NVRAMOS 2020

A Case for Hardware-Based Demand Paging

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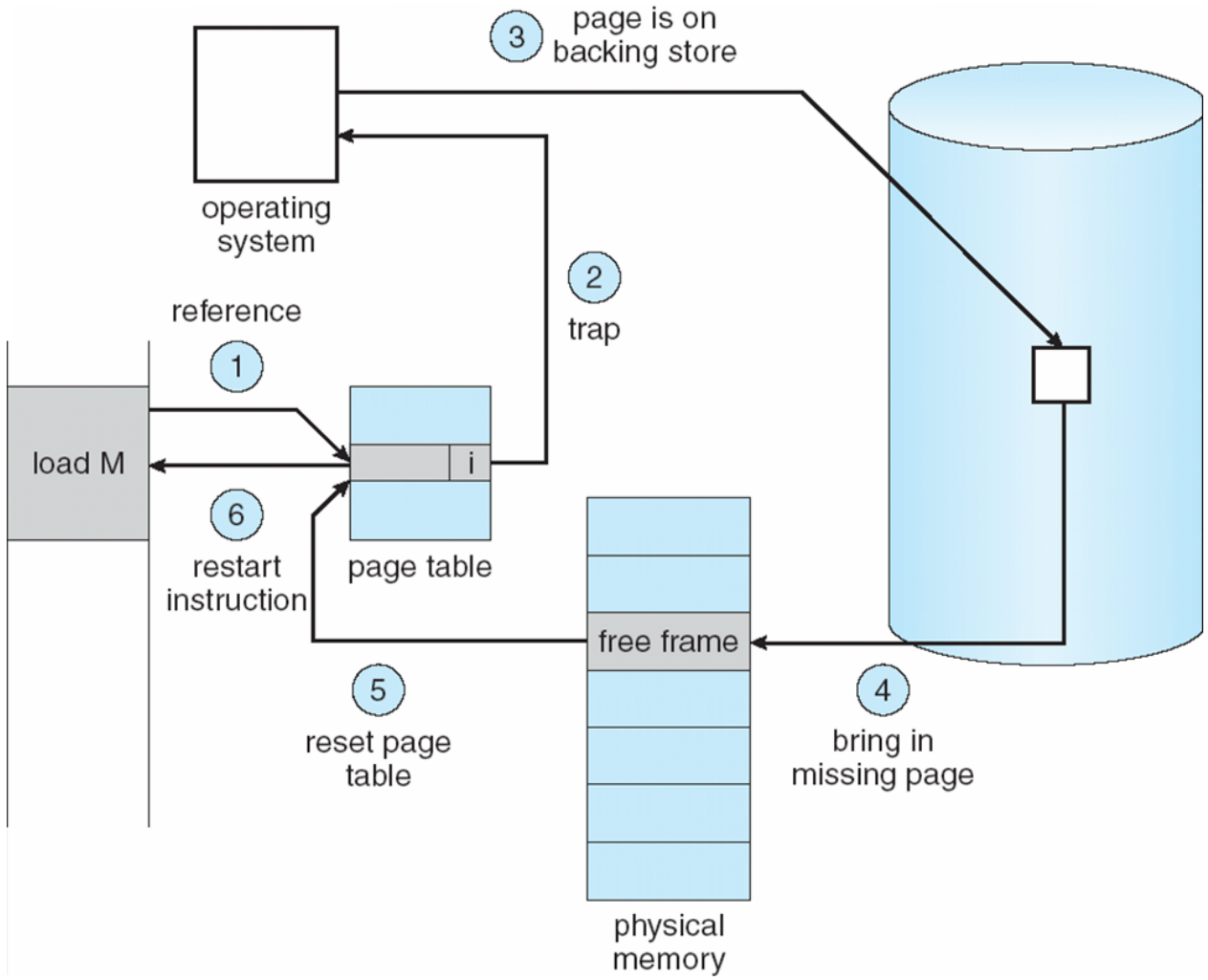
Source: Gyusun Lee*, Wenjing. Jin*, et al., "A Case for Hardware-based Demand Paging," ISCA 2020

Demand Paging

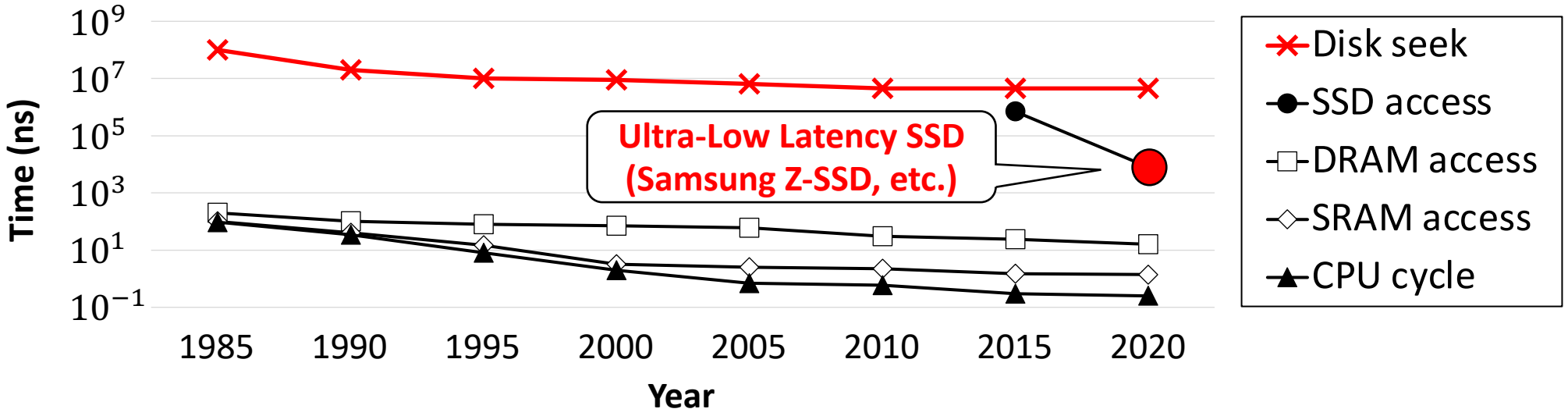
- Core mechanism of virtual memory
  - Memory as a cache of backing storage
  - Prevalent from mobile to cloud computing
- Benefits
  - Fewer I/Os needed
  - Less memory needed
  - Faster response
  - Better support for multiple processes



Source: A. Silberschatz, P. B. Galvin, and G. Gagne, Operating System Concepts, 9th Edition, John Wiley & Sons, Inc. 2014.

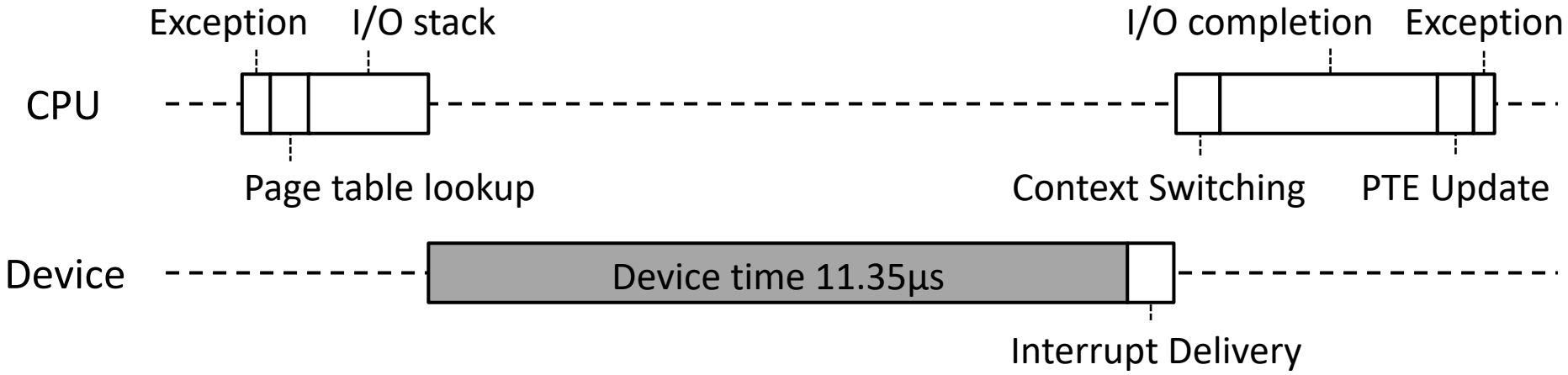
Bottleneck Shift in Demand Paging

Storage Performance Trends



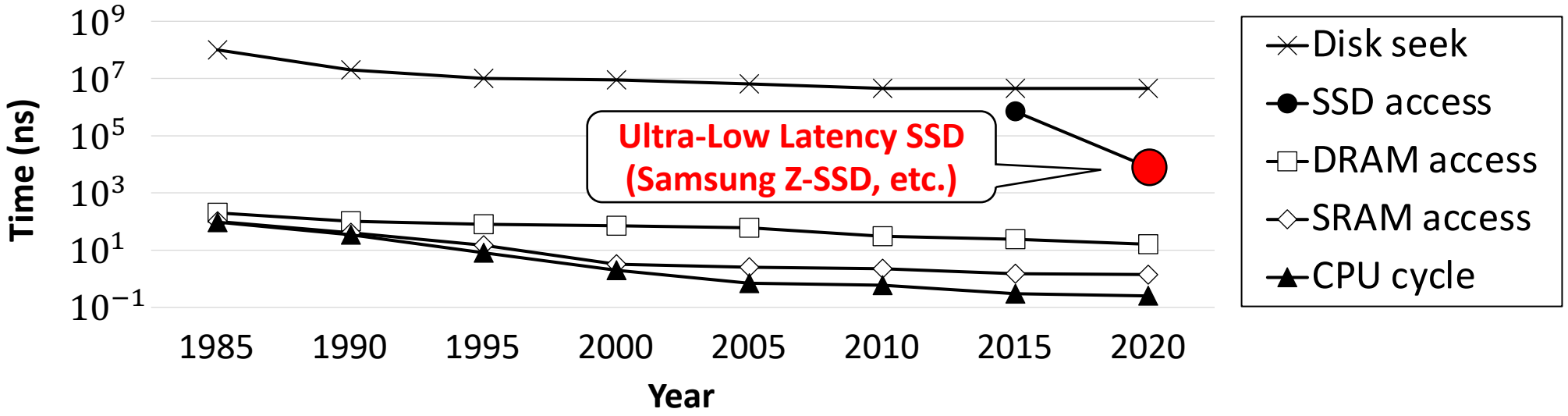
Source: R. E. Bryant and D. R. O'Hallaron, Computer Systems: A Programmer's Perspective, Second Edition, Pearson Education, Inc., 2015

