CSC 252: Computer Organization
Spring 2018: Lecture 22

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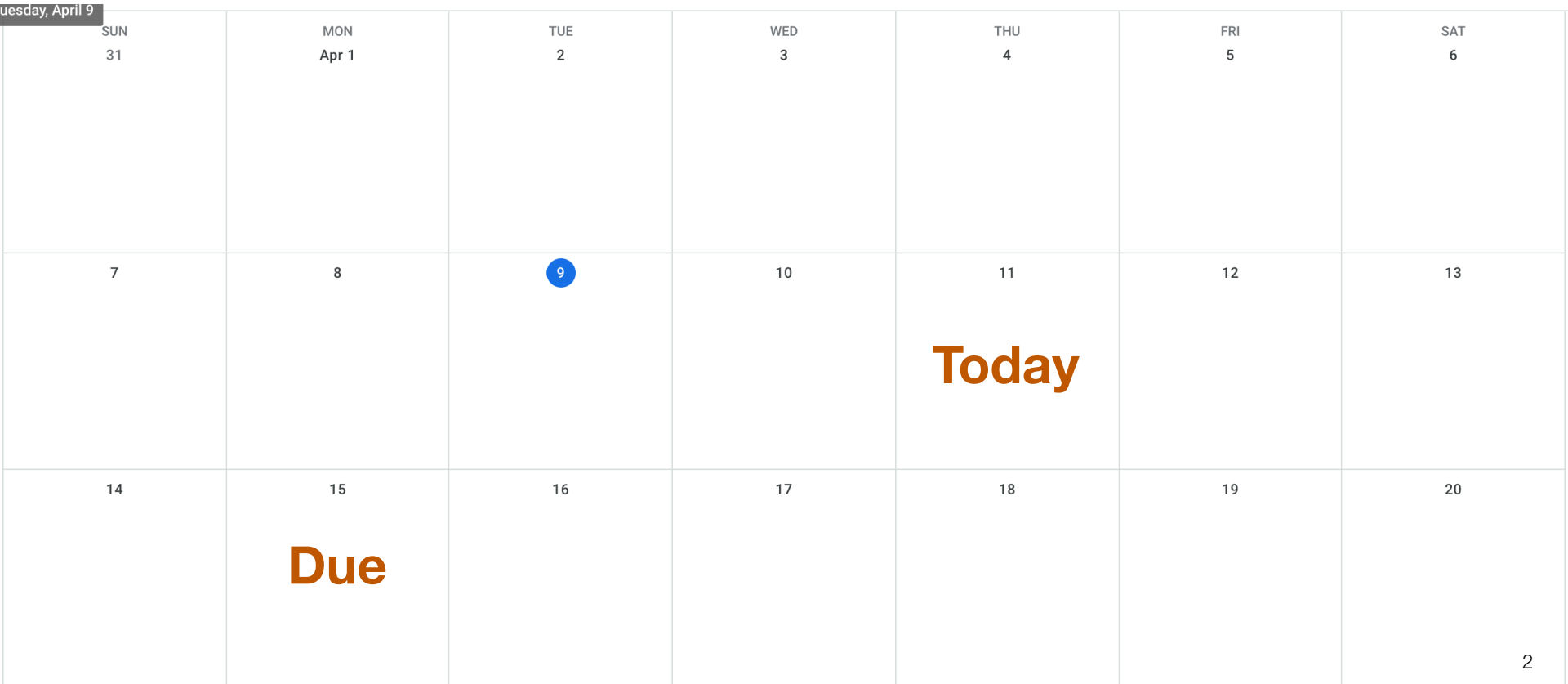
University of Rochester

Action Items:

