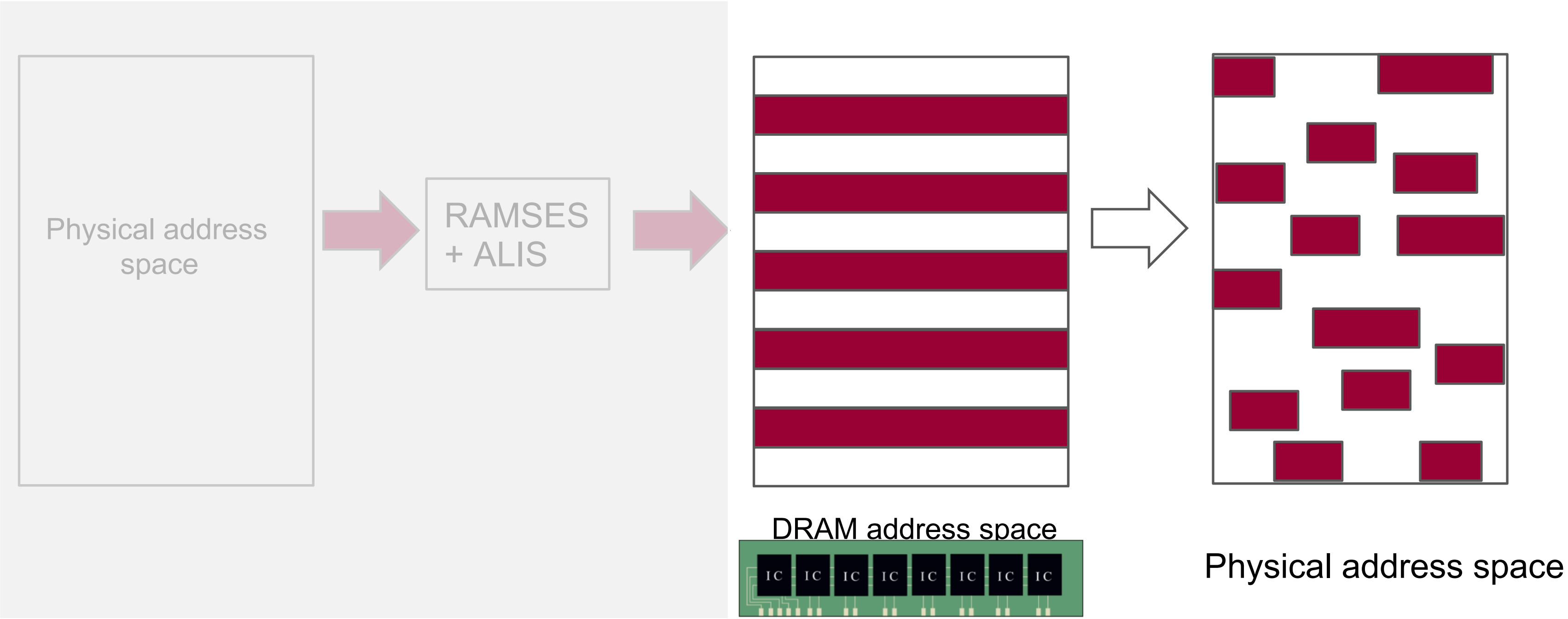
ZebRAM Challenge 1

1. Translating physical addresses to DRAM addresses and placing guard rows



Challenge 2 : Re-mapping physical address space

2. Transparently re-map the data rows and guard rows as two contiguous memory region



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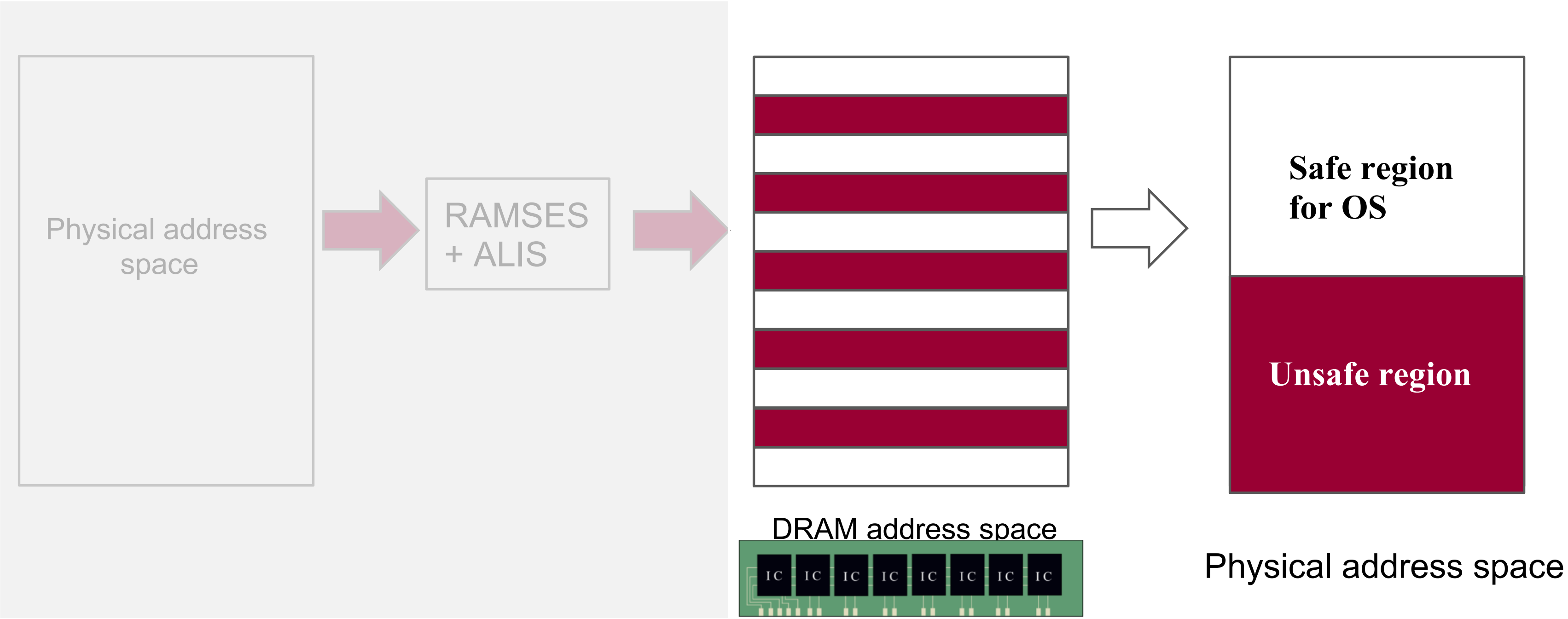
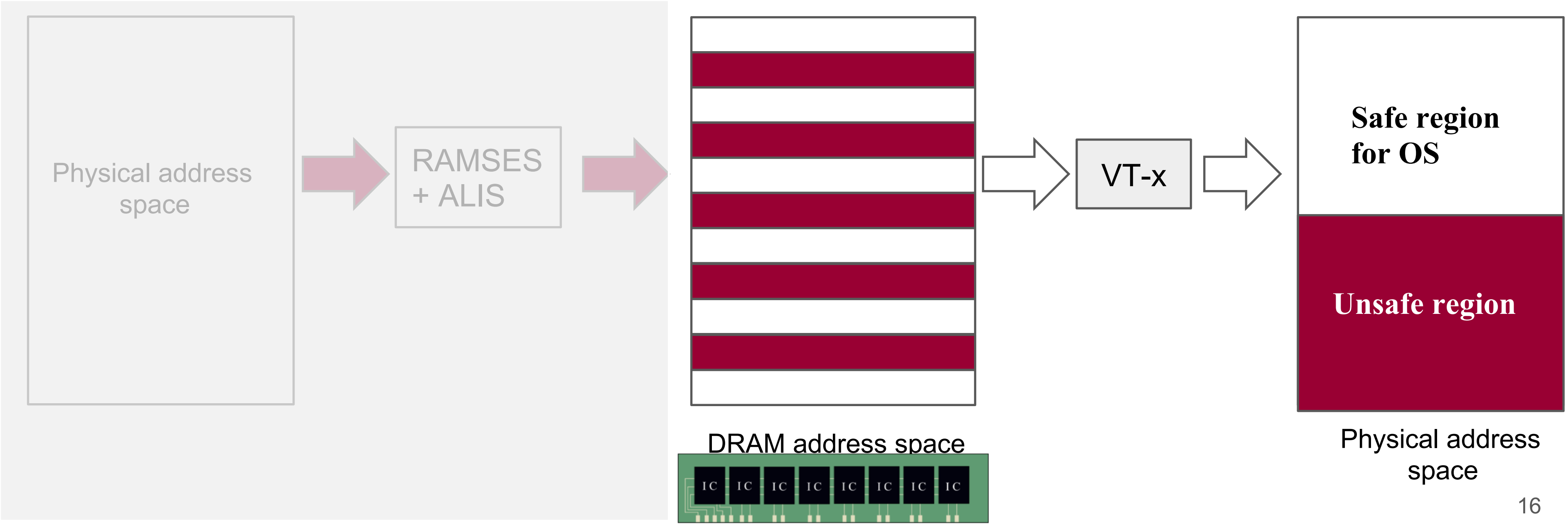


Challenge 2 : Re-mapping physical address space

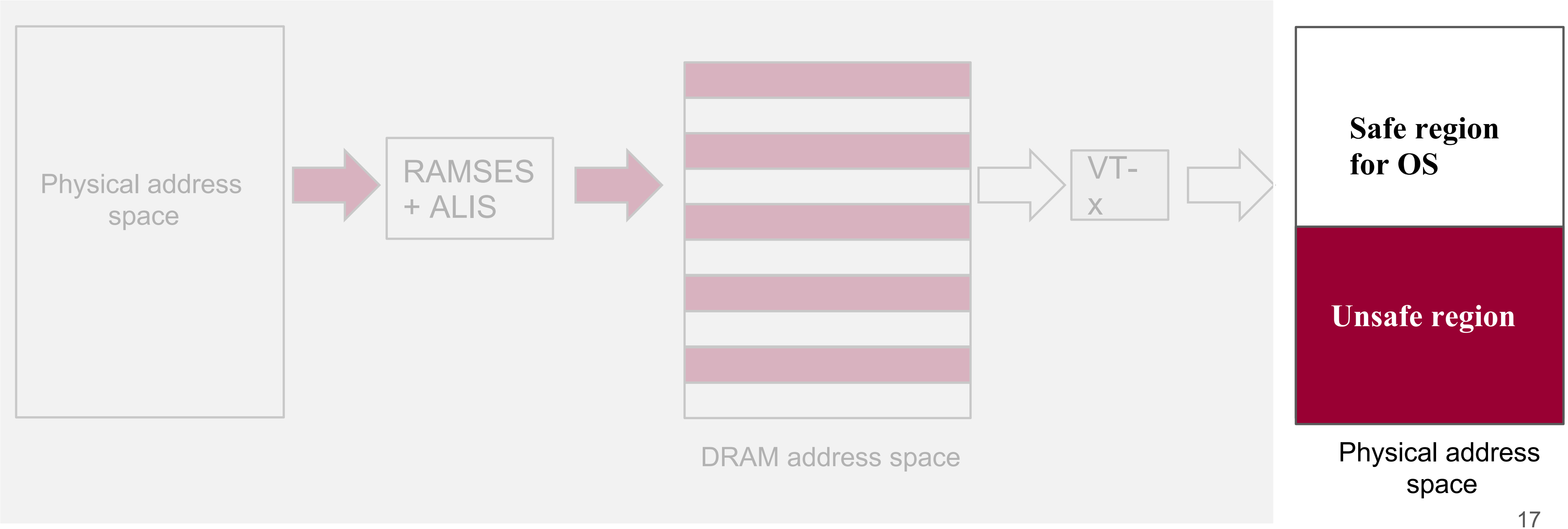
We use virtualization feature like Intel (VT-x) …

…to **transparently** re-map the guard and data rows as two contiguous memory region



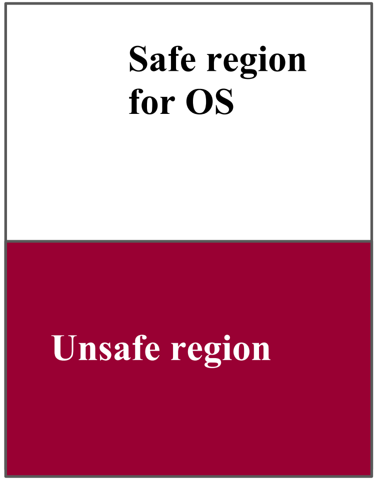
ZebRAM Challenge 3

3. Utilizing the unsafe region **securely** and **efficiently**



Challenge 3 : Utilizing unsafe region

Securely means two things here :