Breakdown of Page Fault Handling



Bottleneck Shift in Demand Paging

Storage Performance Trends



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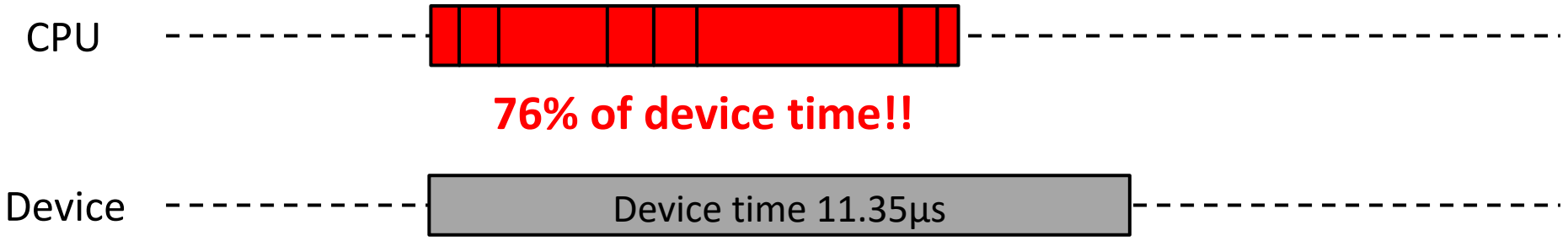
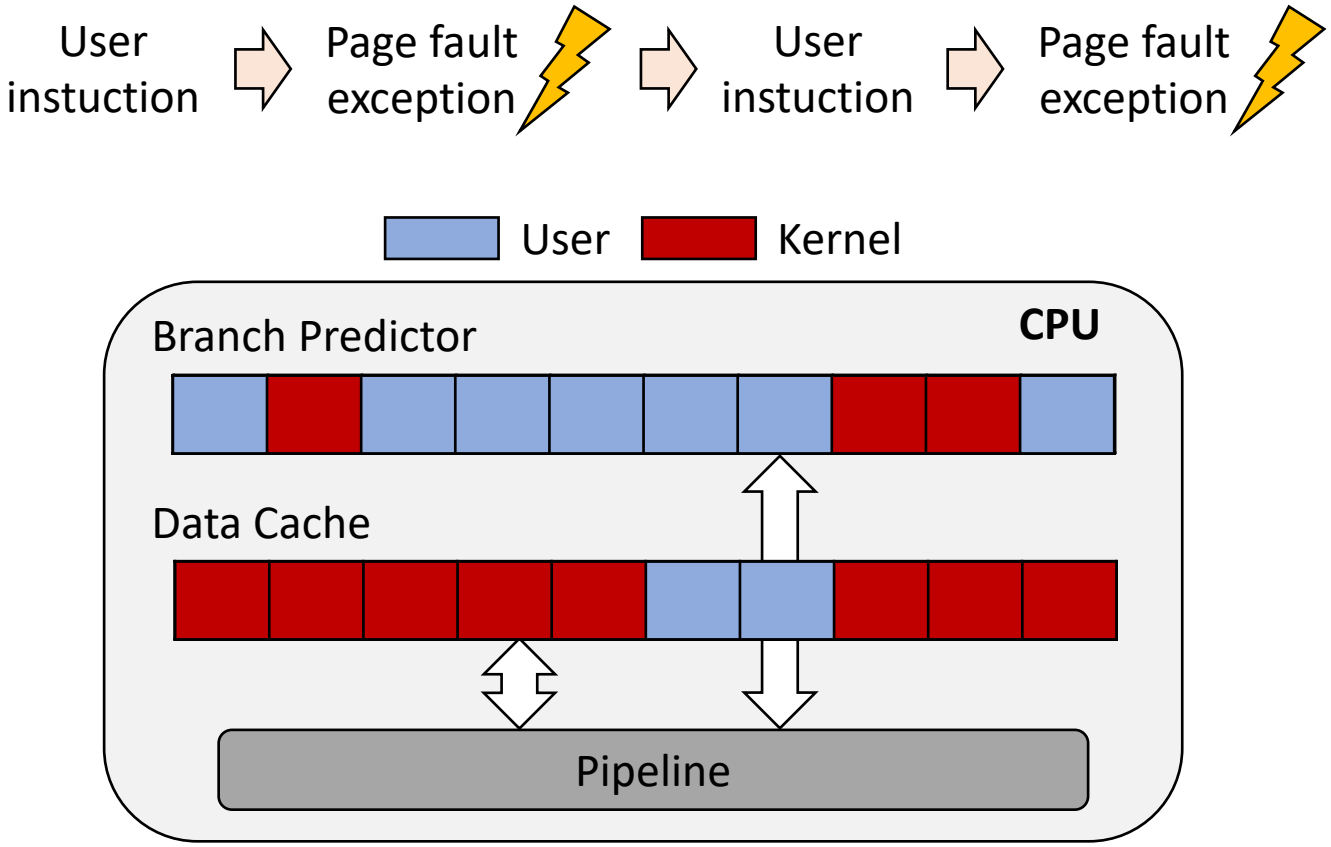
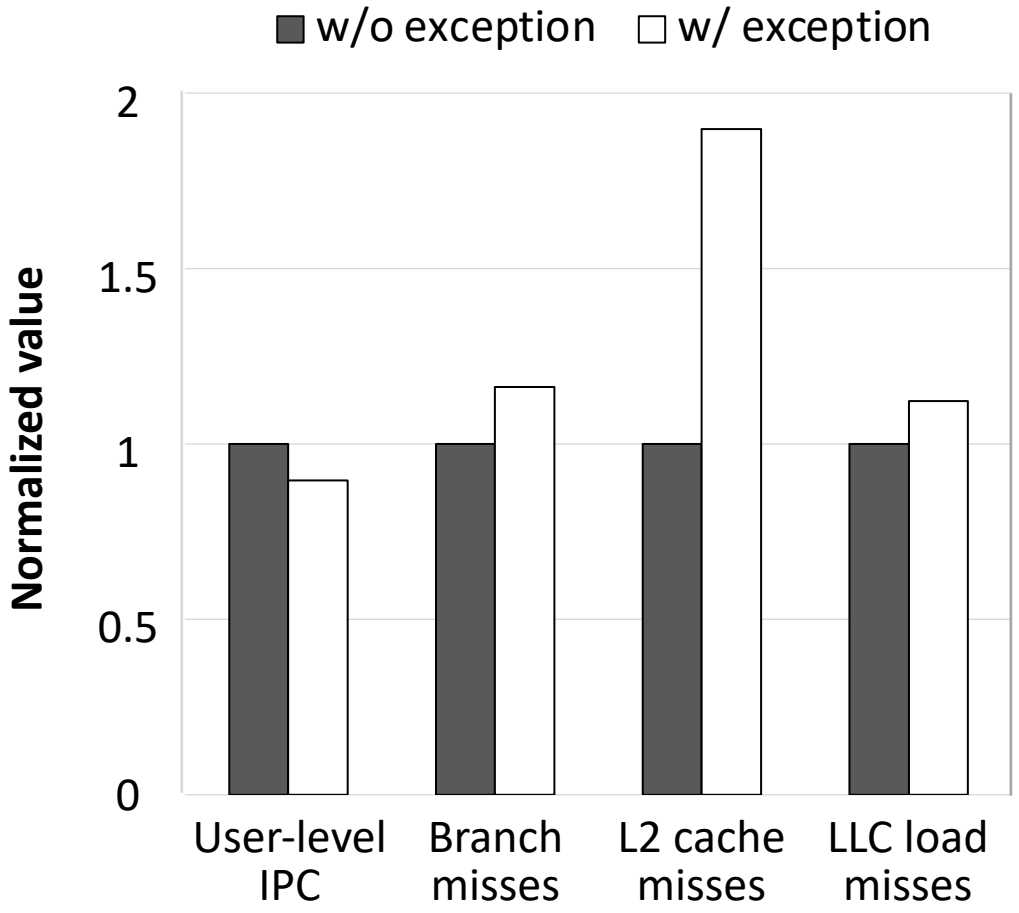
Breakdown of Page Fault Handling



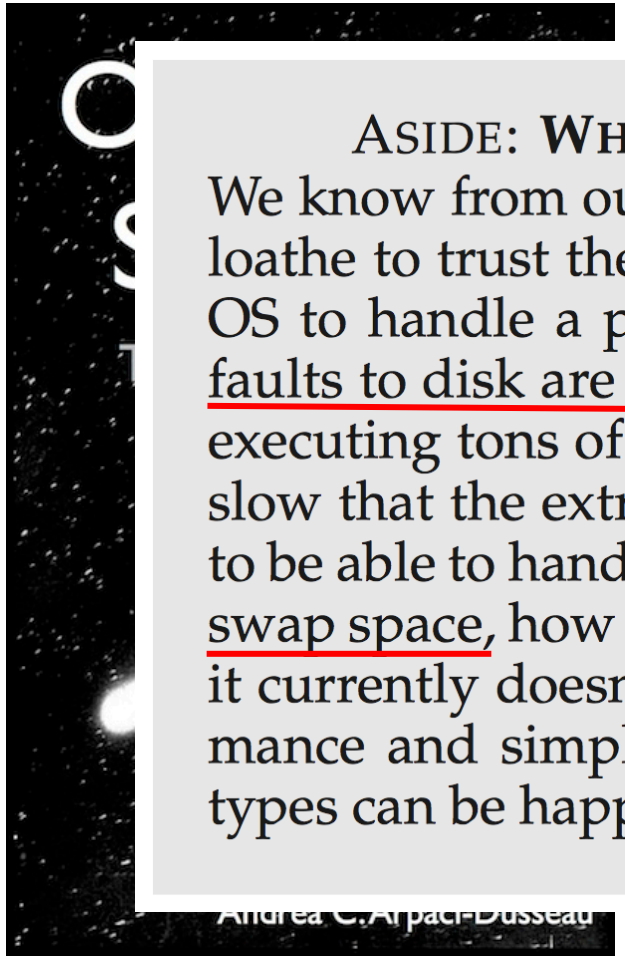
Indirect Cost of Demand Paging

- Architecture resource pollution (branch mispredictions, cache misses) by page faults





Hidden Motivation (feat. OSTEP Book)