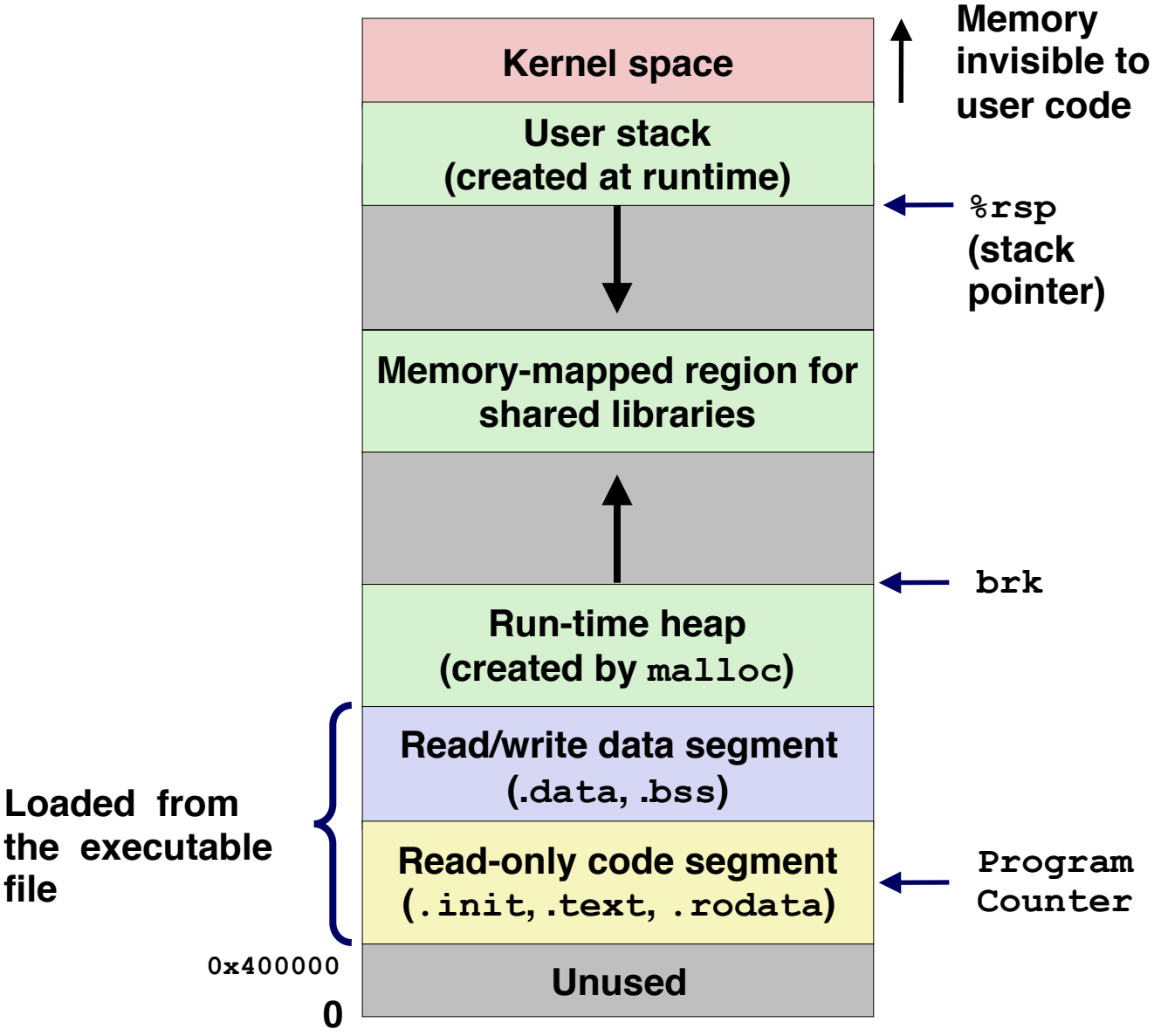
- **Programming Assignment 5 is out**

Announcement

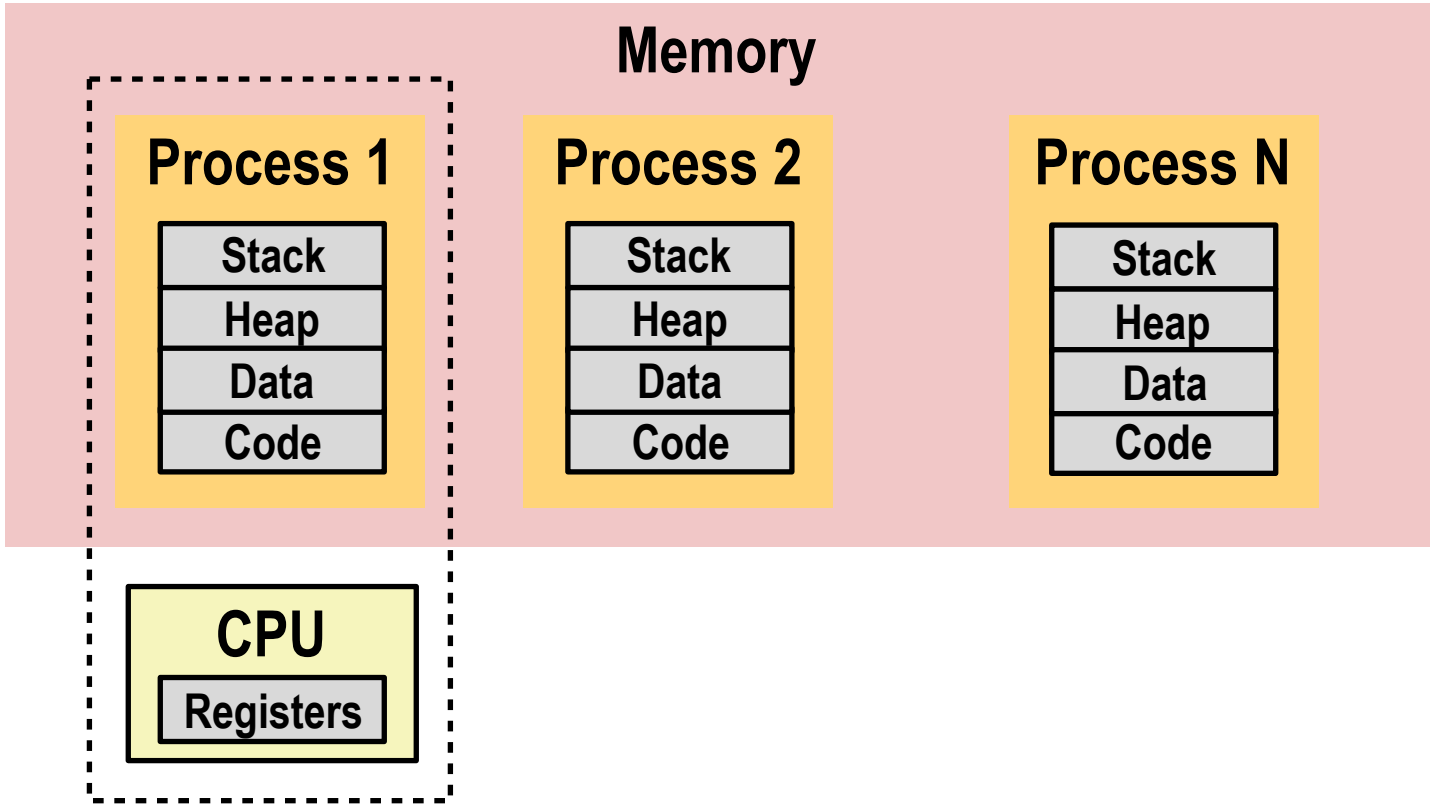
- Programming Assignment 5 is due 11:59pm, Monday, April 15.
- Your shell should emit output that is identical to the reference solution (except the PID). If you output does not match the reference solution, you get a 0. **NO exceptions will be made.**