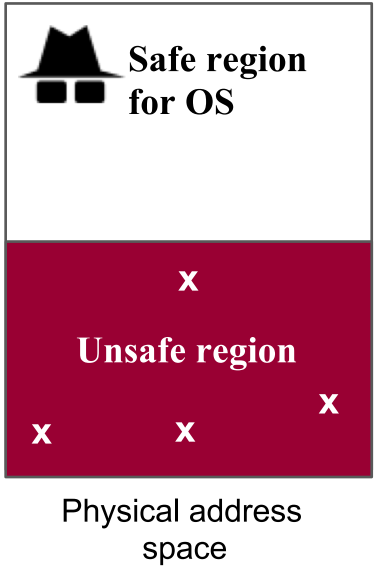


Physical address space

Challenge 3 : Utilizing unsafe region

Securely means two things here :

1. **Handle bit flips that may occur on unsafe region**



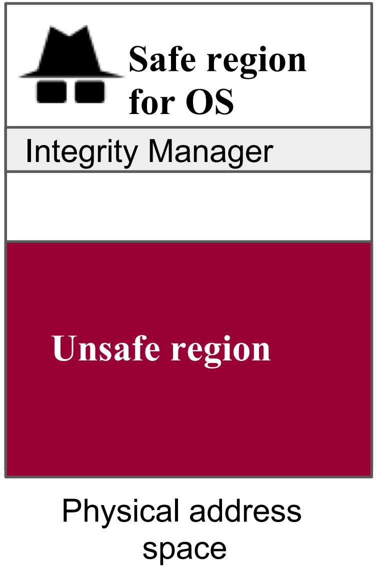
Challenge 3 : Utilizing unsafe region

Securely means two things here :

1. **Handle bit flips that may occur on unsafe region**

ZebRAM implements a **integrity manager** that uses:

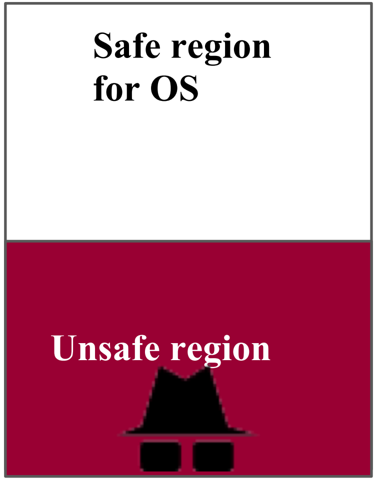
1. Hash verification (SHA-256)
2. Error correction code (ECC)



Challenge 3 : Utilizing unsafe region

Securely means two things:

1. Handle bit flips that may occur on unsafe region
2. **Protect the unsafe region from illegal bit flips**



Physical address space

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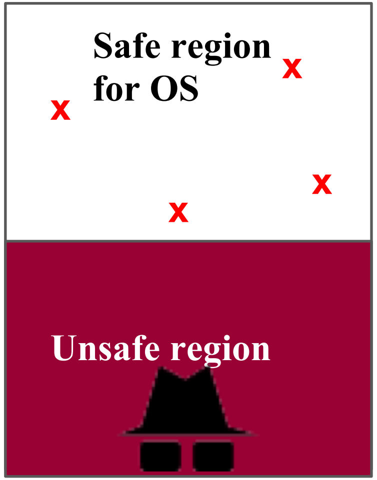

Physical address space

Challenge 3 : Utilizing unsafe region

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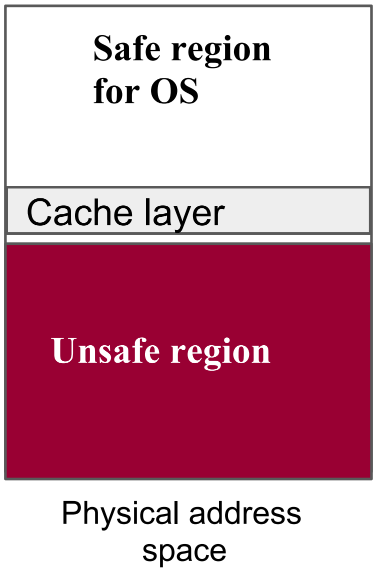
ZebRAM slows down the consecutive accesses to the same location in the unsafe region:



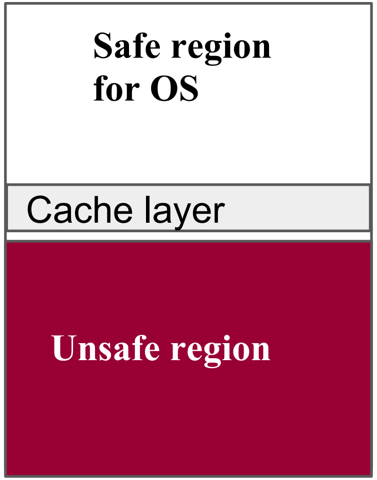
Challenge 3 : Utilizing unsafe region

Securely means two things:

1. Handle bit flips that may occur on unsafe region
2. **Protect the unsafe region from illegal bit flips**

ZebRAM slows down the consecutive accesses to the same location in the unsafe region:

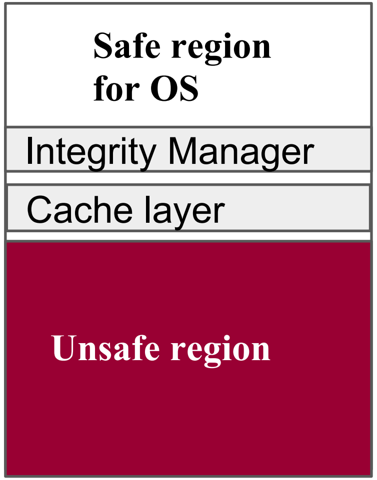
1. By implements a **cache layer** using safe memory
2. Enforcing **Least-recently-added** eviction policy



Physical address space

Challenge 3 : Utilizing unsafe region

Efficiently:

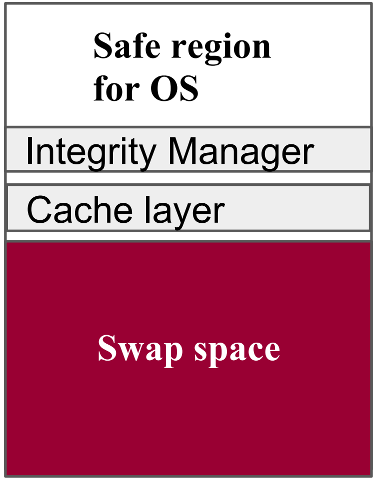


Physical address space

Challenge 3 : Utilizing unsafe region

Efficiently:

- ➢ Exposes the unsafe region as **swap space** to the OS

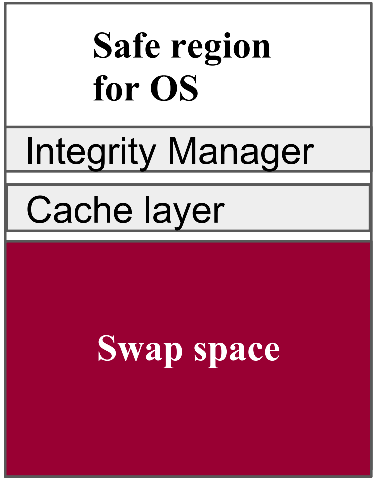


Physical address space

Challenge 3 : Utilizing unsafe region

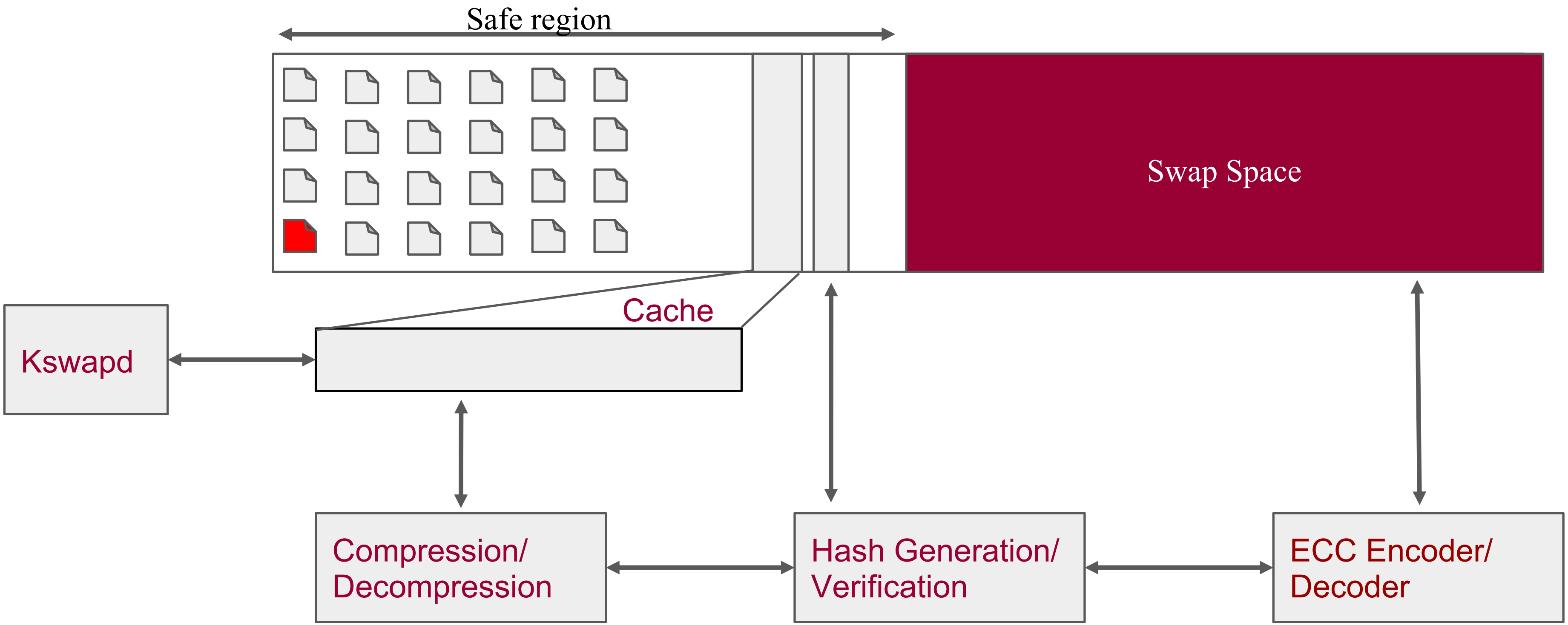
Efficiently:

- ➢ Exposes the unsafe region as **swap space** to the OS
- ➢ Helps to utilize **efficient page replacement policies** in commodity OS



Physical address space

Life of a page in ZebRAM world



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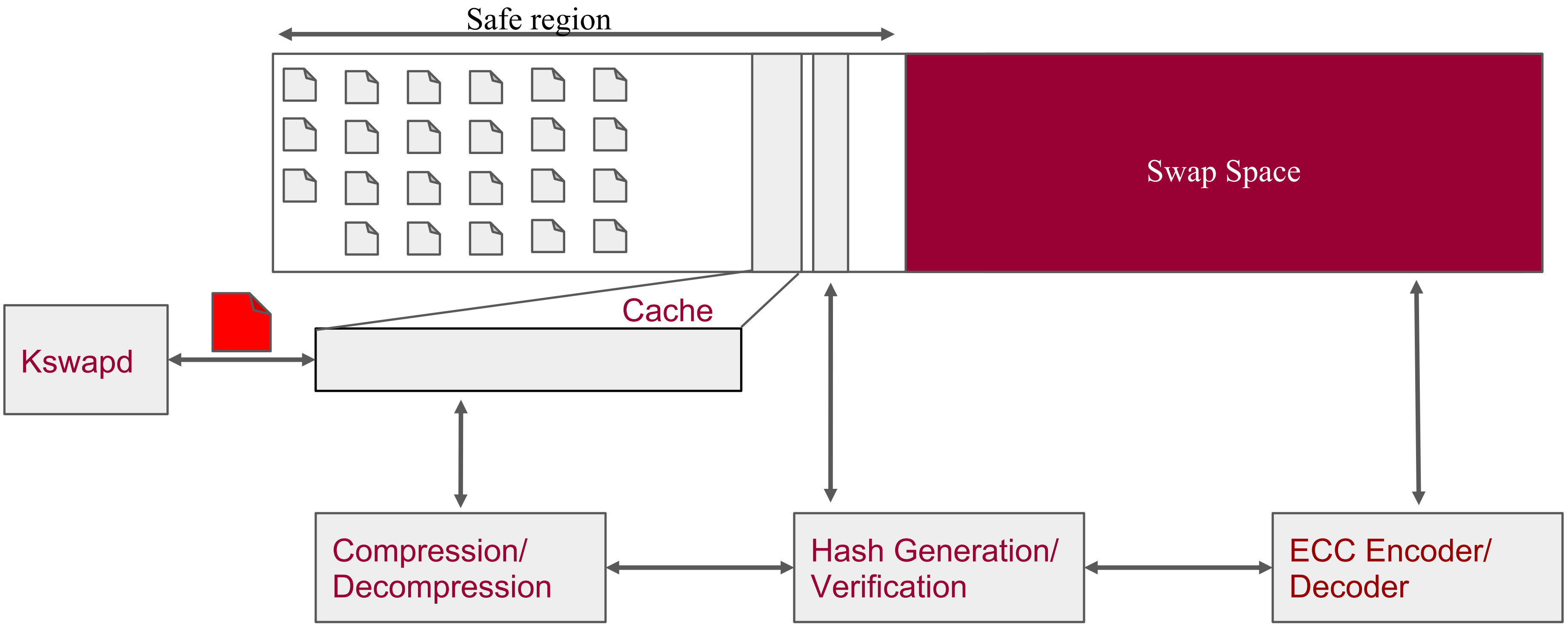