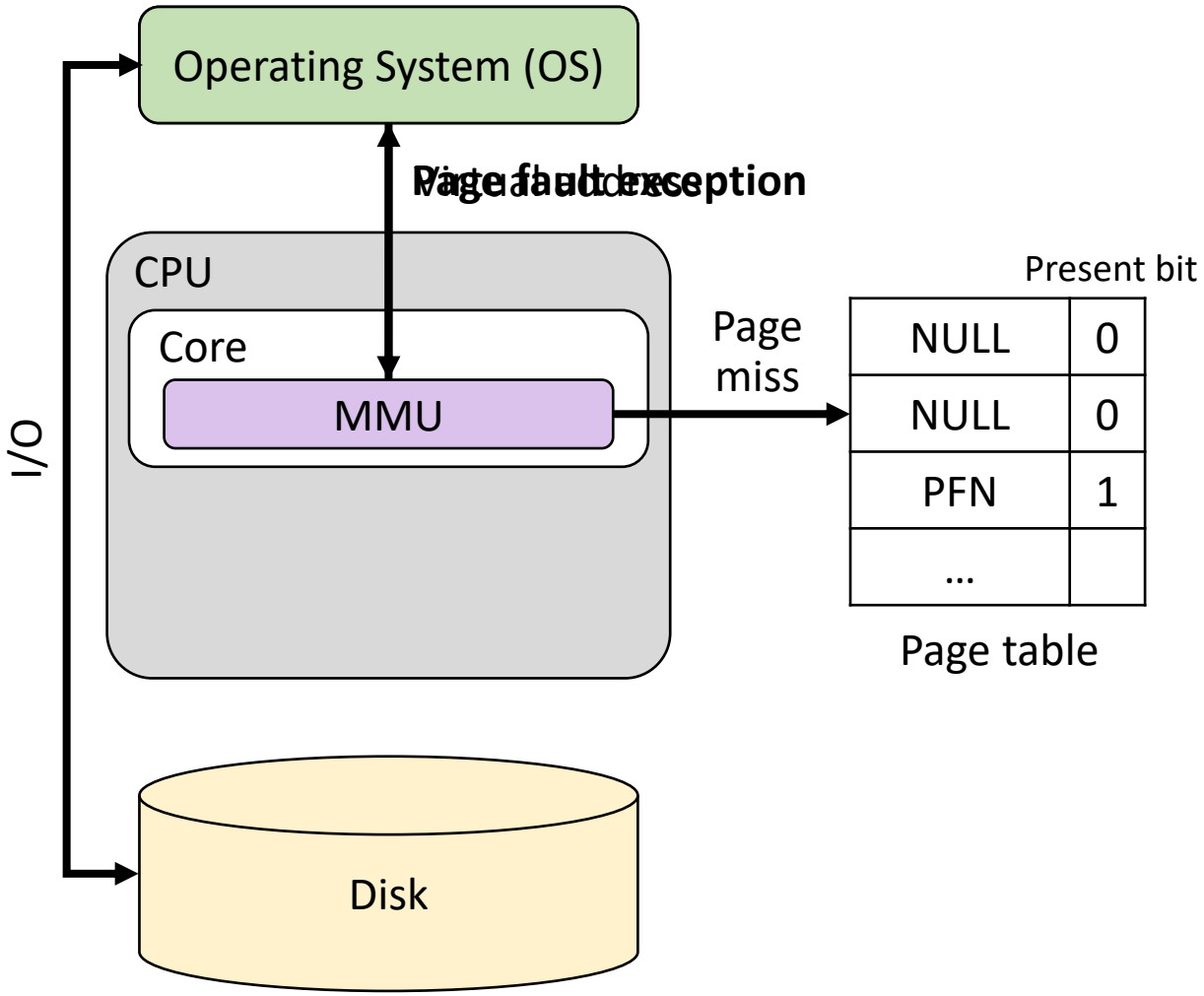


ASIDE: WHY HARDWARE DOESN'T HANDLE PAGE FAULTS

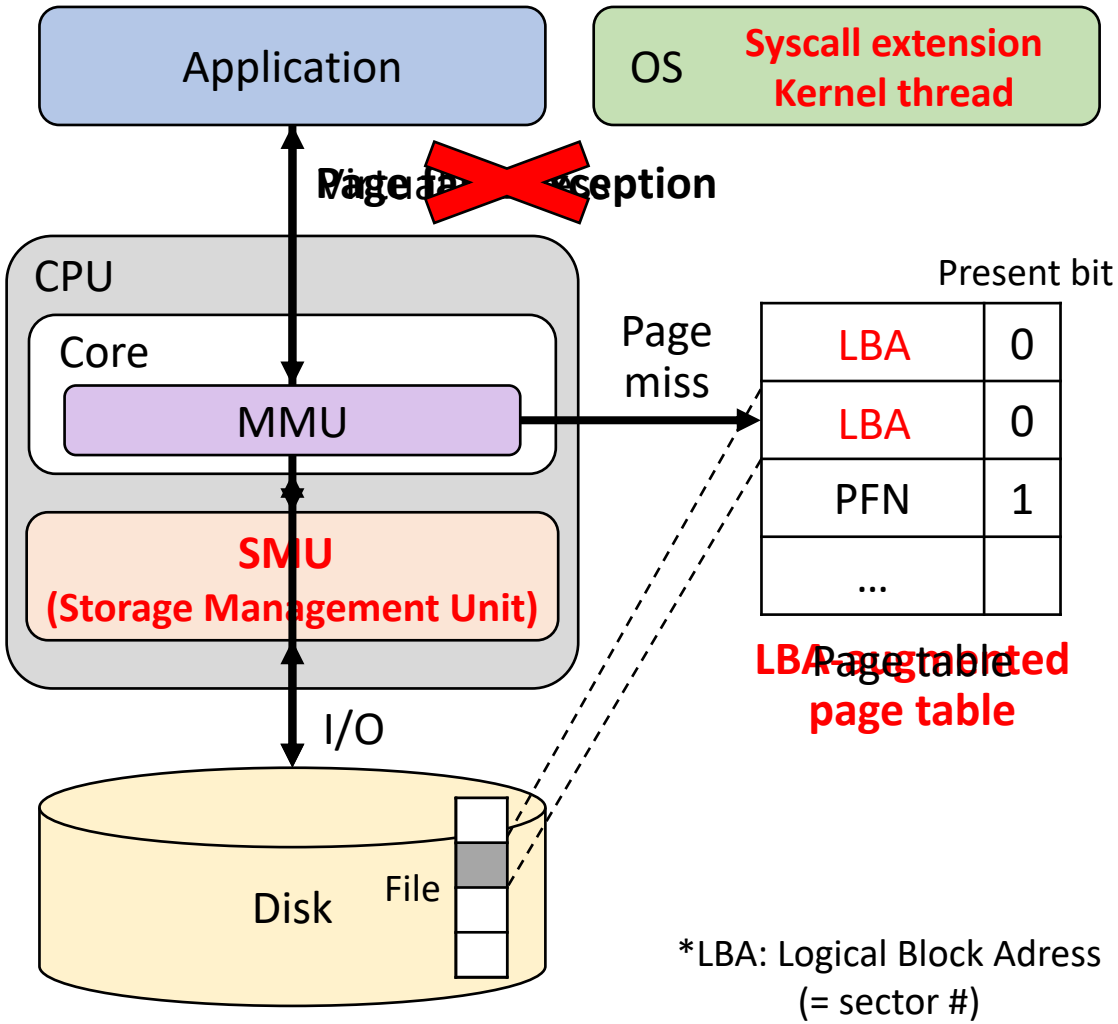
We know from our experience with the TLB that hardware designers are loathe to trust the OS to do much of anything. So why do they trust the OS to handle a page fault? There are a few main reasons. First, page faults to disk are *slow*; even if the OS takes a long time to handle a fault, executing tons of instructions, the disk operation itself is traditionally so slow that the extra overheads of running software are minimal. Second, to be able to handle a page fault, the hardware would have to understand swap space, how to issue I/Os to the disk, and a lot of other details which it currently doesn't know much about. Thus, for both reasons of performance and simplicity, the OS handles page faults, and even hardware types can be happy.

Source: Arpaci-Dusseau, Remzi H., Arpaci-Dusseau, Andrea C. *Operating systems: Three easy pieces*. Arpaci-Dusseau Books LLC, 2018.

Operating System-Based Demand Paging (OSDP)



Hardware-Based Demand Paging (HWDP)



*LBA: Logical Block Adress
(= sector #)

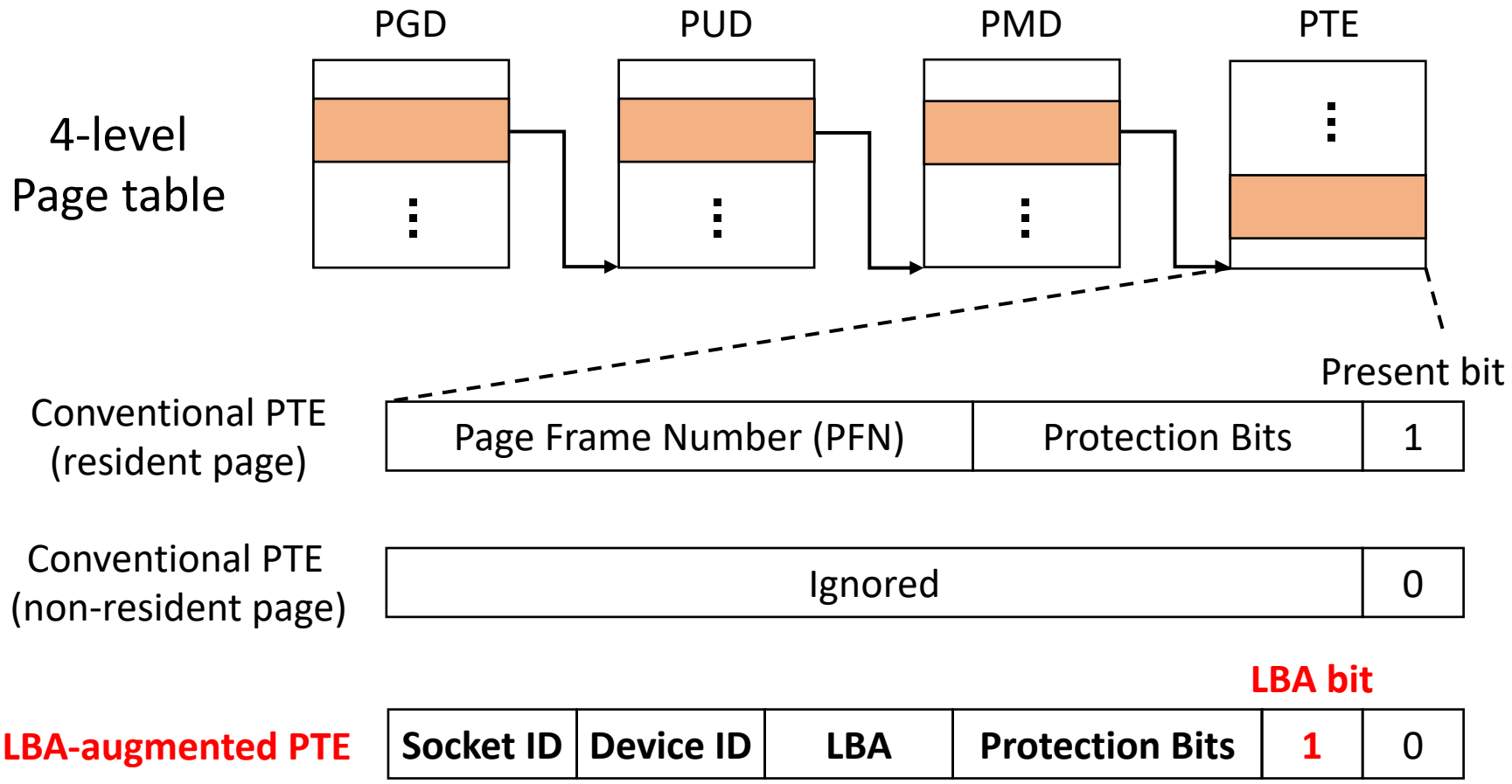
- Challenges
  - How to make a CPU understand storage layout?
    - **LBA*-augmented page table**
  - How to make a CPU control a storage I/O device?
    - **Storage Management Unit**
  - How to handle remaining page fault operations in the OS kernel?
    - **OS extensions (syscall extension, kernel thread..)**
- Benefits
  - Eliminates OS intervention (no exception occurs)
  - Reduces demand paging latency
  - Mitigates architecture resource pollution

Outline

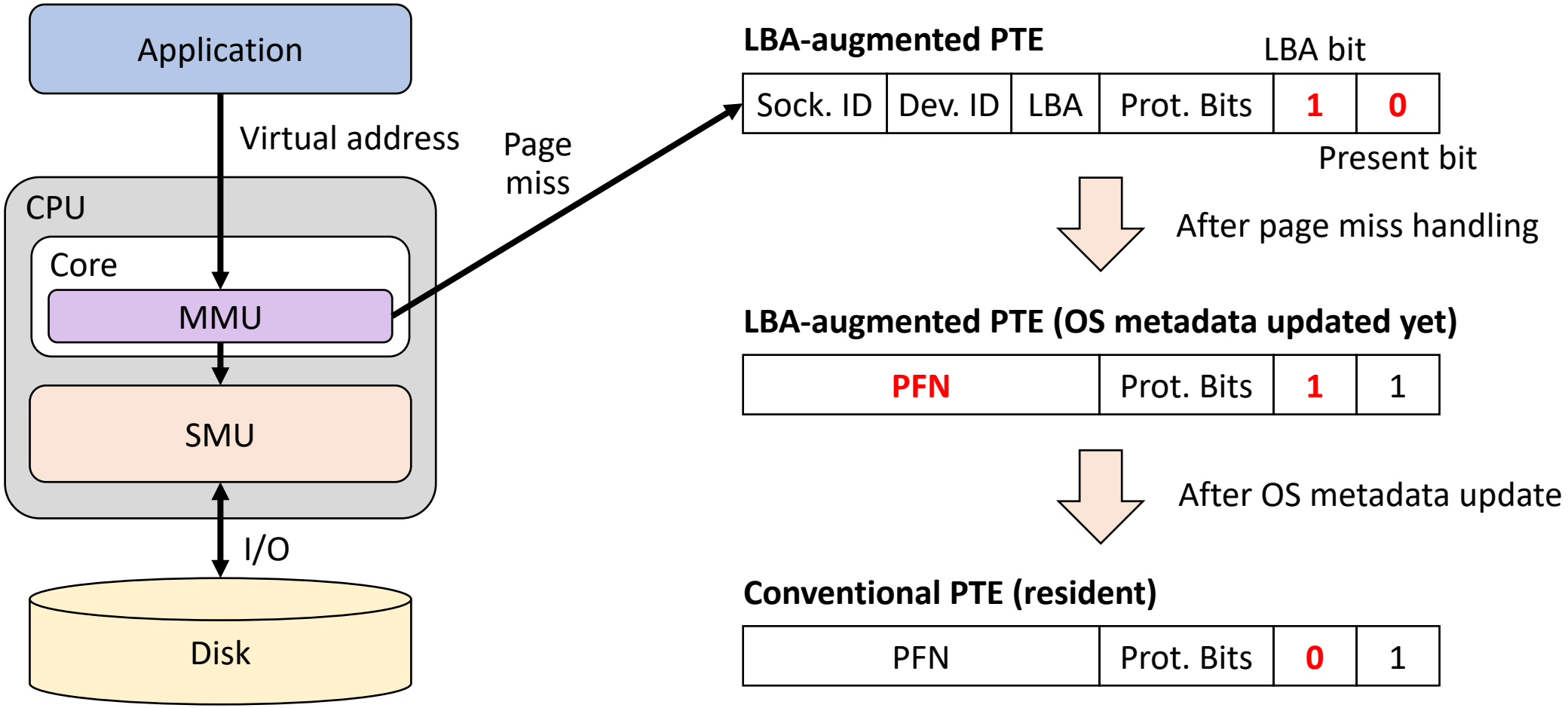
- Overview
- Architectural extensions
  - LBA-augmented page table
  - Storage Management Unit (SMU)
- OS supports
  - Fast file mmap()
  - Updating OS metadata for HWDP
  - Management of free page queue
- Evaluation
- Conclusion
- On-going work