Process Address Space



Multiprocessing Illustration



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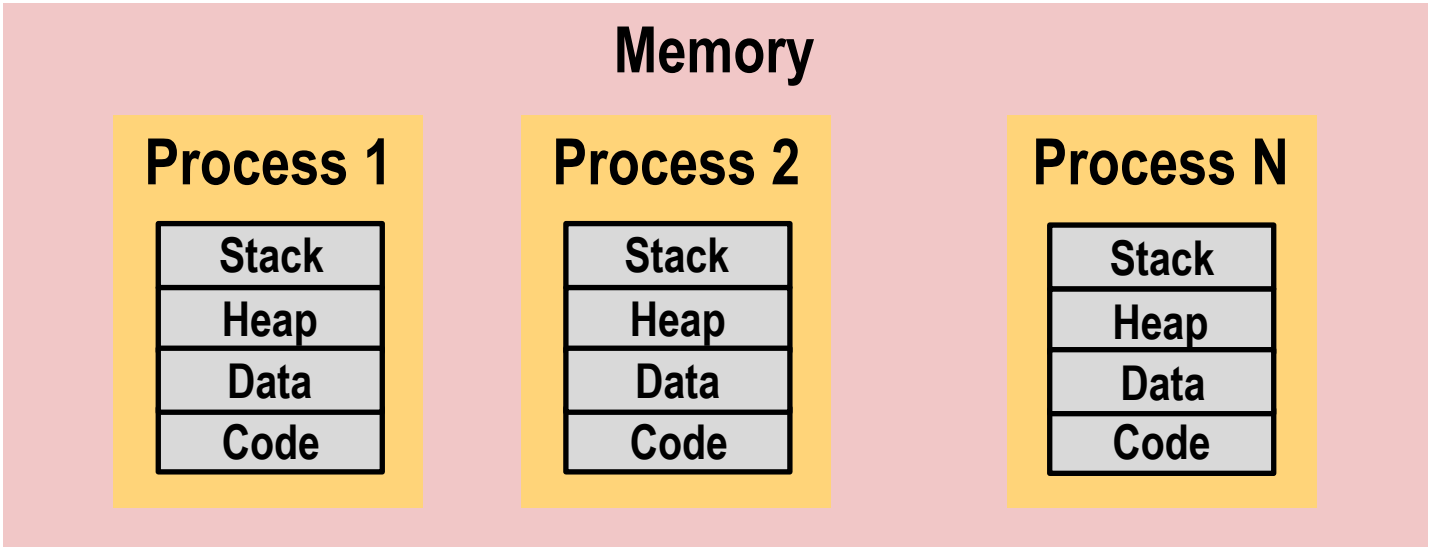

- Space:
  - Each process's address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
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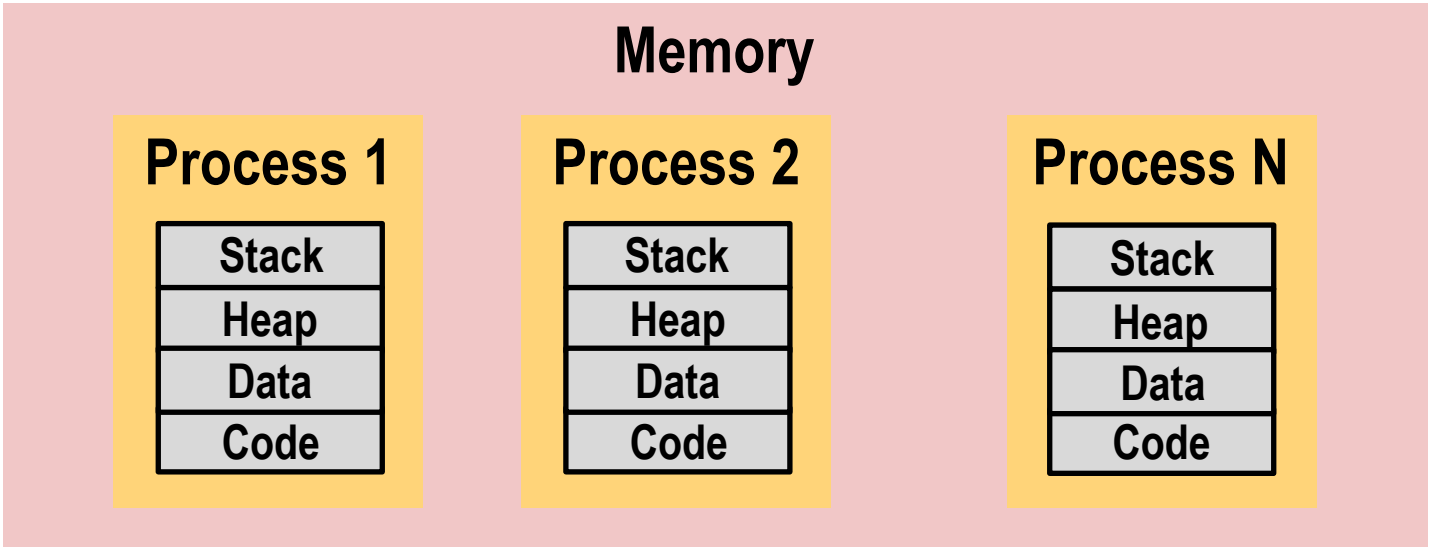