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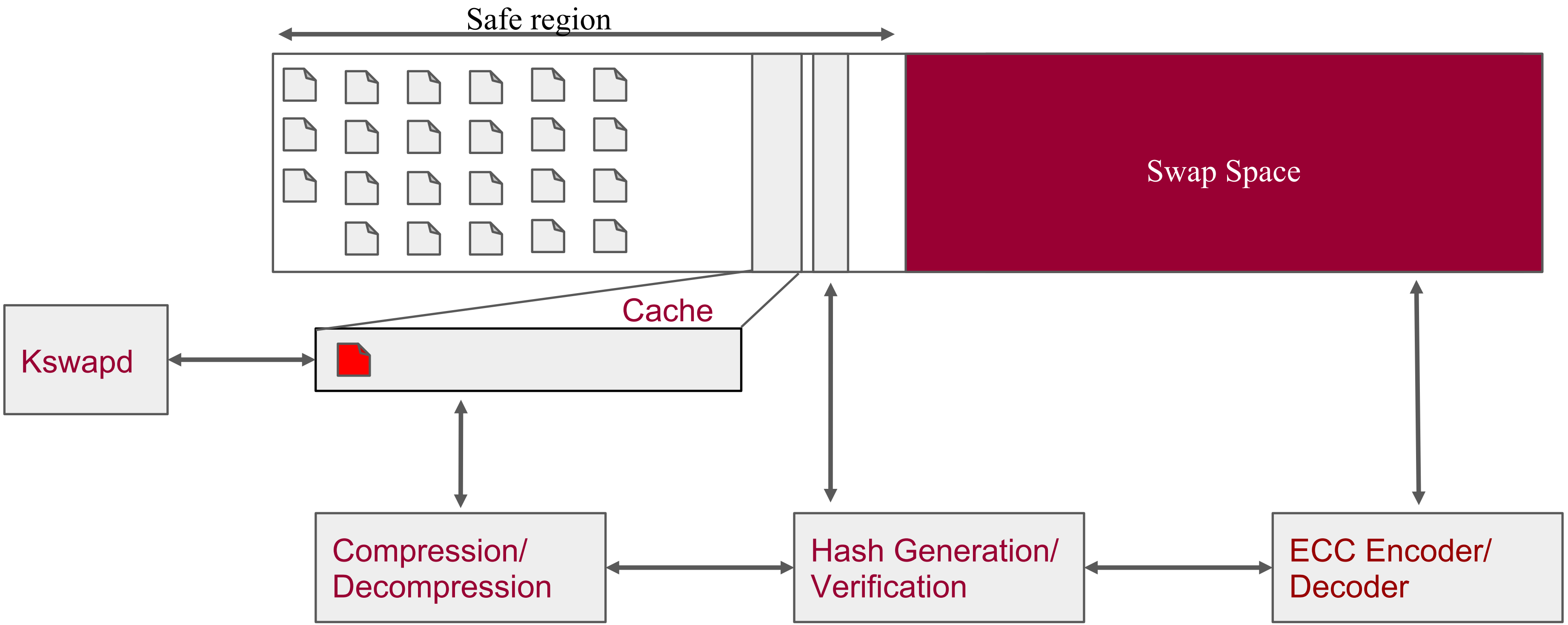

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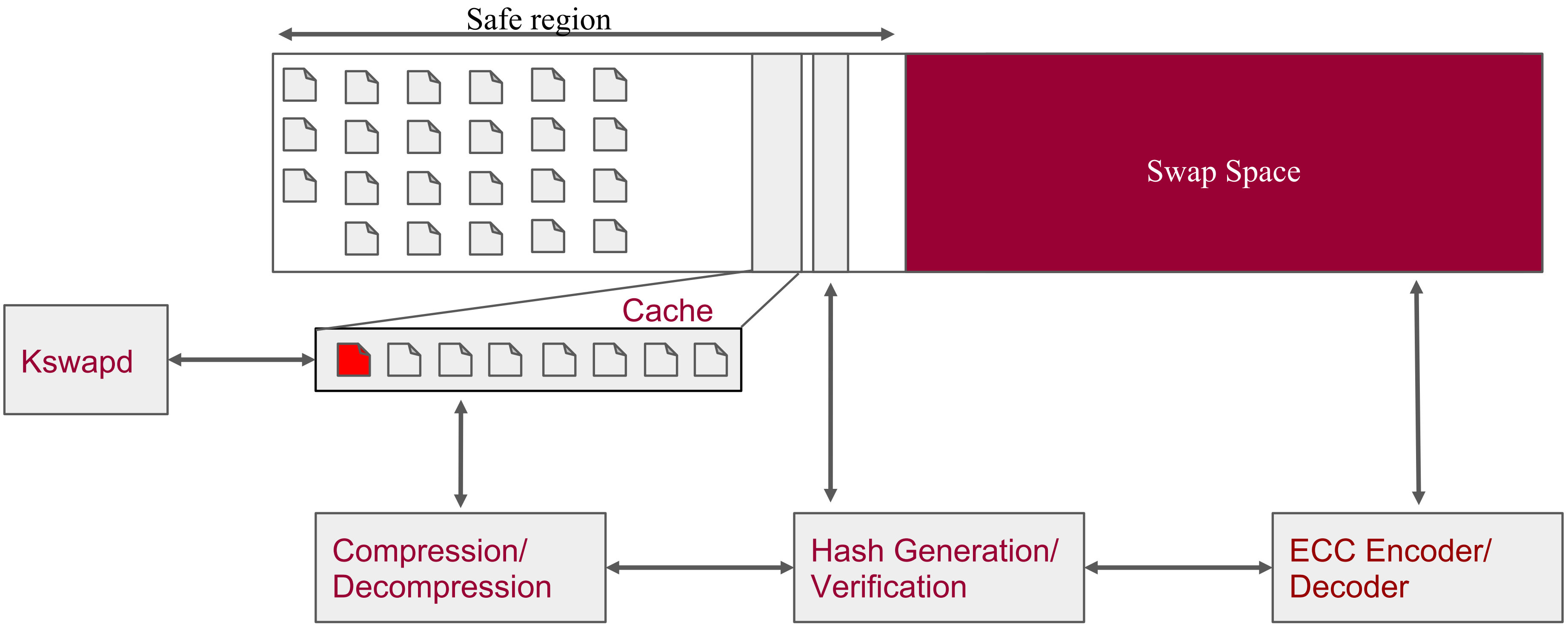

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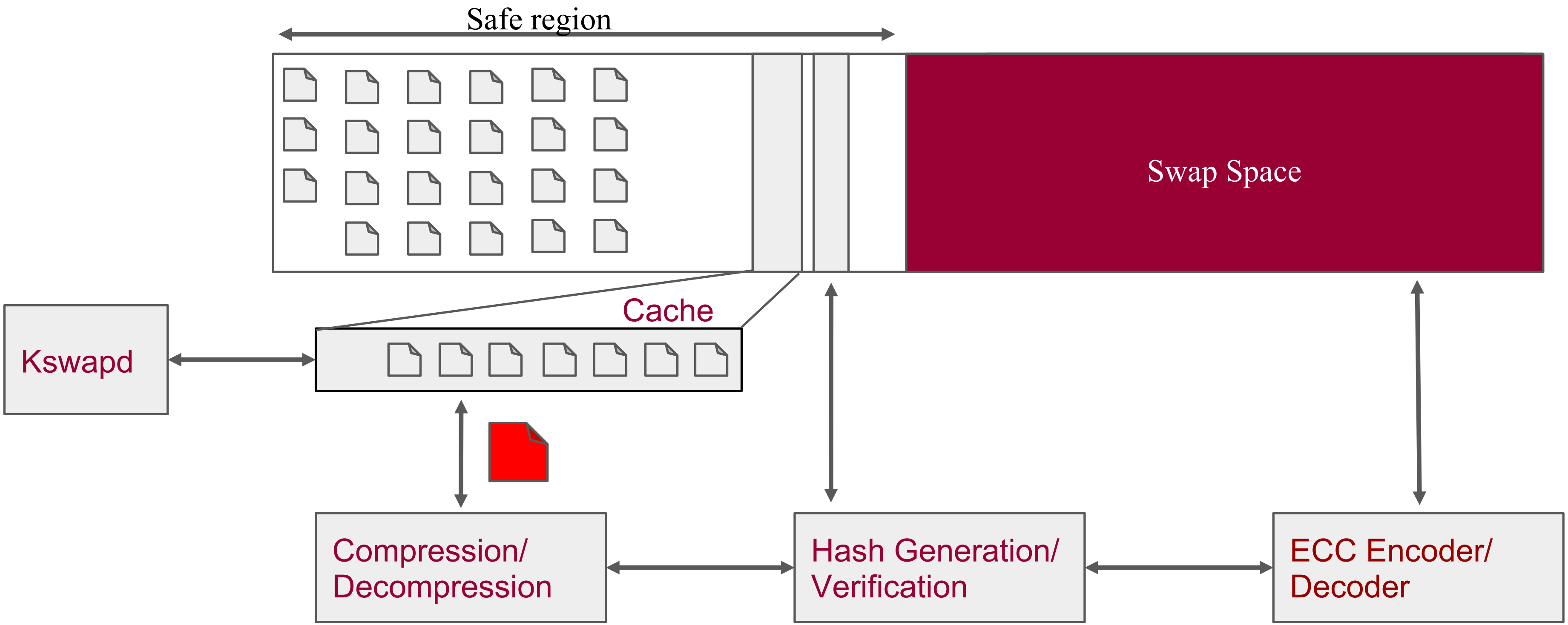