LBA-augmented Page Table

- CPU understand storage layout through LBA-augmented page table

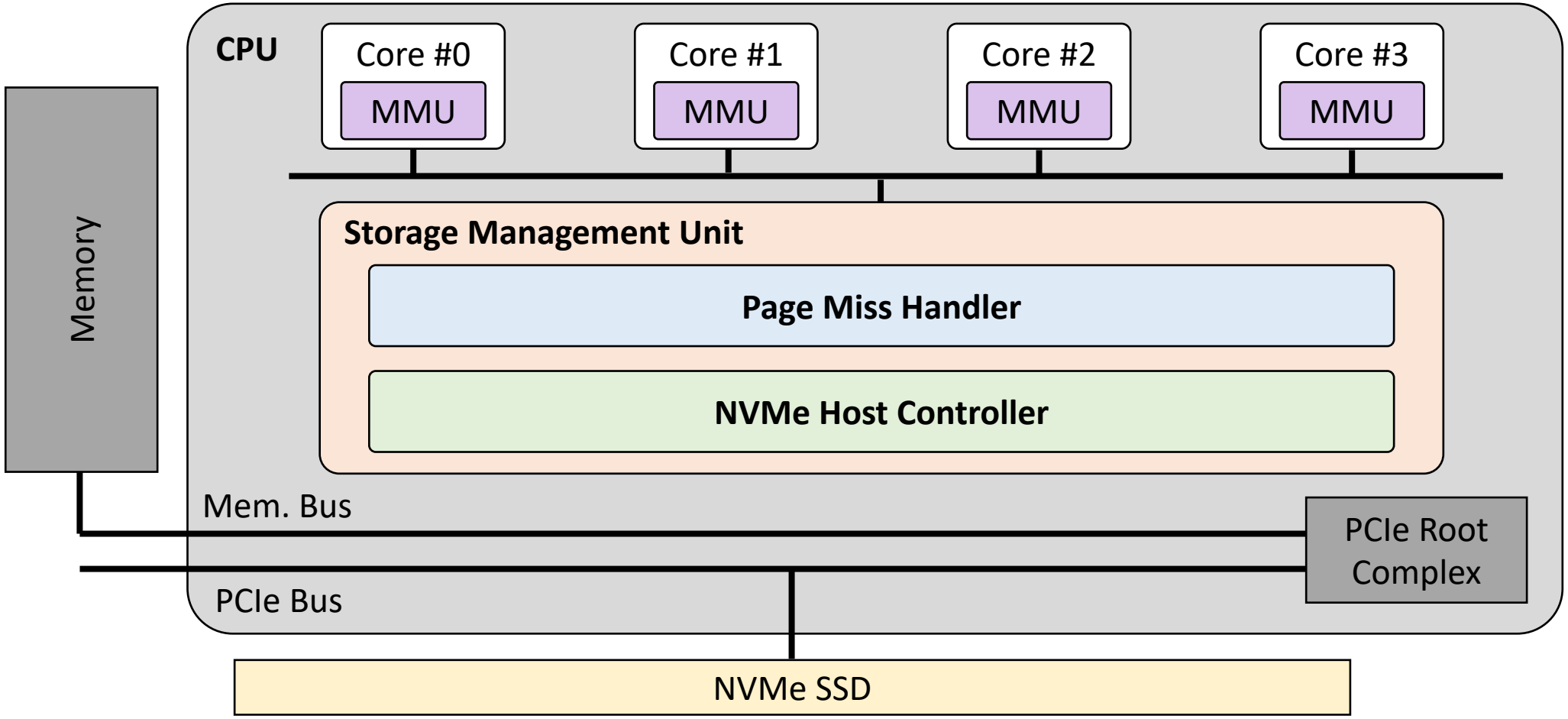


HWDP with LBA-augmented Page Table

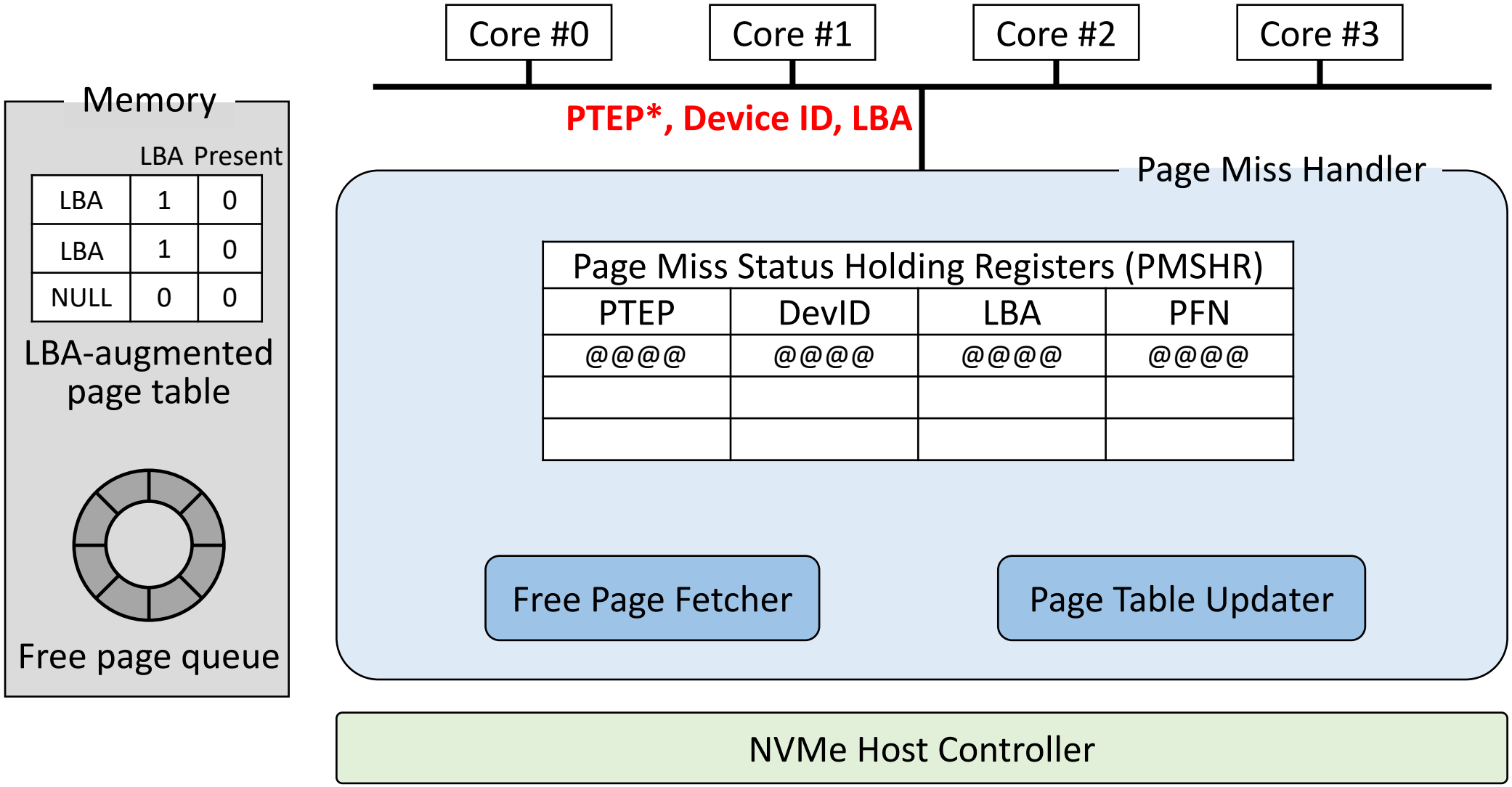


Storage Management Unit (SMU)

- Additional architectural component to handle page miss in hardware

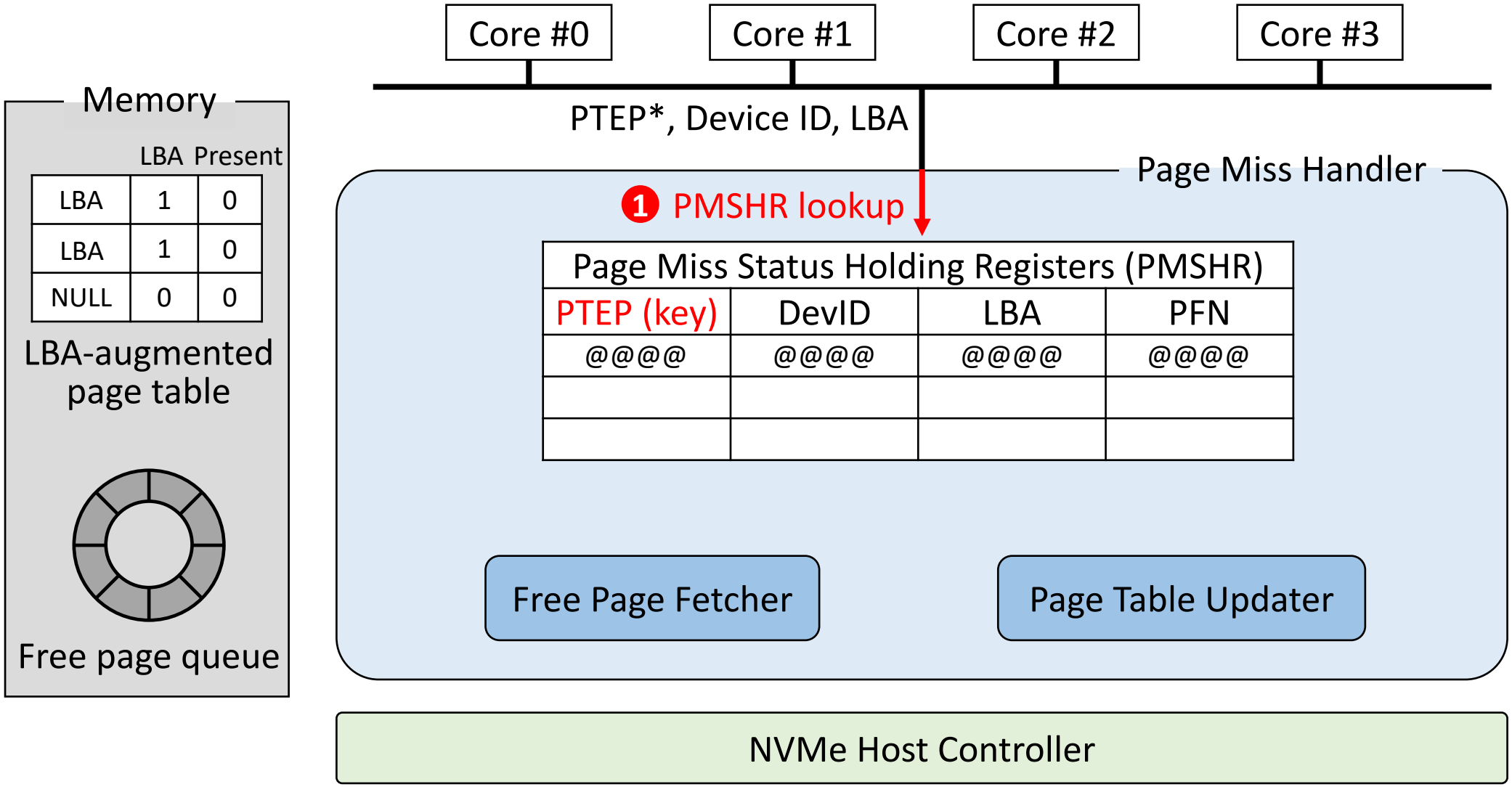


SMU – Page Miss Handler



*PTEP: PTE address

SMU – Page Miss Handler



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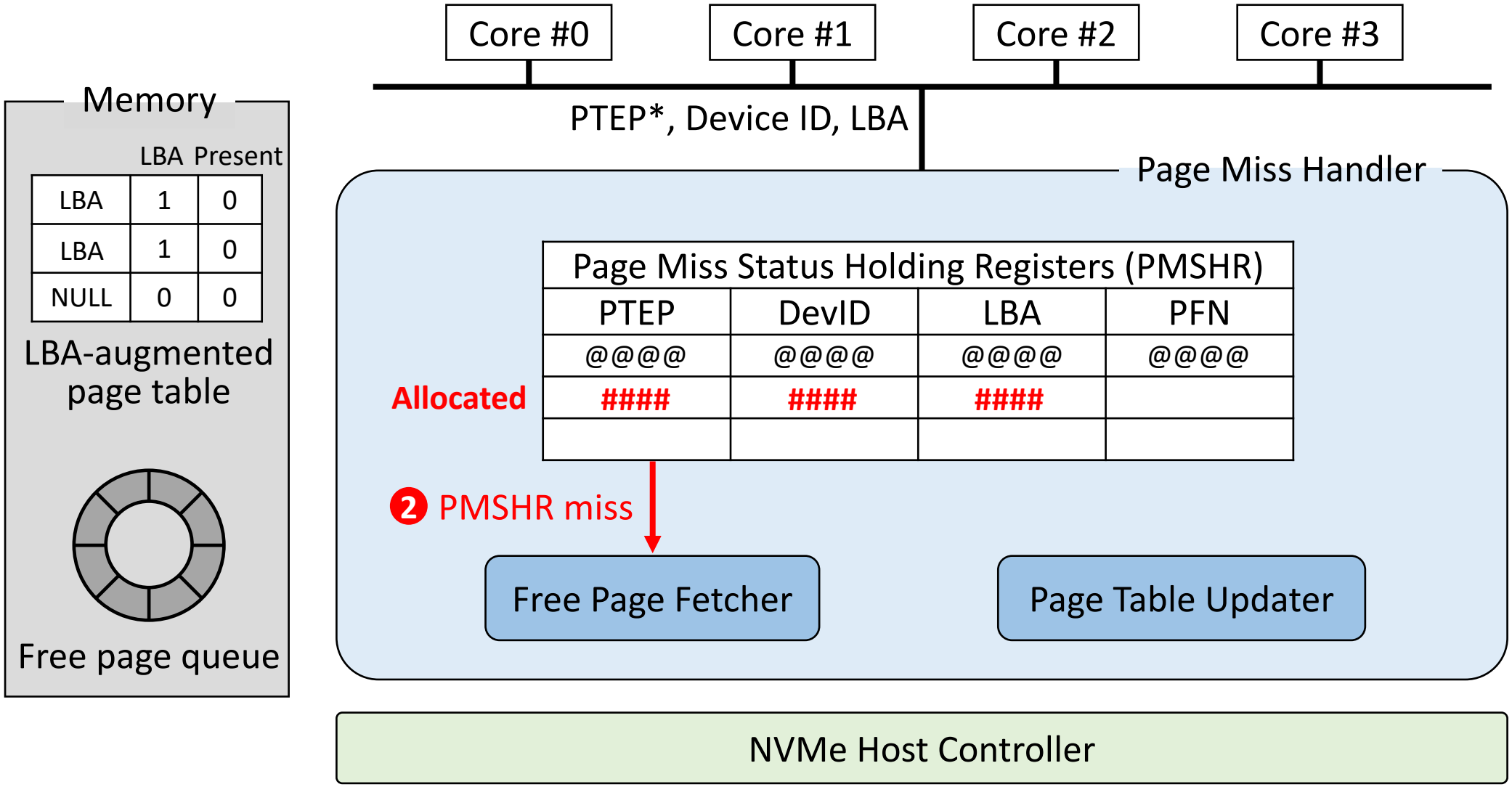

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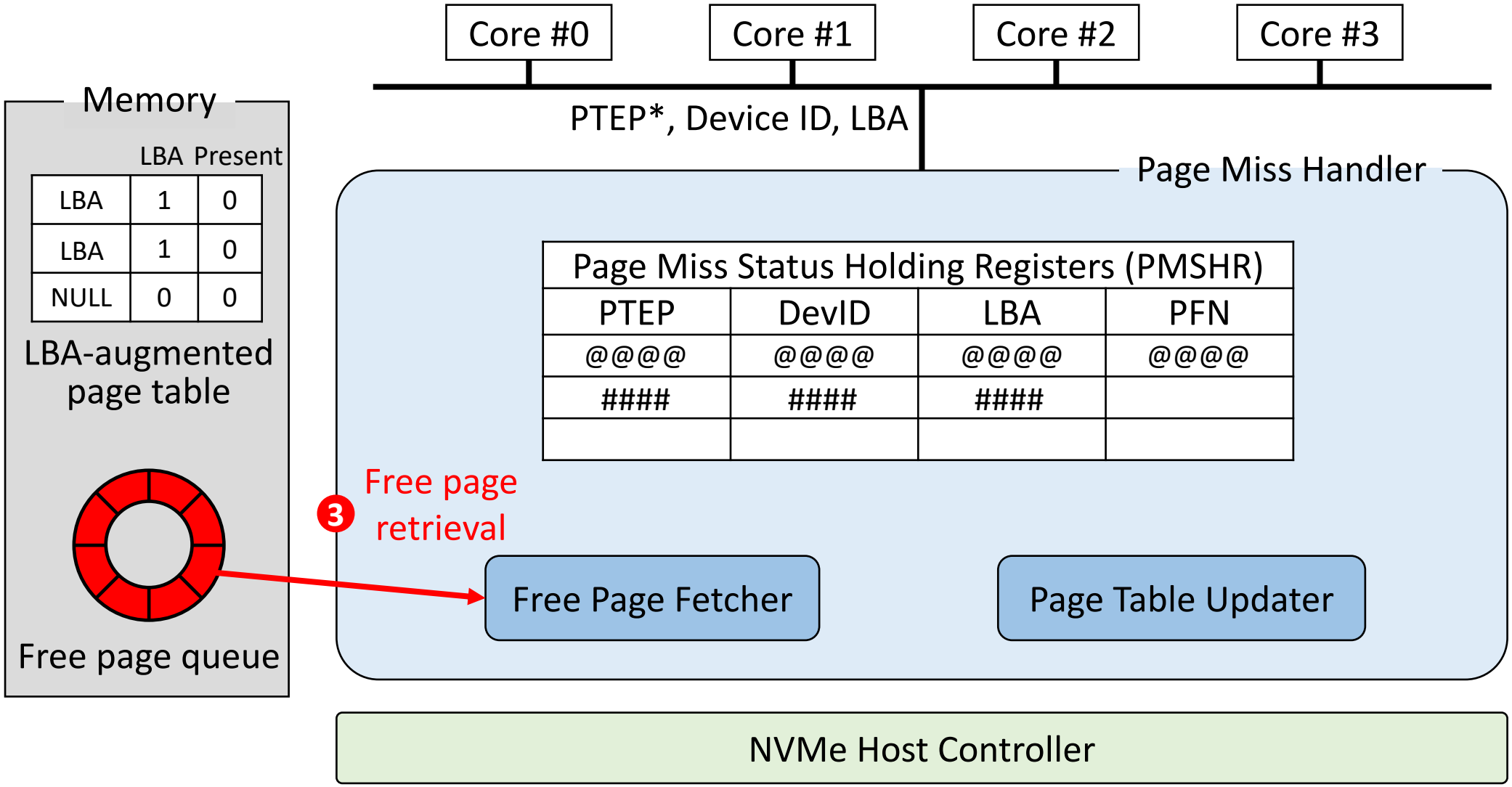

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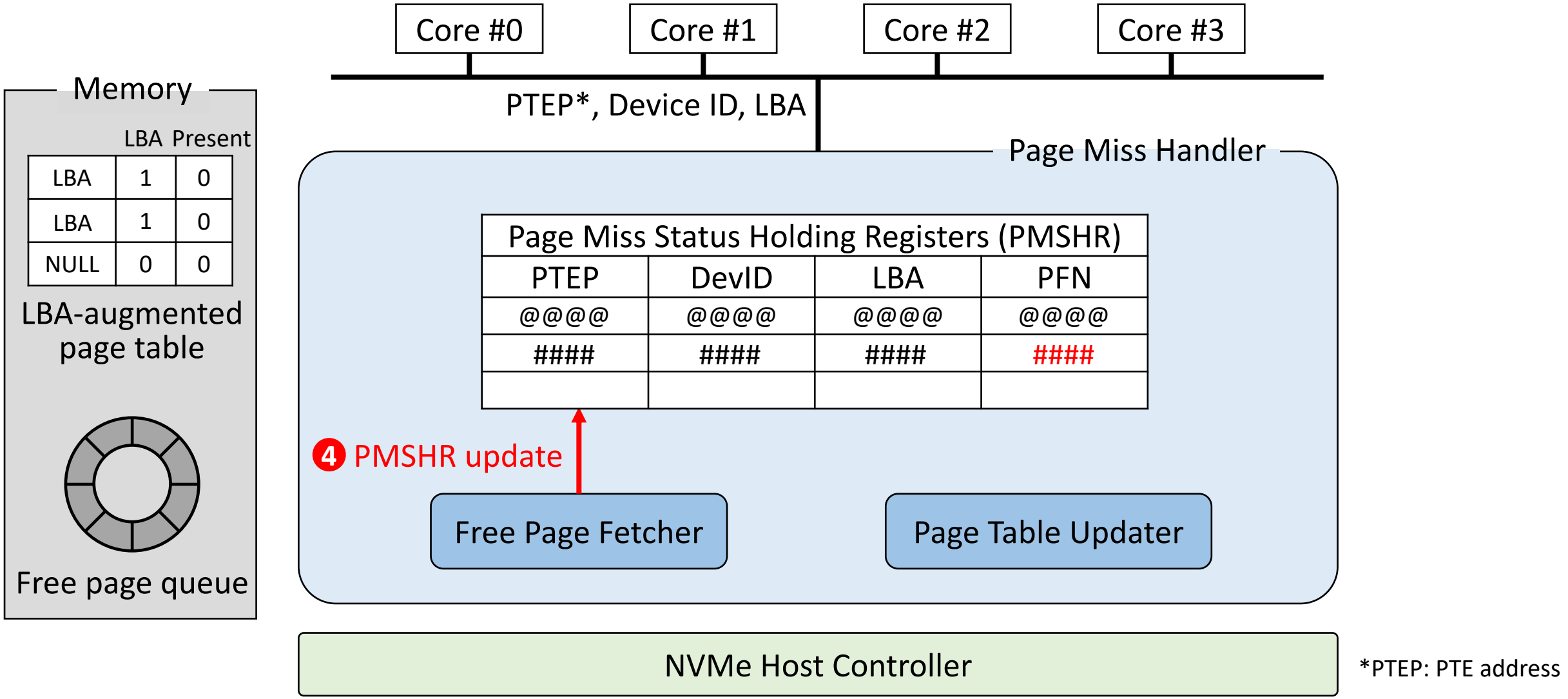

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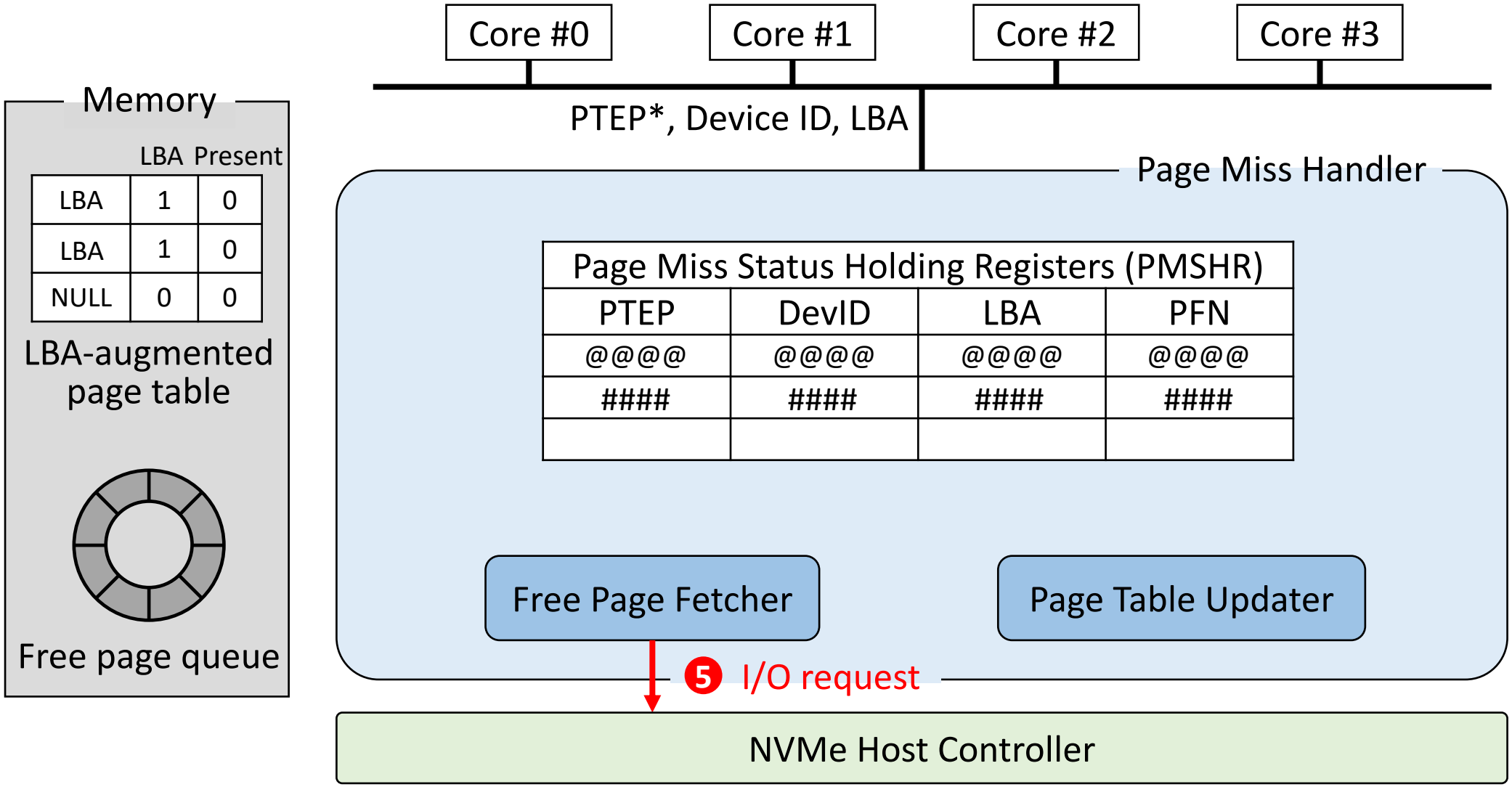