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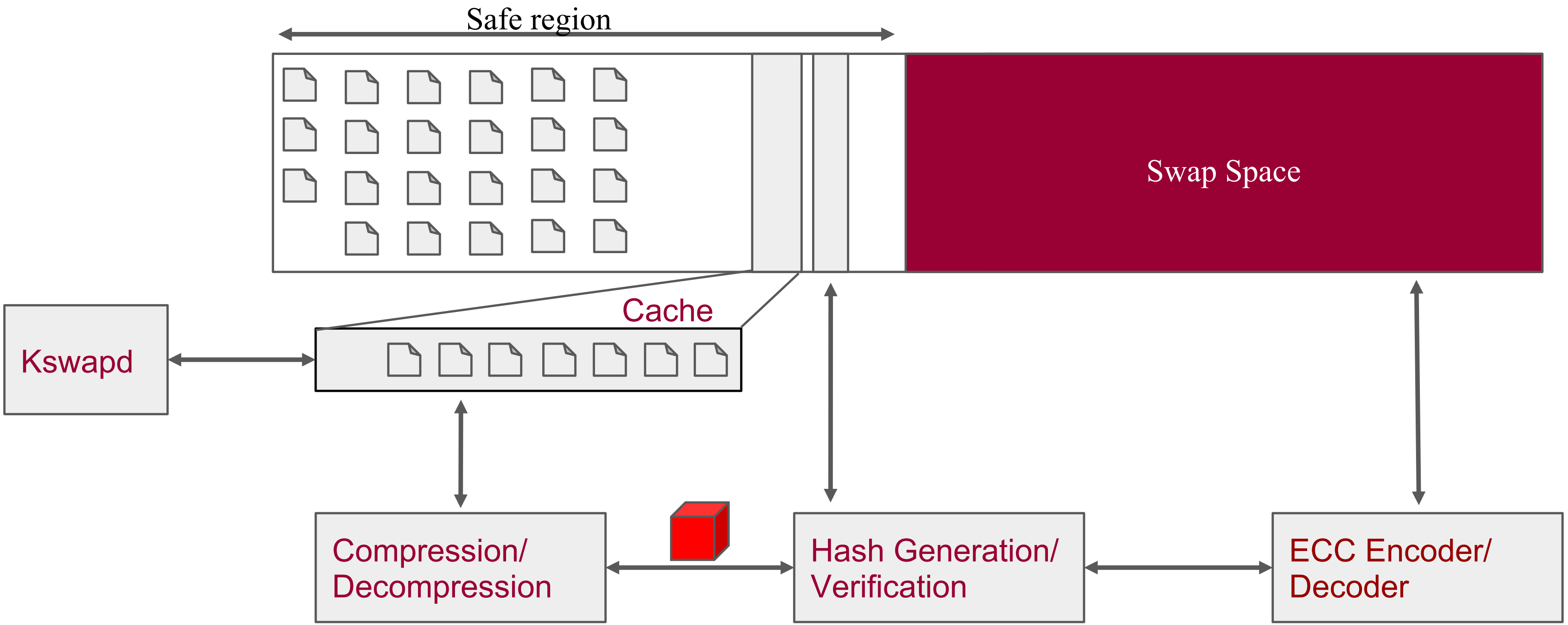

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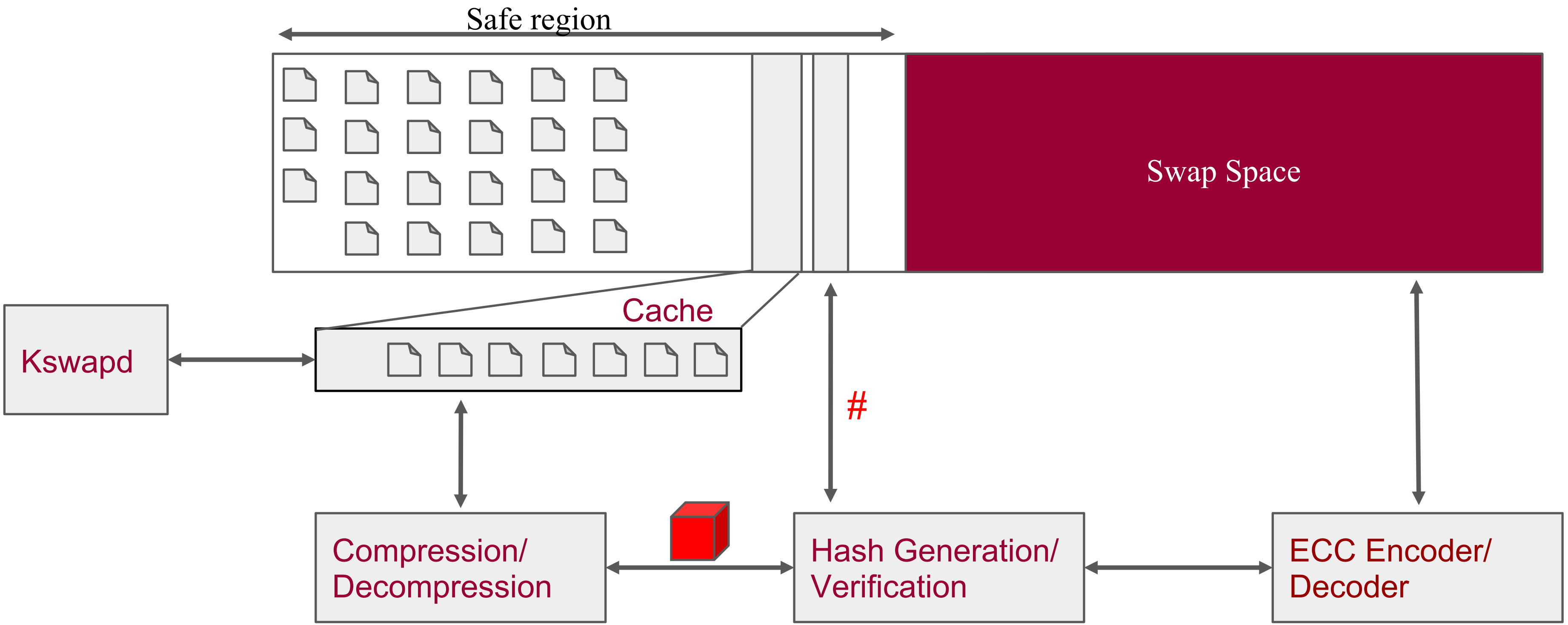

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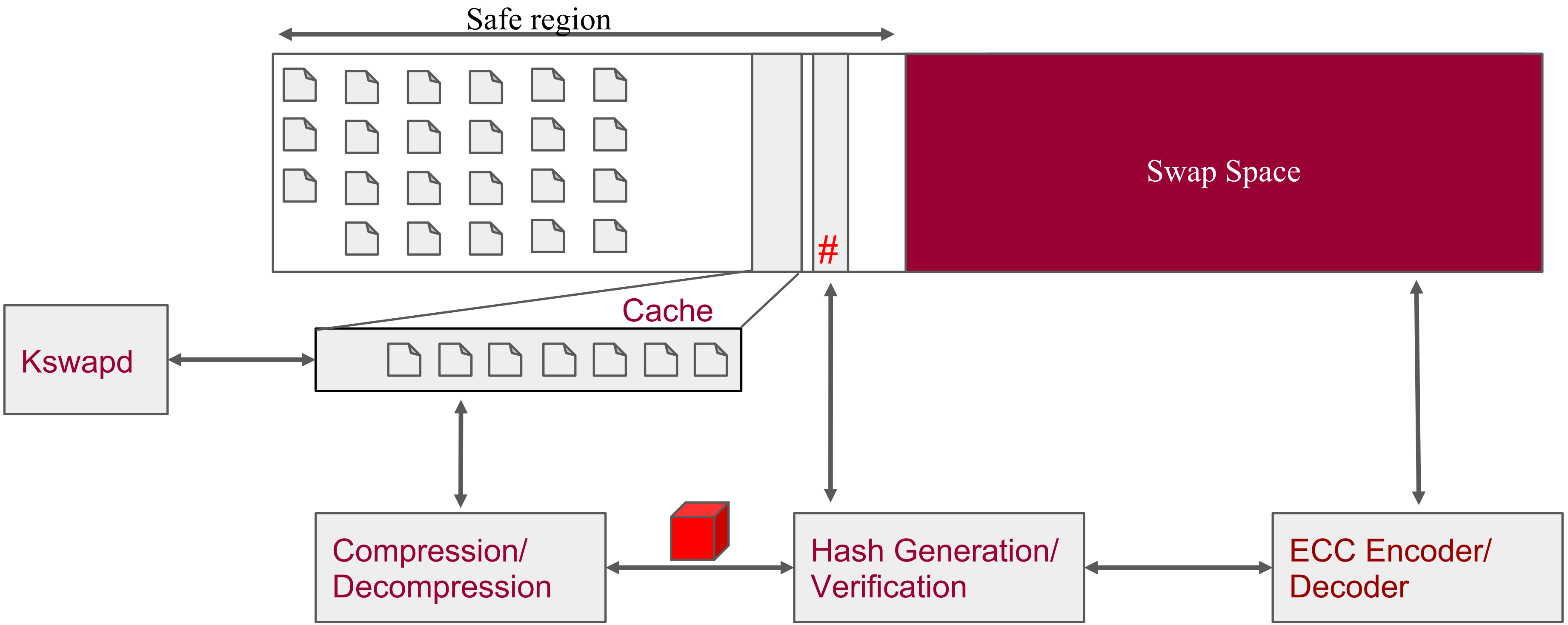

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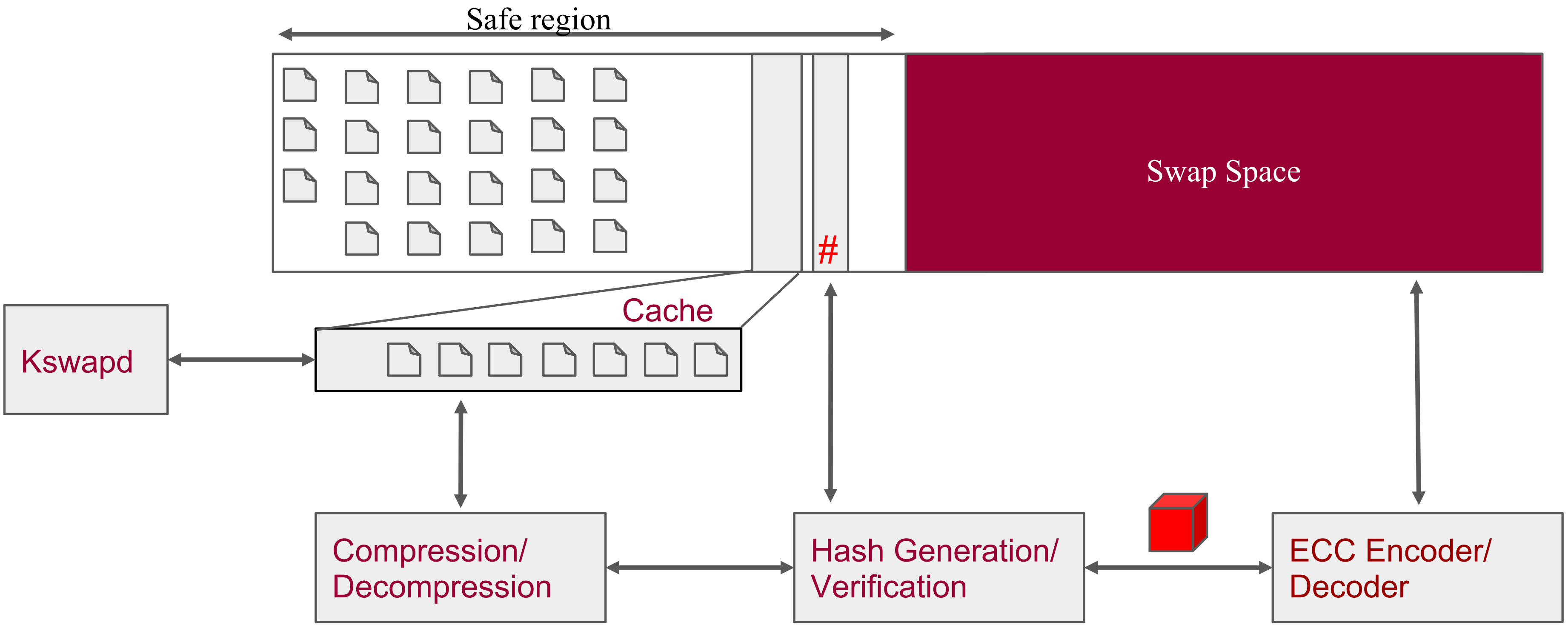

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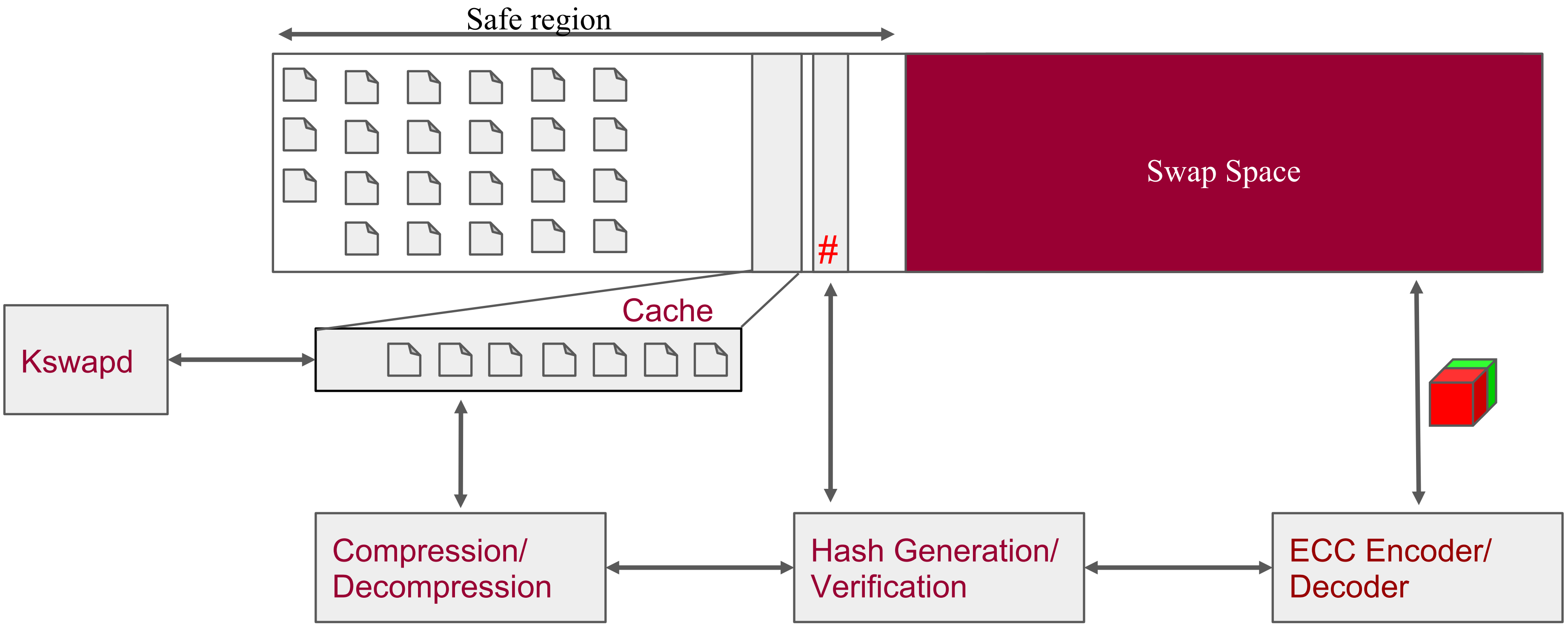

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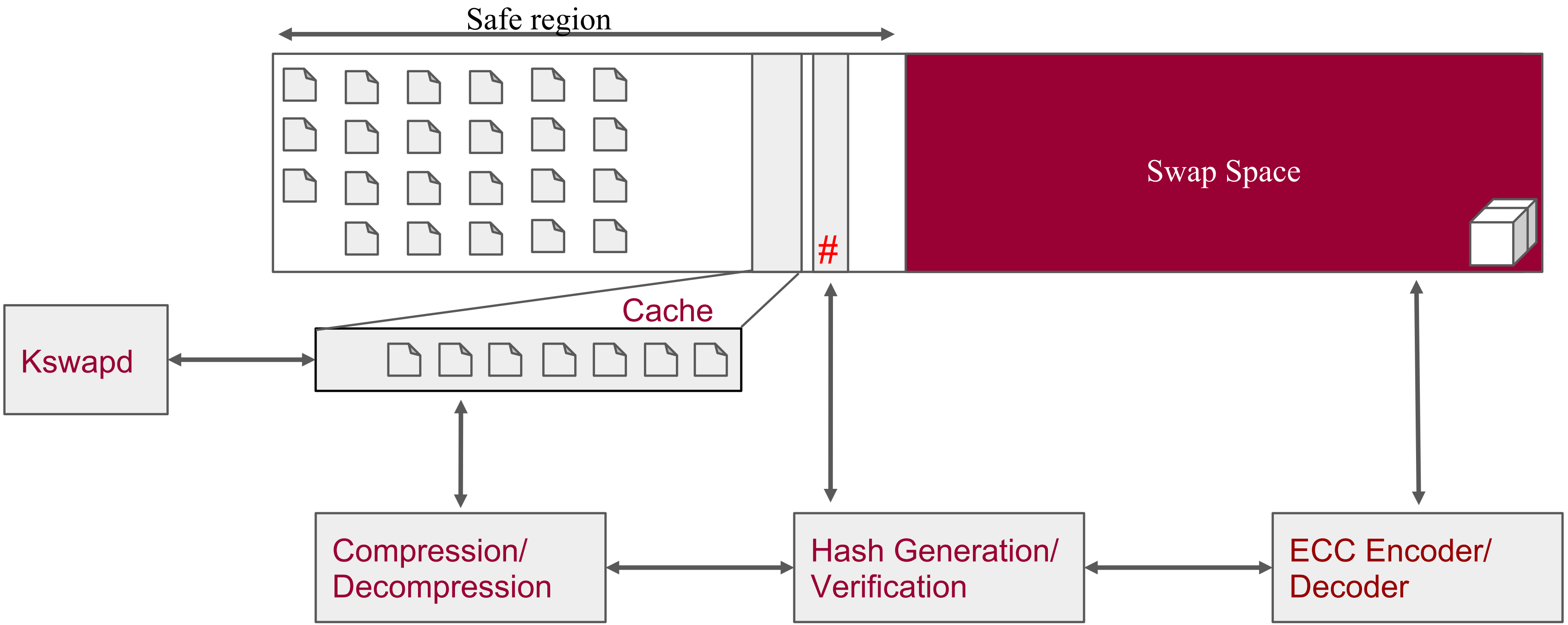

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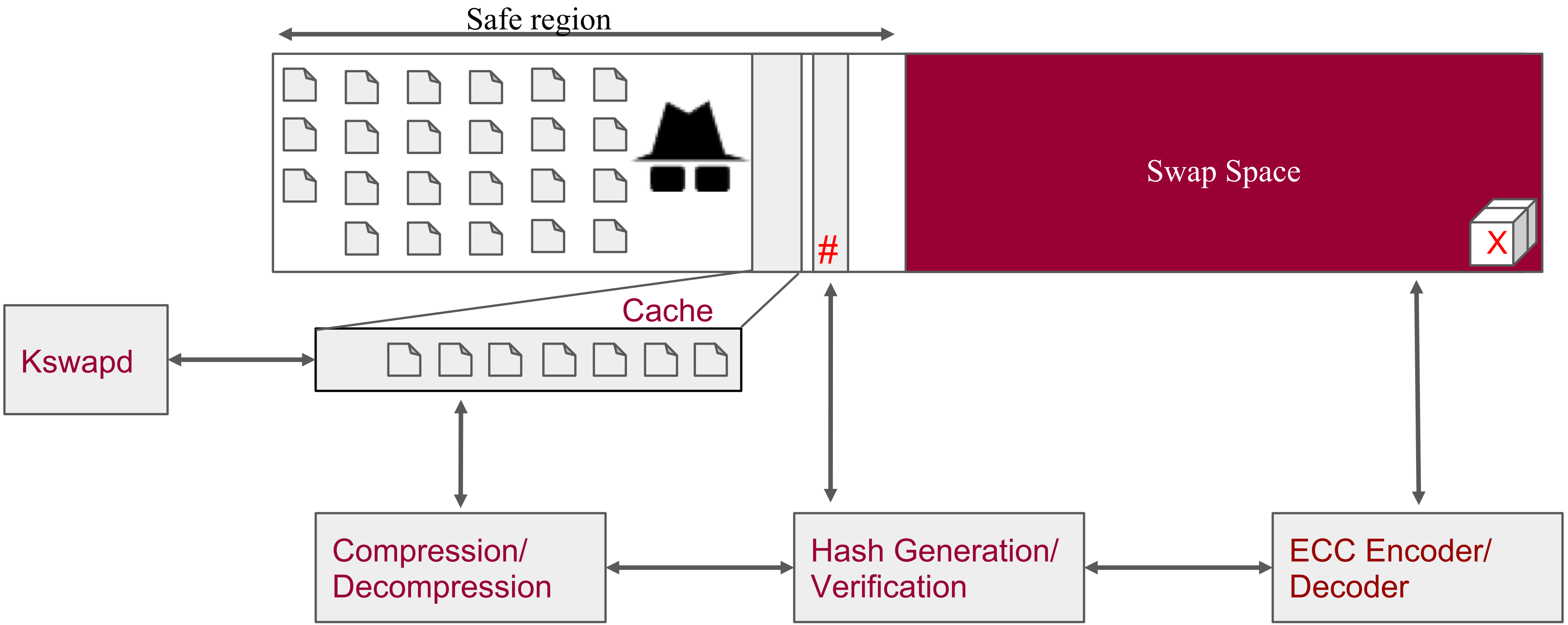

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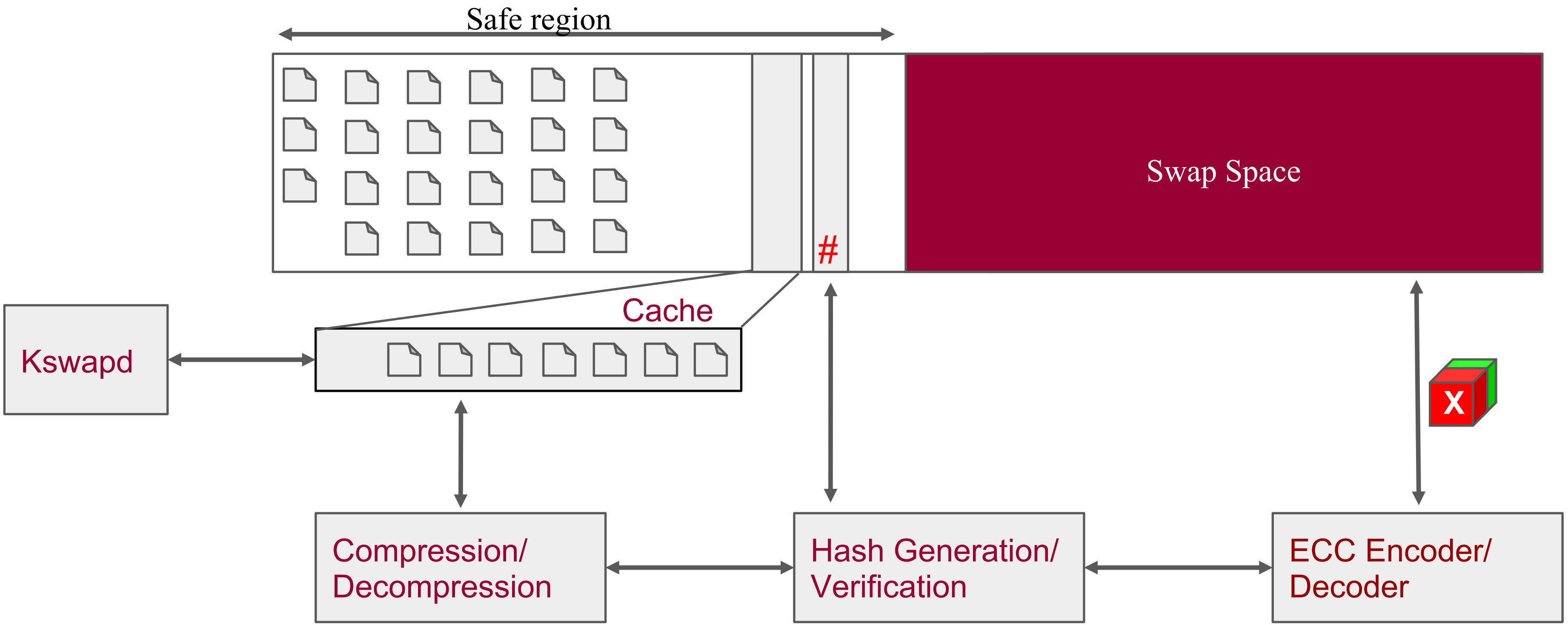