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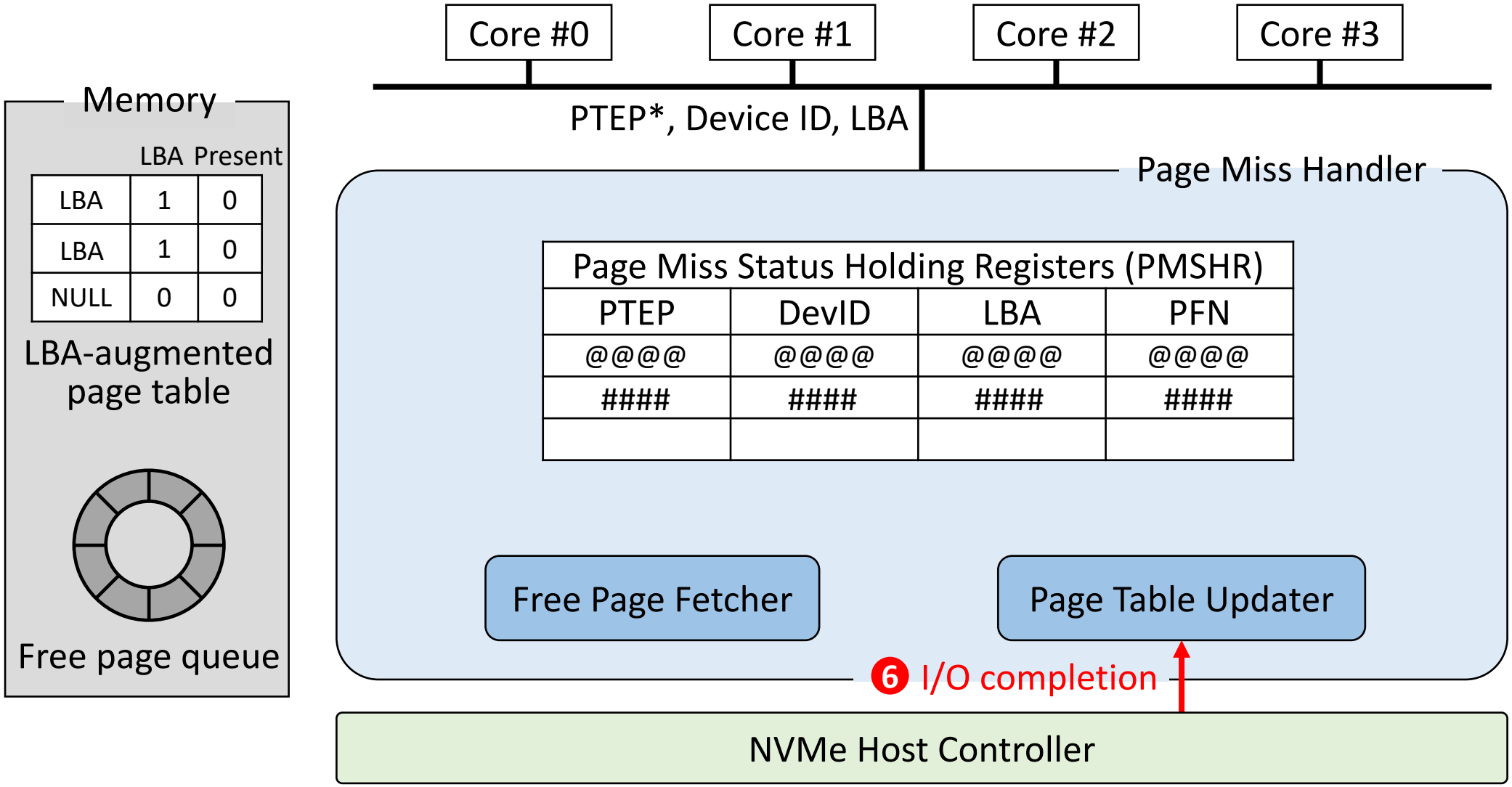

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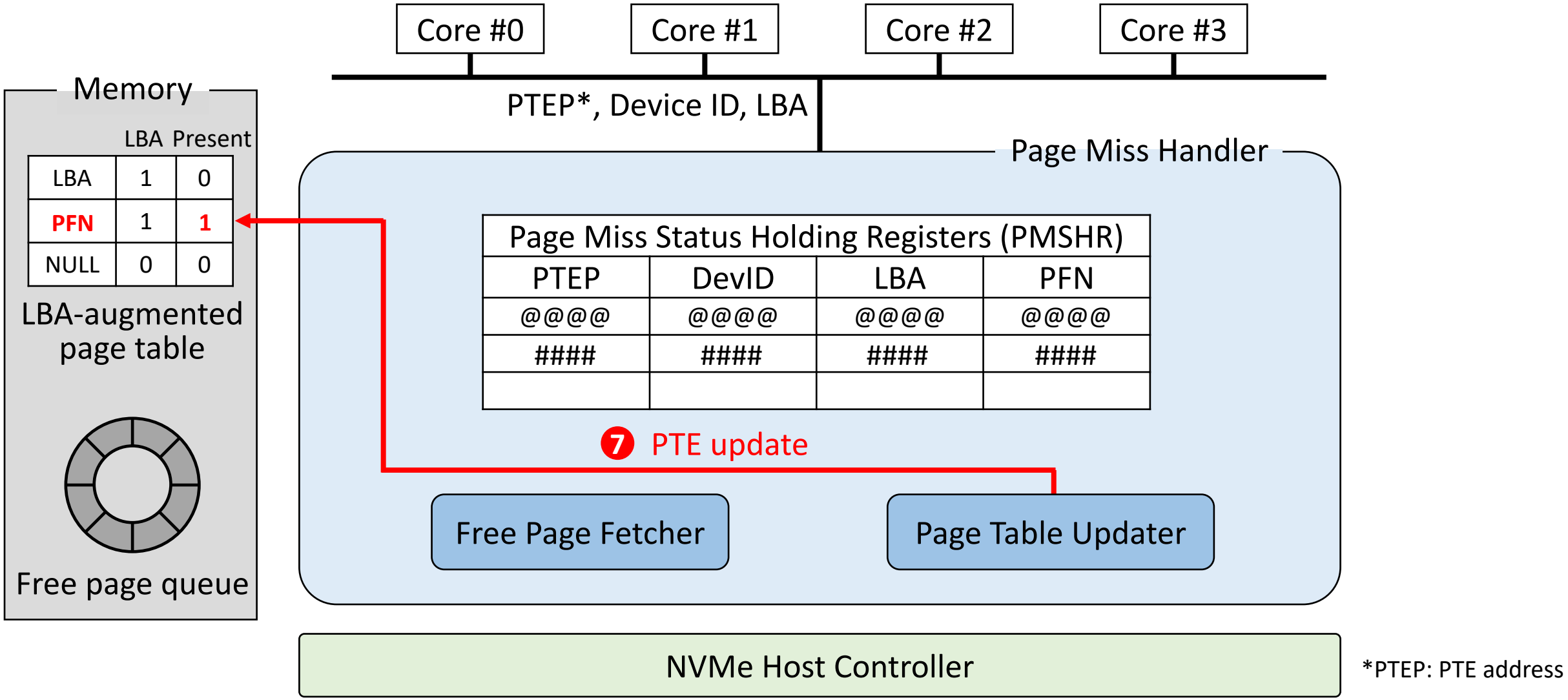

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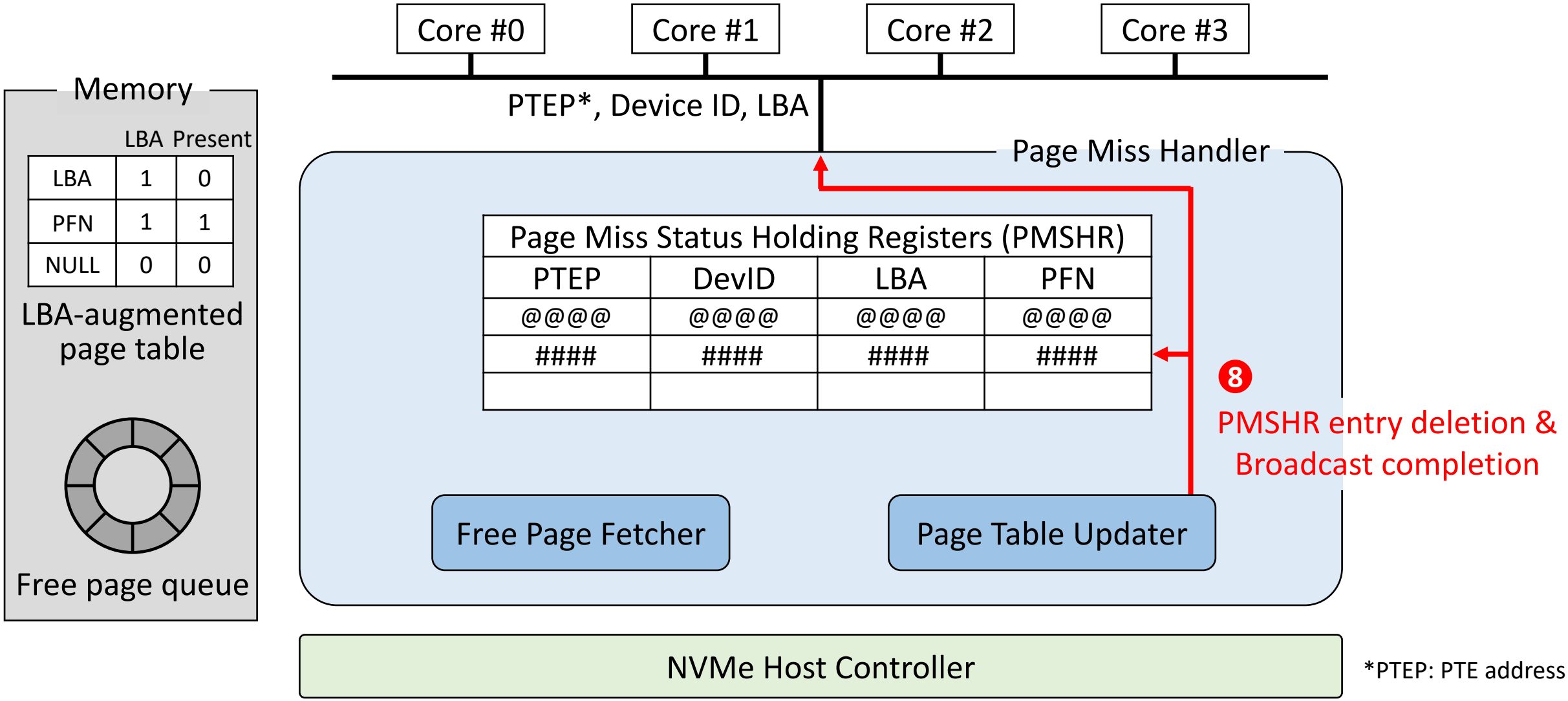
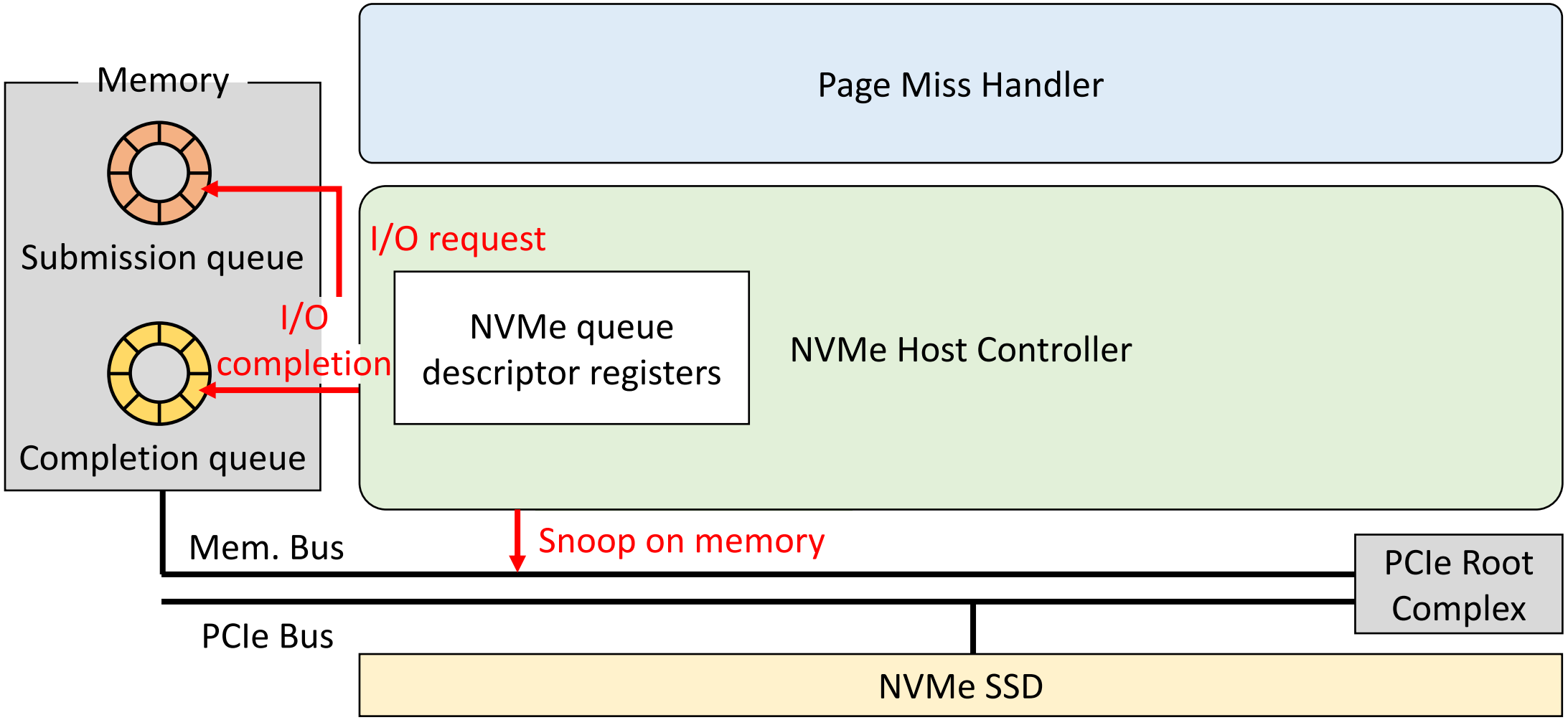