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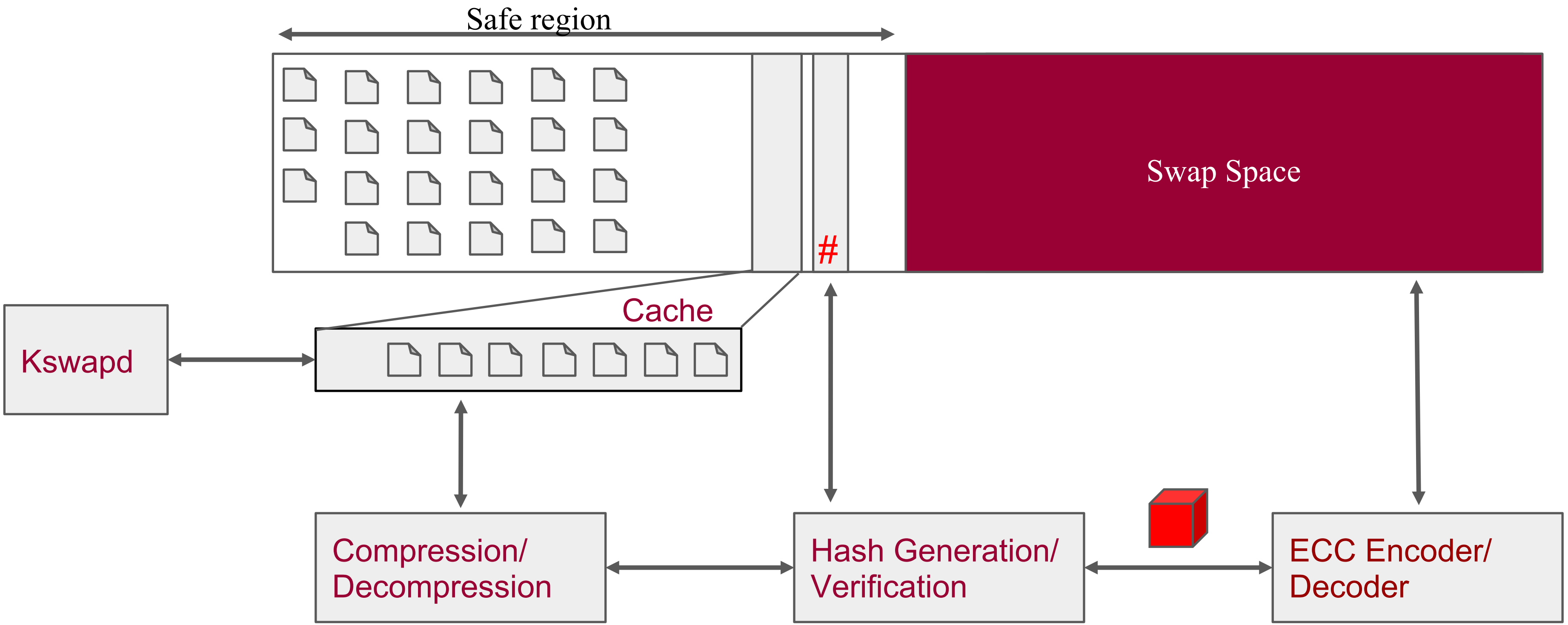

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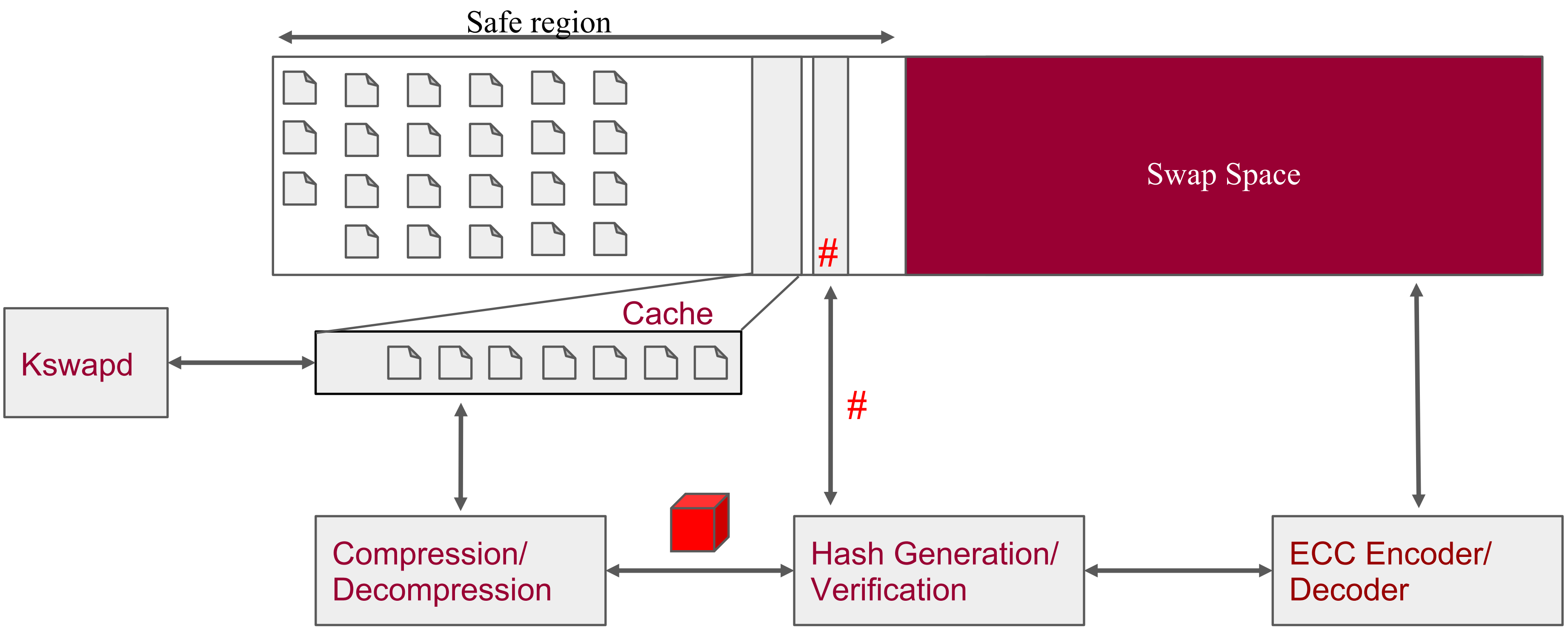

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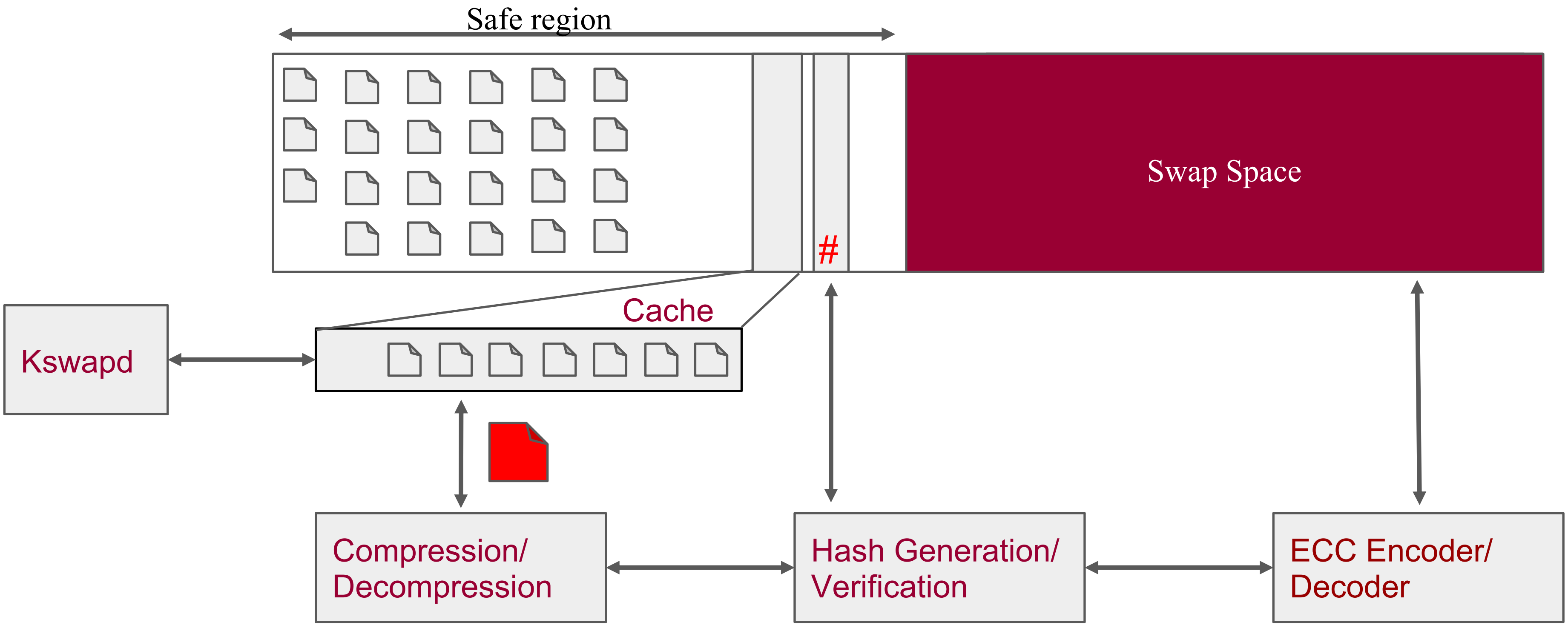

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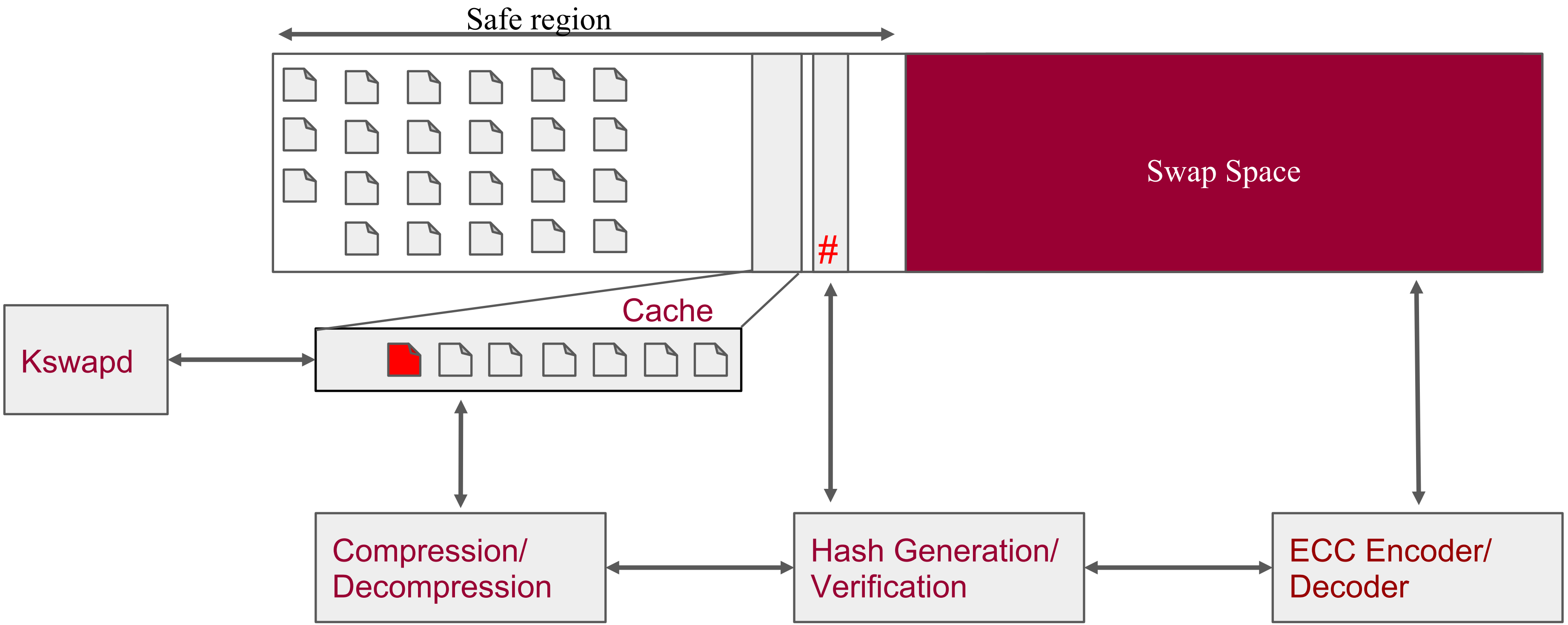

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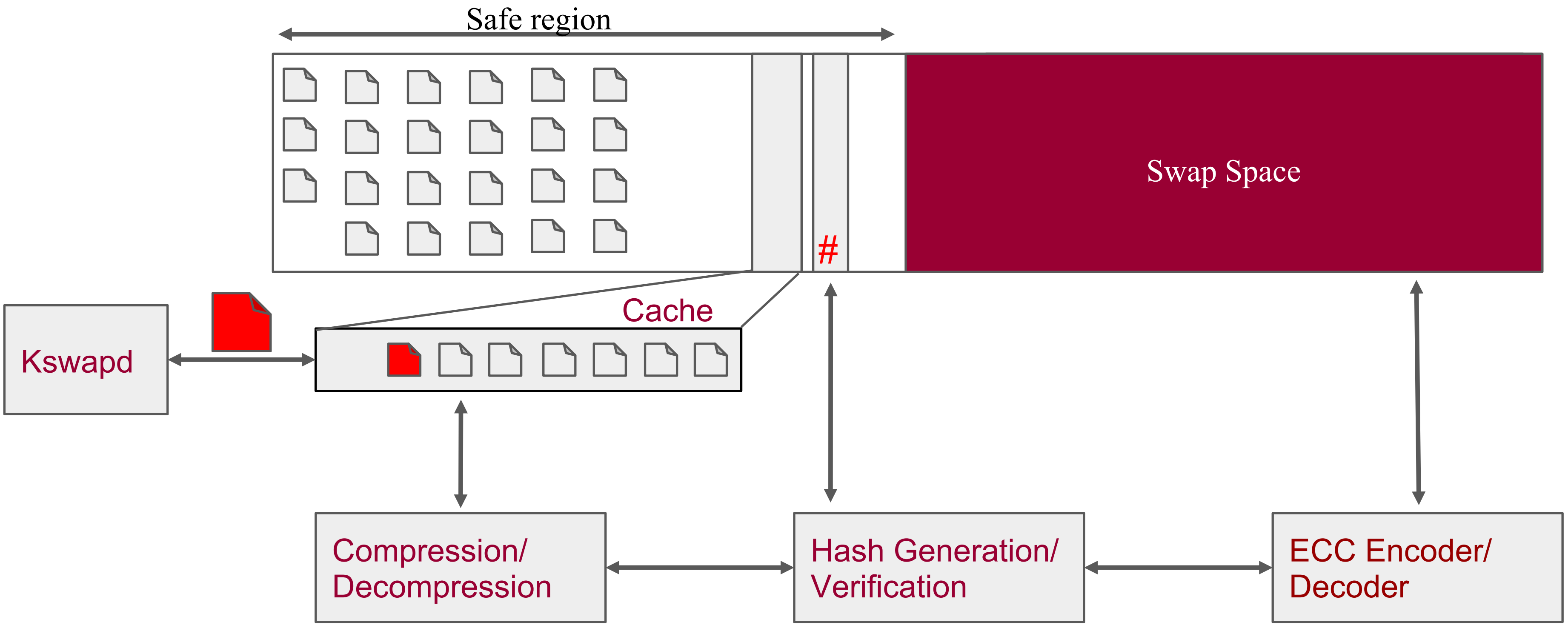

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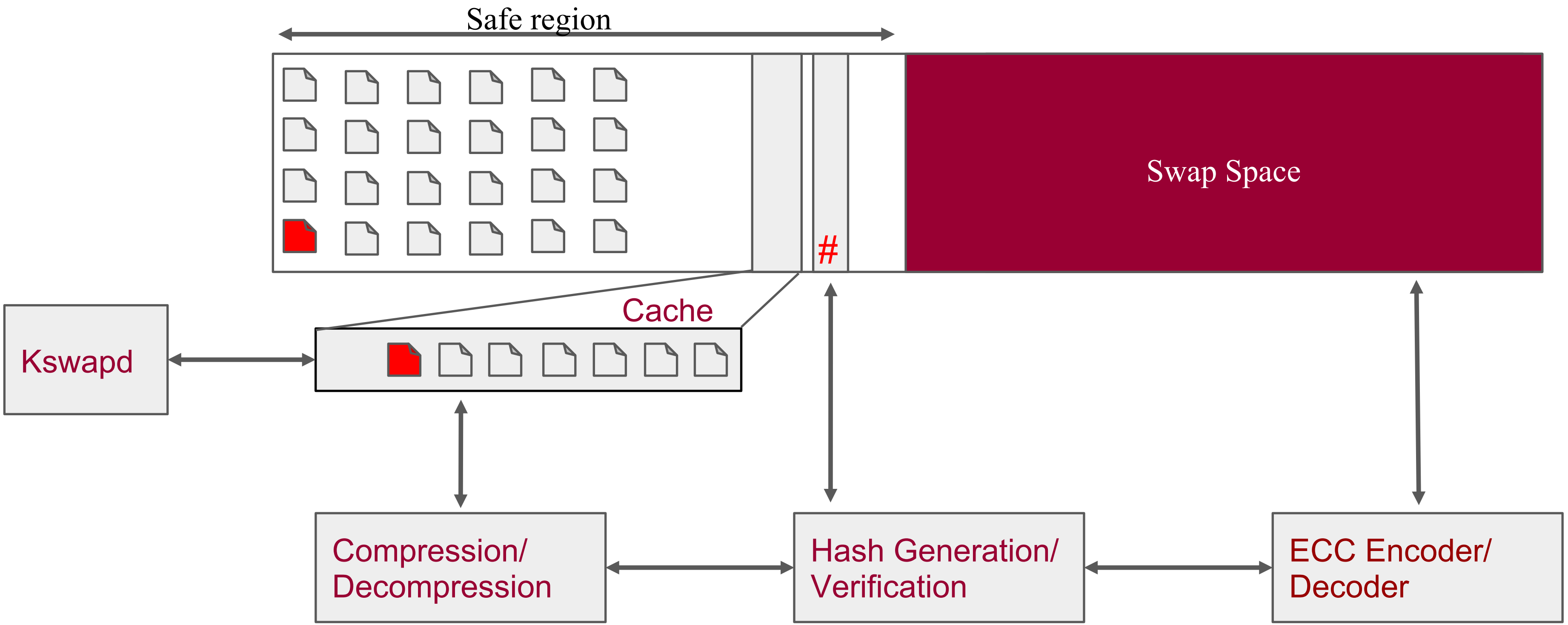
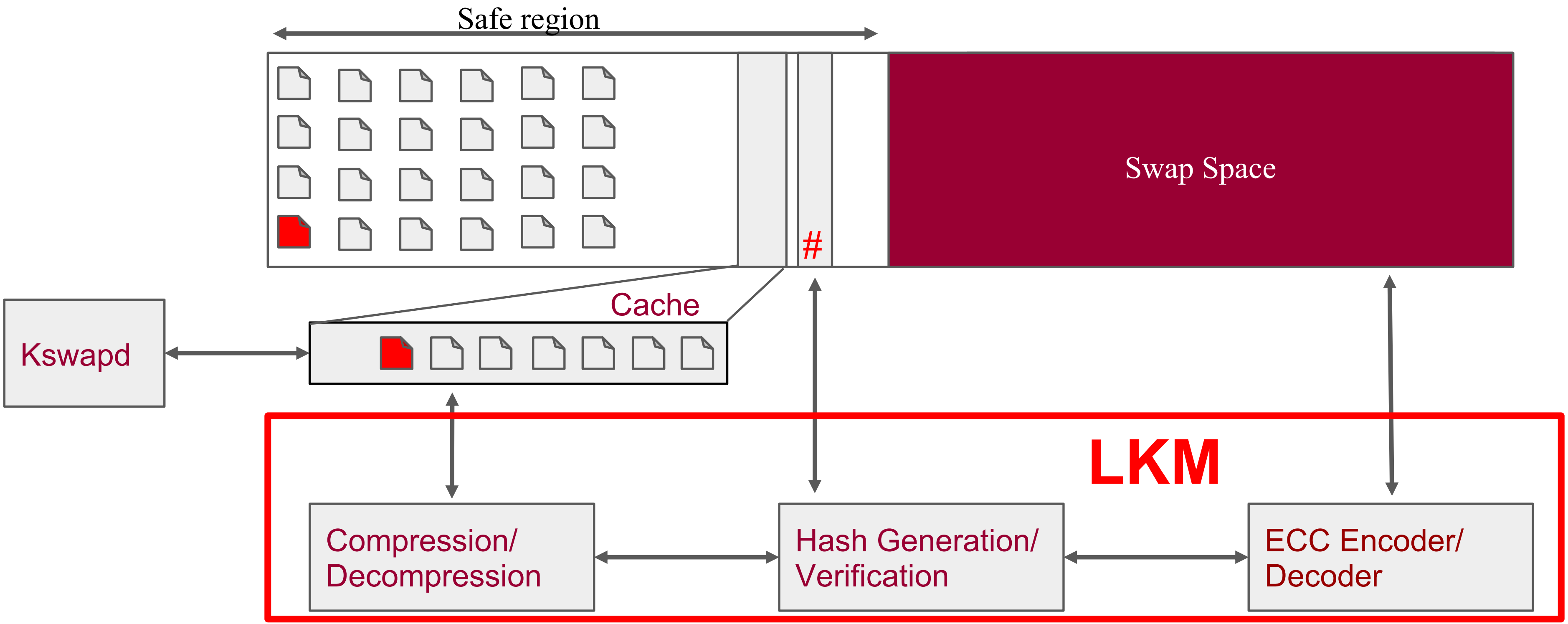


Implementation



Evaluation setup

- Haswell i7-4790 machine
- Qemu-KVM hypervisor to run ZebRAM protected OS
- Ubuntu 16.04 64-bit OS
- 100Gbit/s link

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- SPEC
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- **SECURITY**
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Security Evaluation

We ran the Rowhammer exploit on the ZebRAM protected OS

Run no.	1 bit flip in 64 bits	2 bit flips in 64 bits	Total bit flips	ZebRAM detection performance Detected bit flips	ZebRAM detection performance Corrected bit flips
1	4,698	2	4,702	4,702	4,698
2	5,132	0	5,132	5,132	5,132
3	2,790	0	2,790	2,790	2,790
4	4,216	1	4,218	4,218	4,216
5	3,554	0	3,554	3,554	3,554

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Take away:

- ECC module alone **detected 100%** the bit flips
- ECC module **corrected 99.97 %** of the bit flips

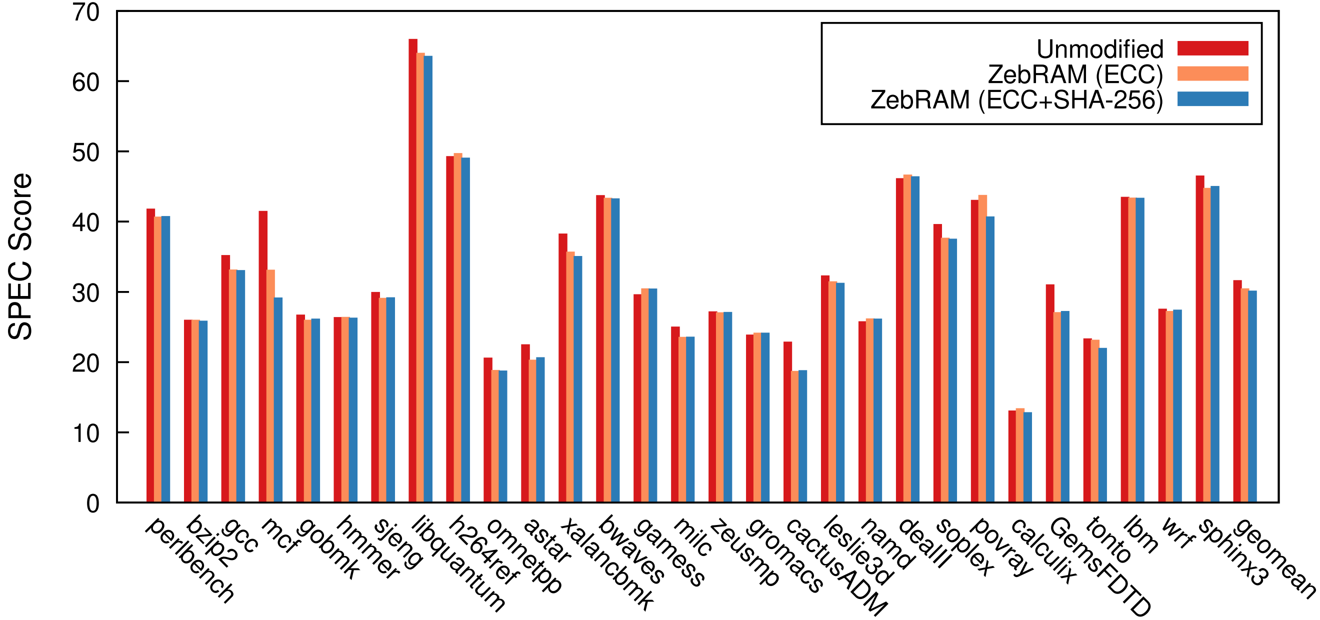
Performance Evaluation

We ran spec 2006 on three different setup:

- Baseline (unmodified Linux) with 4GB memory
- ZebRAM (ECC only)
- ZebRAM (ECC + SHA-256)