SMU – NVMe Host Controller



Outline

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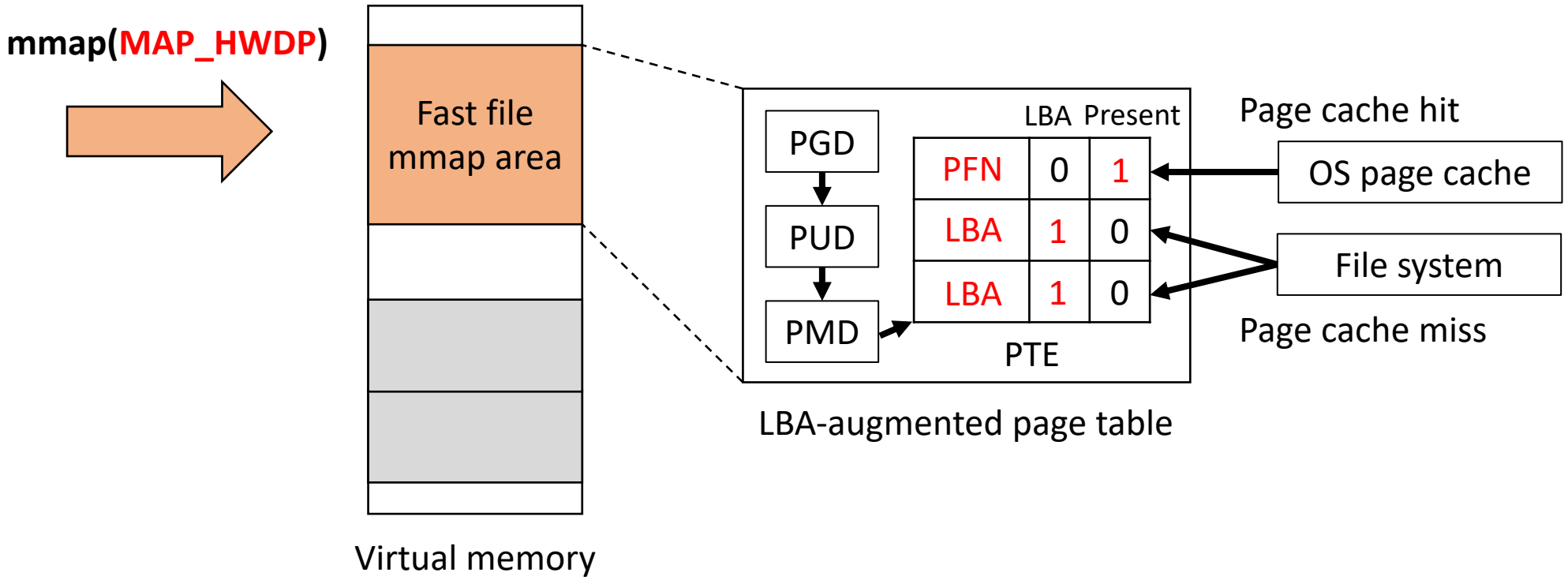
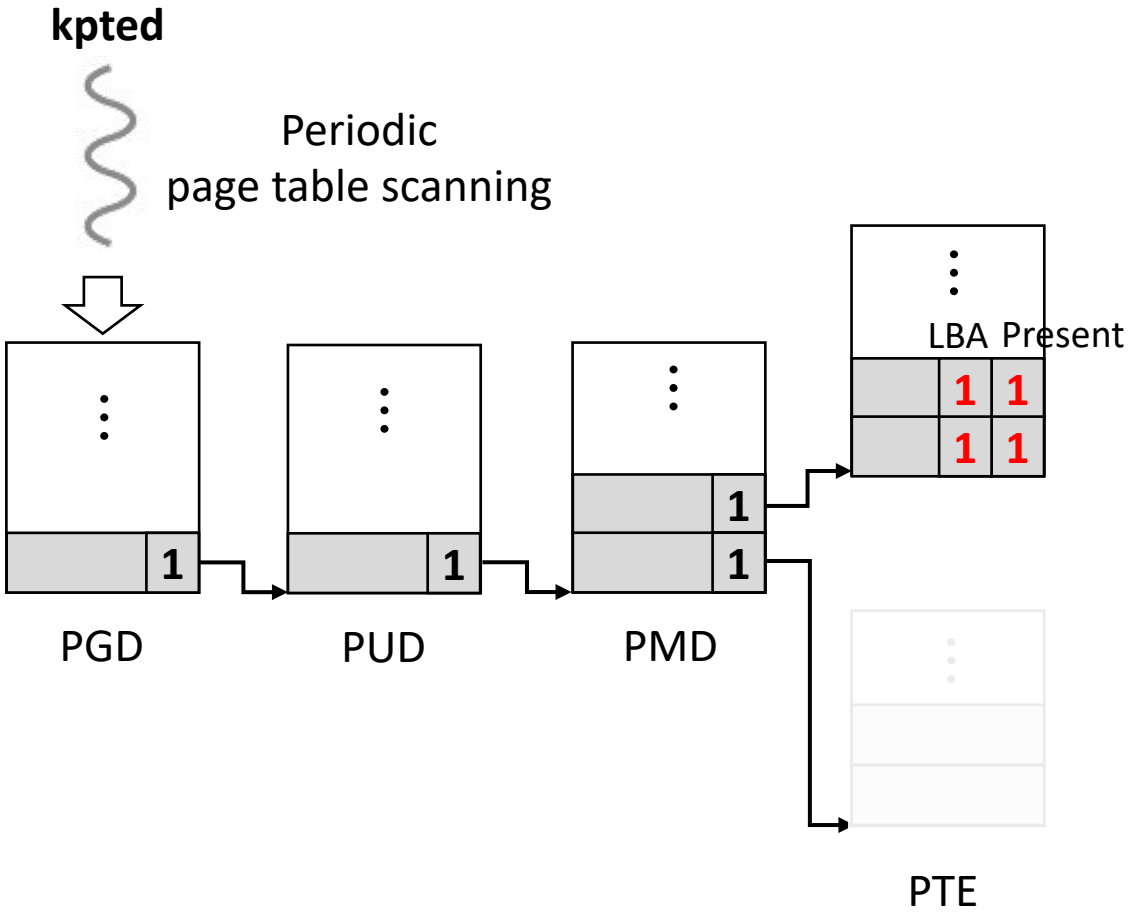
Fast File mmap()

- A new interface to utilize HWDP
  - Allocate a region of memory-mapped file to use HWDP
  - Update associated metadata lazily
  - Currently, only for files that are not shared across multiple processes



Updating OS Metadata for HWDP

- Introduces a kernel thread (*kpted*) to update OS-managed metadata in background



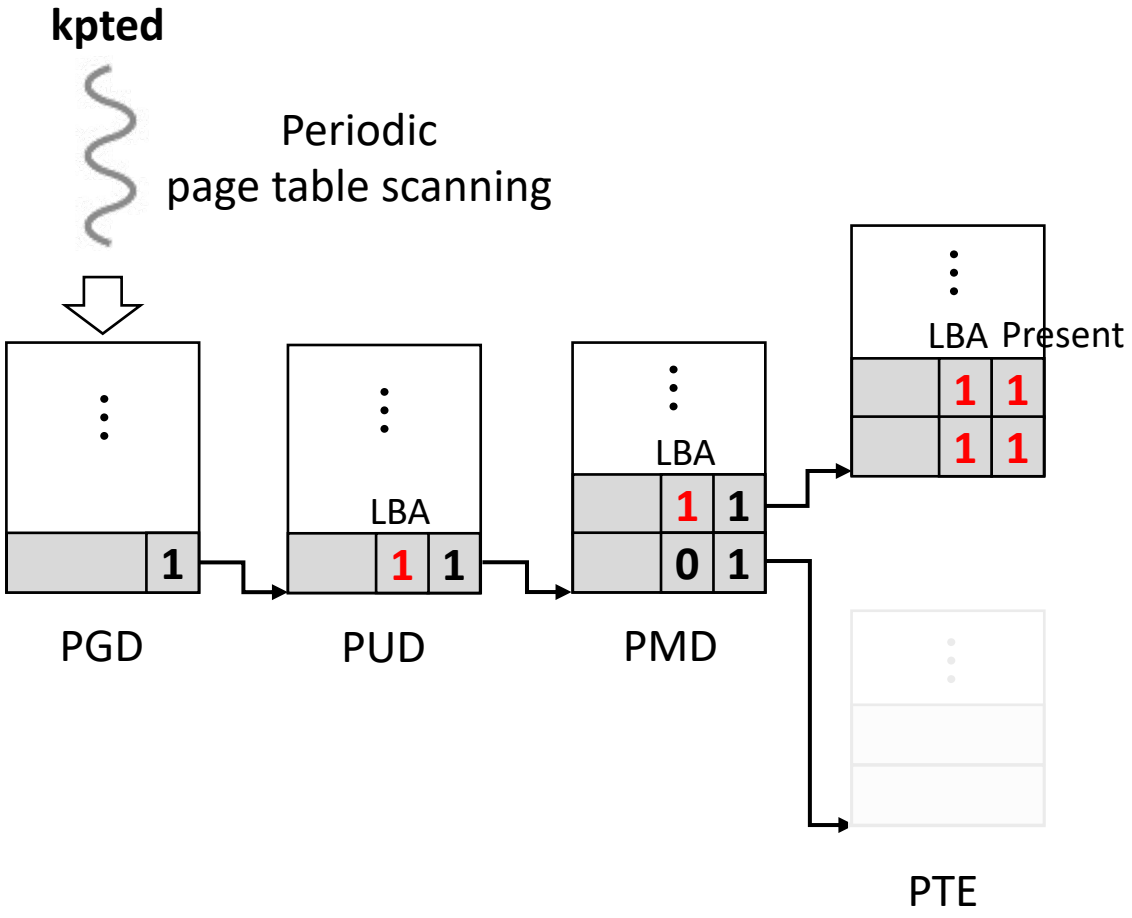
if (**PUD**) {
  Goes to next-level (PMD);
}
PUD

if (**PMD**) {
  Goes to next-level (PTE);
}
PMD

if (**PTE→LBA bit** && **PTE→present bit**) {
  Updates OS metadata; (inserts page to LRU list ..)
  Clears PTE→LBA bit;
}
PTE

Updating OS Metadata for HWDP

- Introduces a kernel thread (*kpted*) to update OS-managed metadata in background



PUD

if (**PUD→LBA bit**) {
  Clears PUD→LBA bit;
  Goes to next-level (PMD);
}

PMD

if (**PMD→LBA bit**) {
  Clears PMD→LBA bit;
  Goes to next-level (PTE);
}

PTE

if (**PTE→LBA bit** && **PTE→present bit**) {
  Updates OS metadata; (inserts page to LRU list ..)
  Clears PTE→LBA bit;
}

Management of Free Page Queue

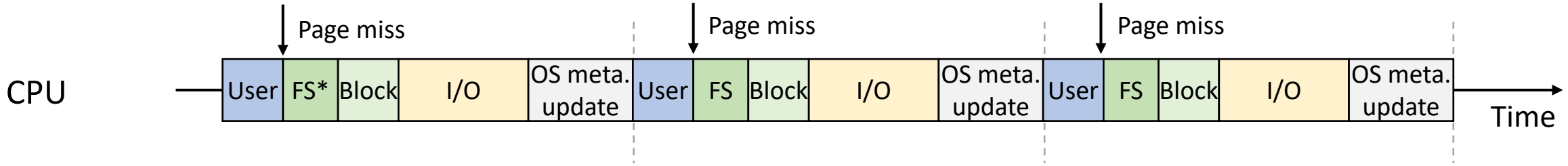
- Synchronous free page refill
  - SMU raises a page fault exception when it fails to allocate a free page
  - OS page fault handler handles the page fault and refills the free page queue

- Asynchronous free page refill
  - A background kernel thread (*kpoold*) periodically refills free pages
  - 44-78% reduction of synchronous page refills (in YCSB workloads)

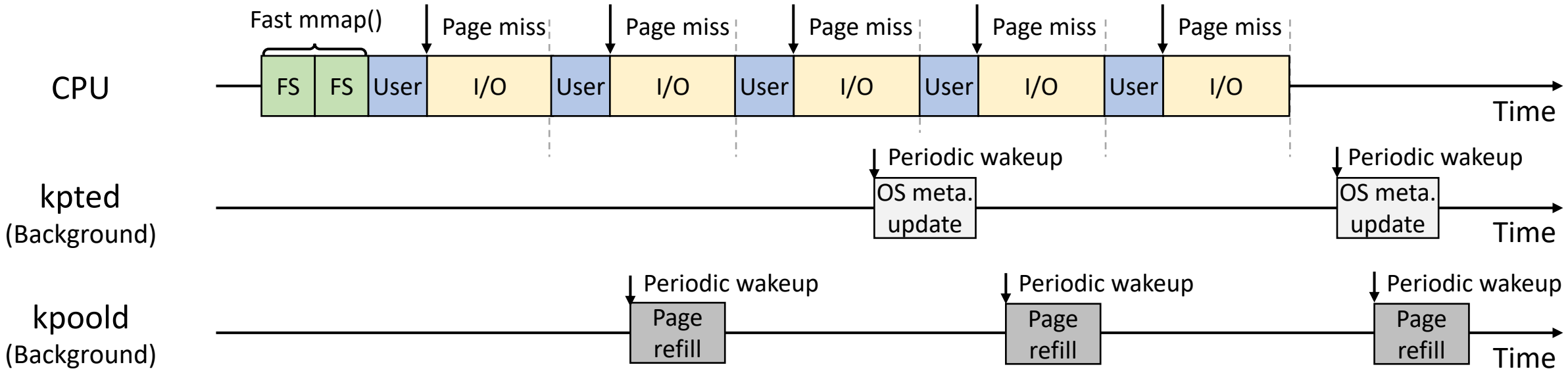
Summary - Demand Paging Comparison

OS-based Demand Paging (OSDP)

*FS: File System



Hardware-based Demand Paging (HWDP)



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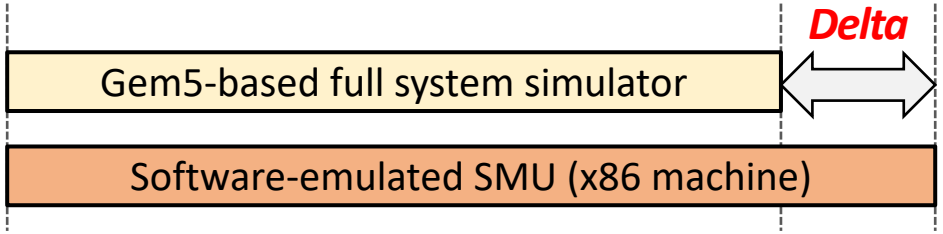
Evaluation

- Experimental Setup
  - Micro-architecture-level evaluation
    - Gem5-based full system simulator integrated with the SSD model
  - End-to-end system level evaluation
    - Implementating HWDP on real x86 machine (**software-emulated SMU**)

  - Delta measurement of single page miss handling



  - HWDP performance estimation (Ops/sec)

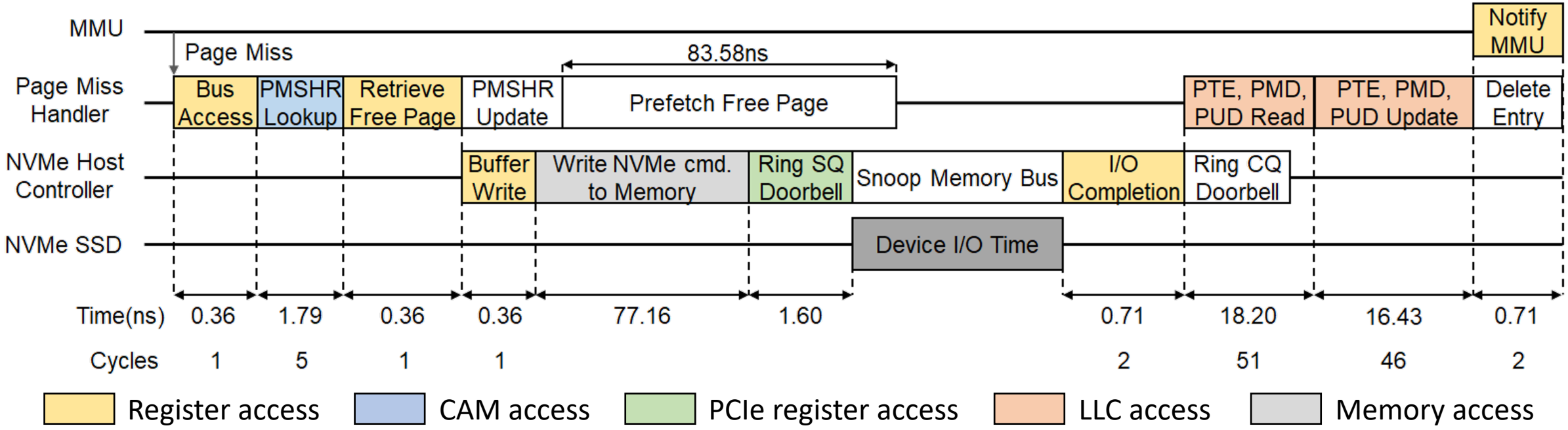
$$\frac{\#\ of\ operations}{Execution\ time\ of\ workload - \#\ of\ page\ misses * Delta}$$

  - x86 machine configuration

Server	Dell R730
OS	Ubuntu 16.04.6
Base kernel	Linux 4.9.30
CPU	Intel Xeon E5-2640v3 2.6GHz 8 physical cores (Hyperthreading on)
Memory	DDR4 32GB
Storage devices	Samsung SZ985 800GB Z-SSD

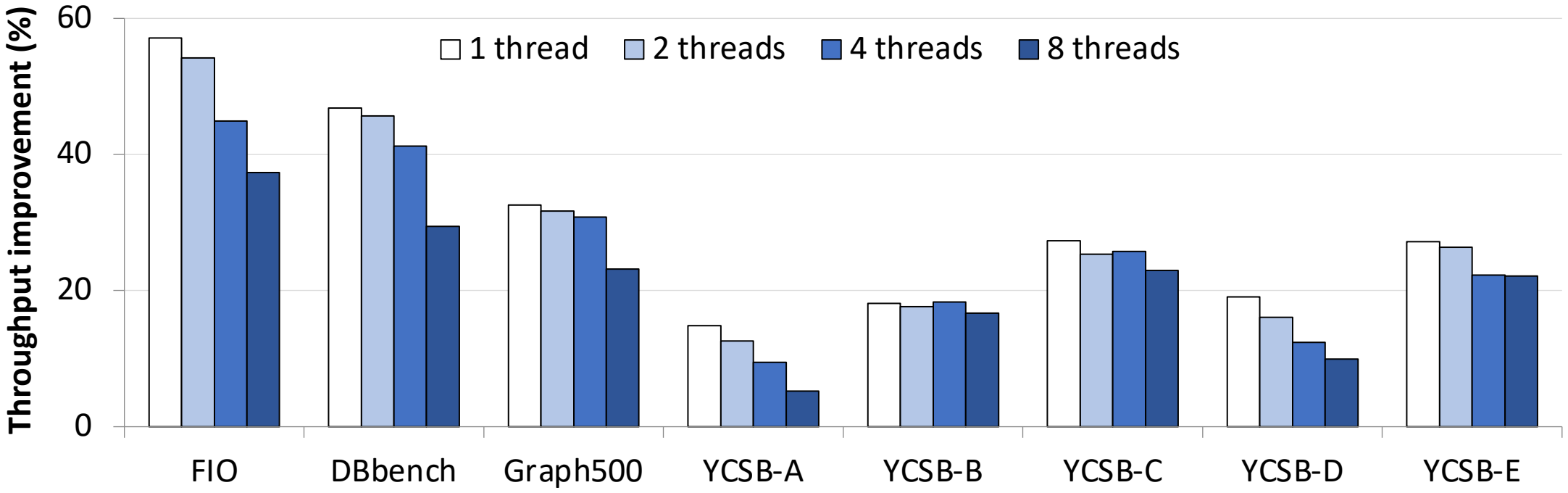
Page Miss Analysis

- SMU prototyping using full system simulation
  - Gem5 simulator (ARM64) + Simple SSD 2.0 simulator (Samsung Z-SSD)
  - 각 컴포넌트별 세부 모델링/타이밍 시뮬레이션
  - I/O path overhead: 0.12 µs per 4KB I/O (= 8M IOPS)
    - Cf. Linux kernel: 9 µs per 4KB I/O (= 111K IOPS)



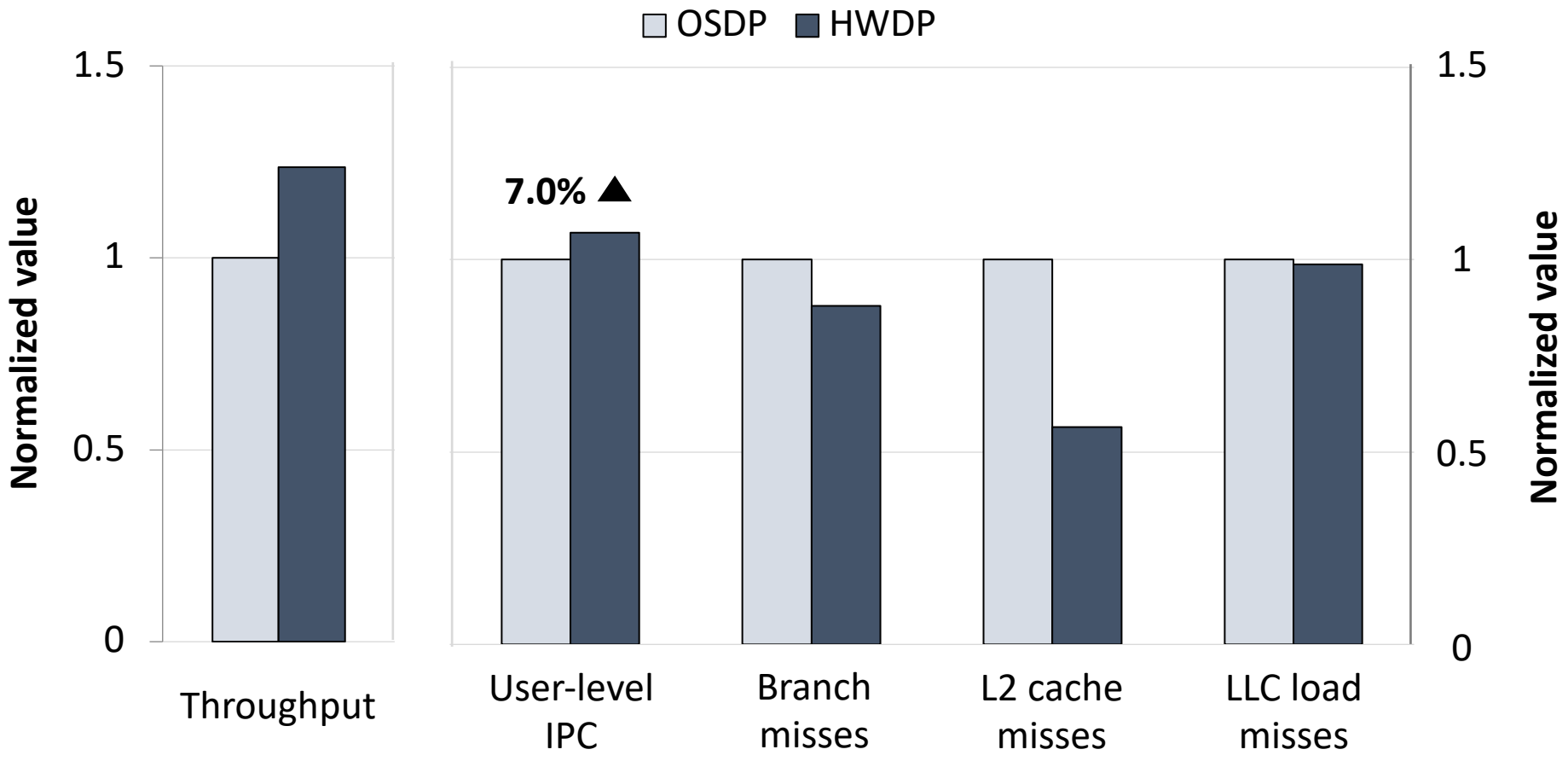
End-to-End Performance

- SMU prototyping using SW emulation on x86
  - Synthetic benchmark (FIO, DBbench): 성능 최대 **57.1%** 향상 (FIO)
  - Cloud service benchmark (YCSB on RocksDB): 성능 최대 **27.3%** 향상 (YCSB-C)
  - Large-scale graph analytics (Graph500): 성능 최대 **32.6%** 향상



Architecture Resource Pollution

- Architectural resource pollution improvement
  - OS 개입 빈도 감소를 통해 CPU resource pollution 개선



Conclusion

- Scaling SSD performance is exposing performance inefficiency in traditional software stack
- A case for hardware-based demand paging
  - New architectural extensions + OS supports
  - Page misses (mostly) handled in hardware
  - Fast demand paging performance + improved user-level IPC
  - Up to 27% throughput improvement in realistic workload (YCSB-C on RocksDB)

Q&A

- Thank you