Performance Evaluation

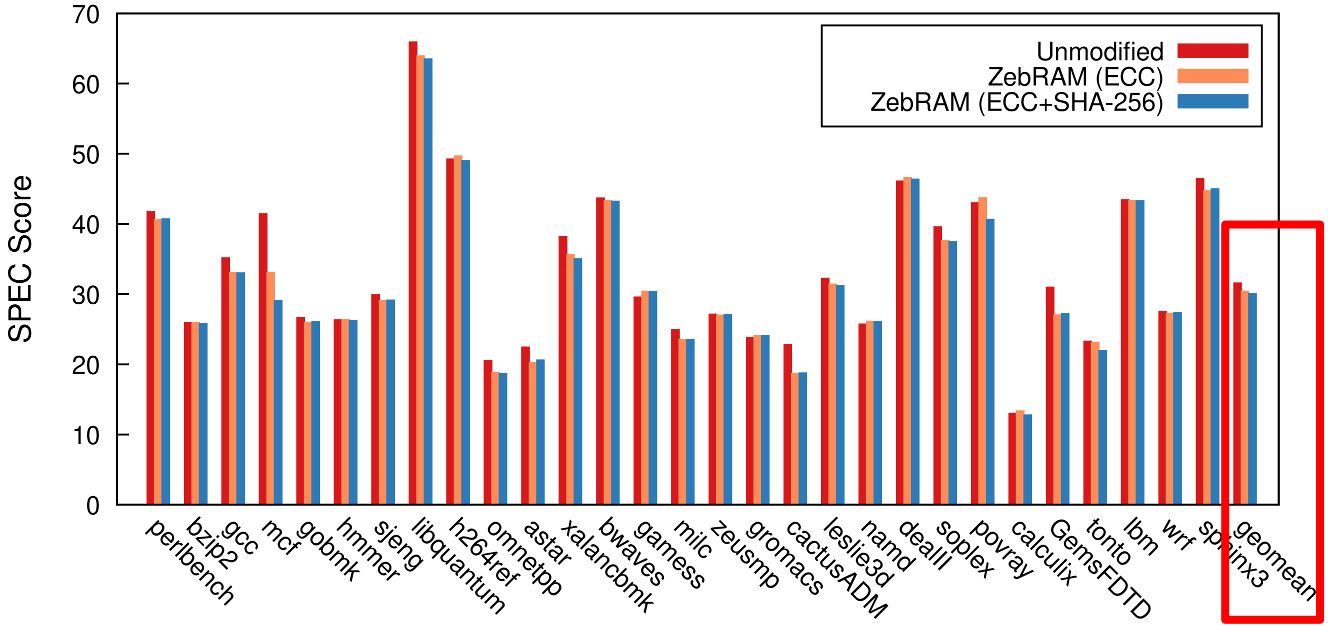
Spec 2006 benchmark shows ...



Performance Evaluation

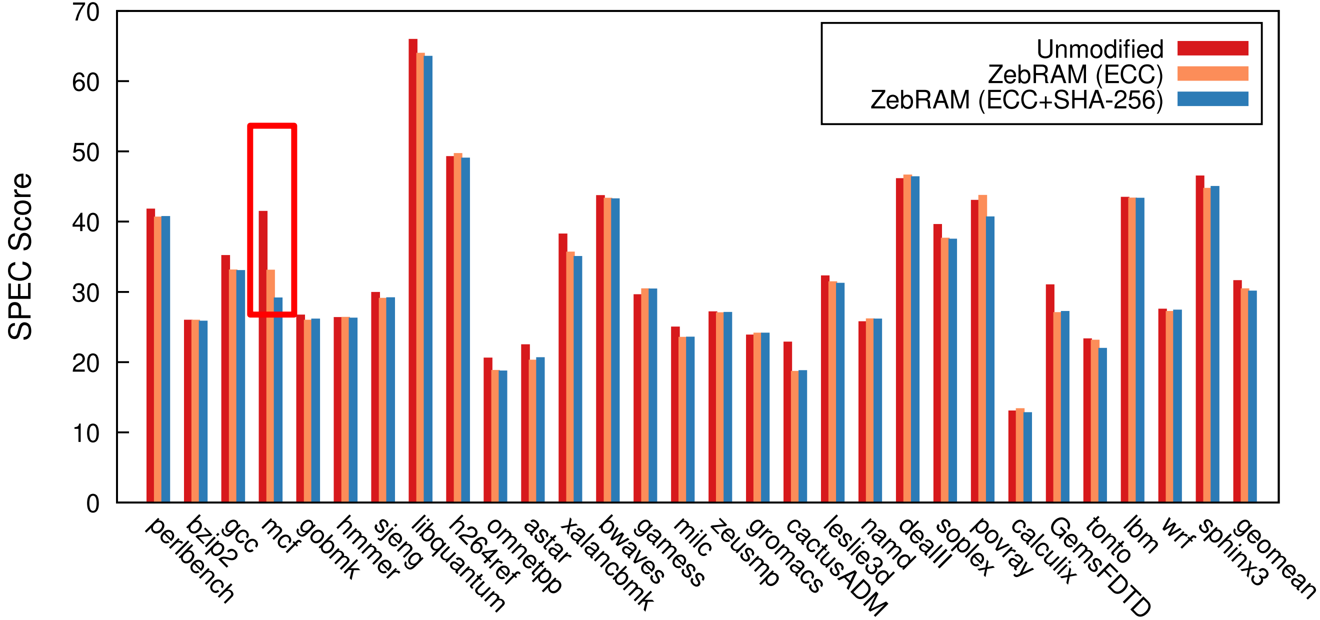
Spec 2006 benchmark shows …

… 5% (geometric mean) overhead from unavailability of transparent huge page



Performance Evaluation

MCF benchmark shows more than 5% performance overhead



Performance Evaluation : Working Set Size

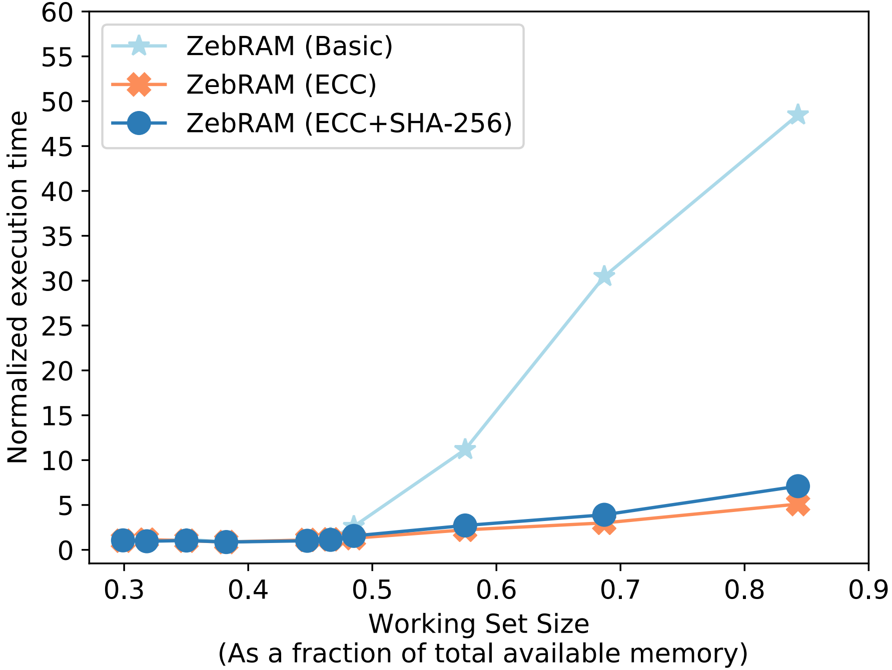
YCSB to generate the load and induce different working set size ...

… for **redis** (4.0.8) key-value store

We ran experiments on different setups:

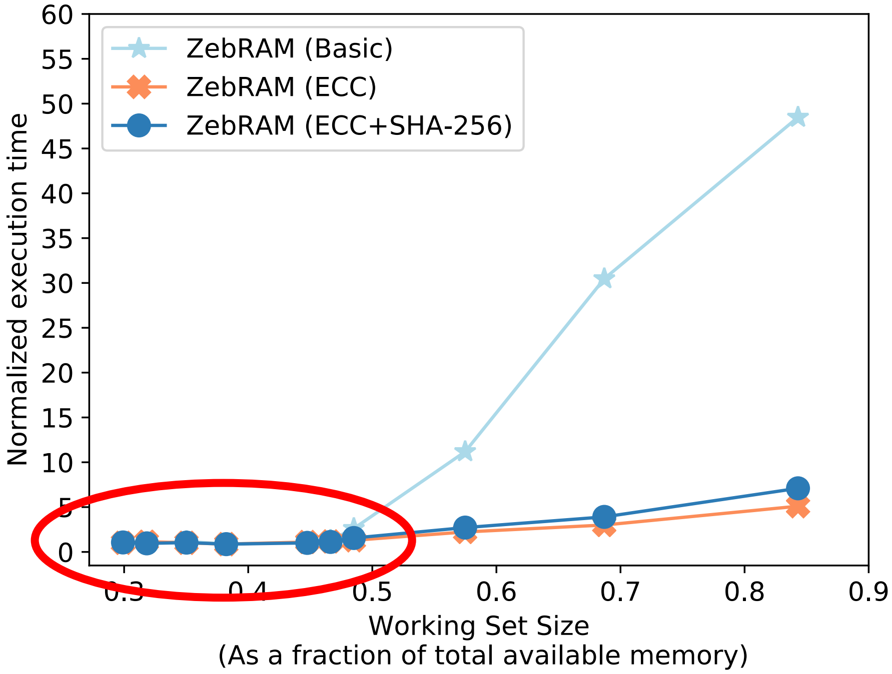
- ZebRAM Basic – uses only safe region and swaps out to SSD
- ZebRAM (ECC only)
- ZebRAM (ECC + SHA-256)
- Baseline

Performance Evaluation



Performance Evaluation

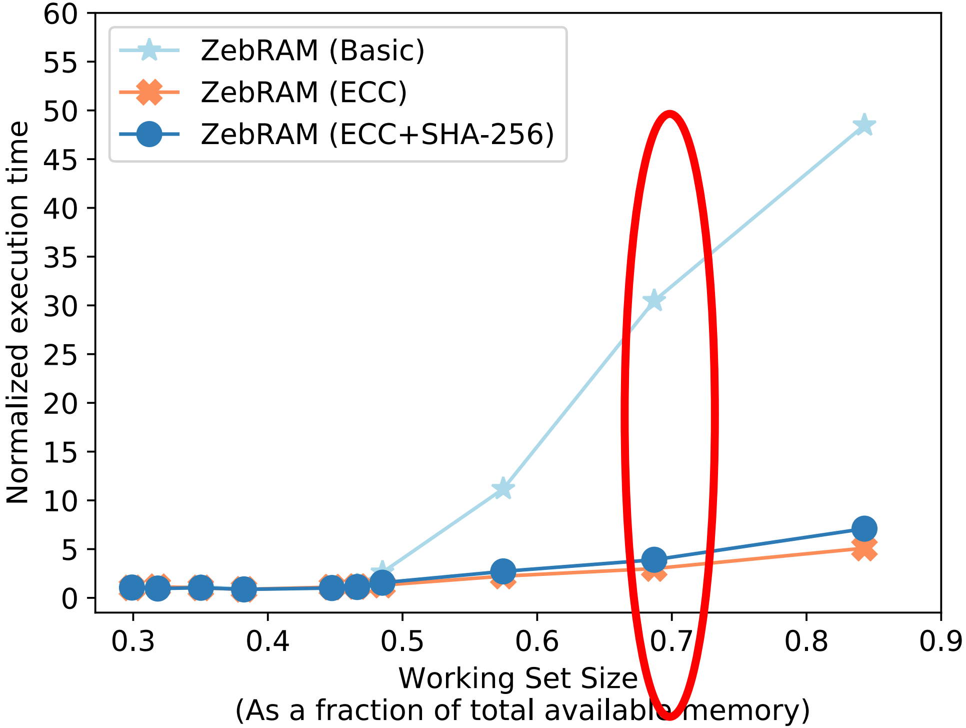
1.05x performance overhead till it starts using swap



Performance Evaluation

When active working set is using 70% of the memory:

- ZebRAM (Basic) = 30x
- ZebRAM (ECC) = 3x
- ZebRAM (ECC + SHA-256) = 3.9x



Summary

- The ZebRAM is the first solution to provide complete protection against Rowhammer attacks
- Performance overhead:
  - Minimal when the active working set fits in the safe region
  - Function of the active working set size when it does not fit in the safe region
- Code for ZebRAM will be available soon at https://github.com/vusec