- Space:
  - Each process's address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
  - There are multiple processes, increasing the overhead further
- Solution: store all the data in disk, and use memory only for most recently used data
  - Does this sound similar?

The Big Idea: Virtual Memory

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- What Does a Programmer Want?

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- Infinitely large, infinitely fast memory
  - Preferably automatically moved to where it is needed

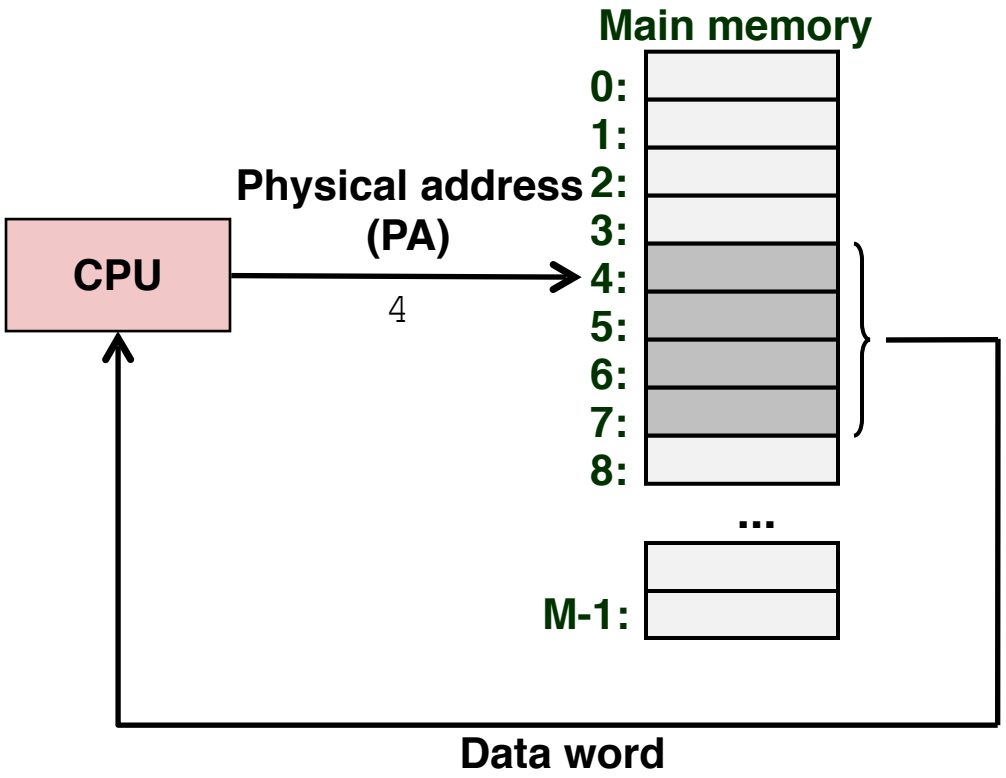
The Big Idea: Virtual Memory

- What Does a Programmer Want?
- Infinitely large, infinitely fast memory
  - Preferably automatically moved to where it is needed
- Virtual memory to the rescue
  - Present a large, uniform memory to programmers
  - Data in virtual memory by default stays in disk
  - Data moves to physical memory (DRAM) "**on demand**"
  - Disks (~TBs) are much larger than DRAM (~GBs), but 10,000x slower.
  - Effectively, virtual memory system transparently share the physical memory across different processes
  - Manage the sharing automatically: hardware-software collaborative strategy (too complex for hardware alone)

Today

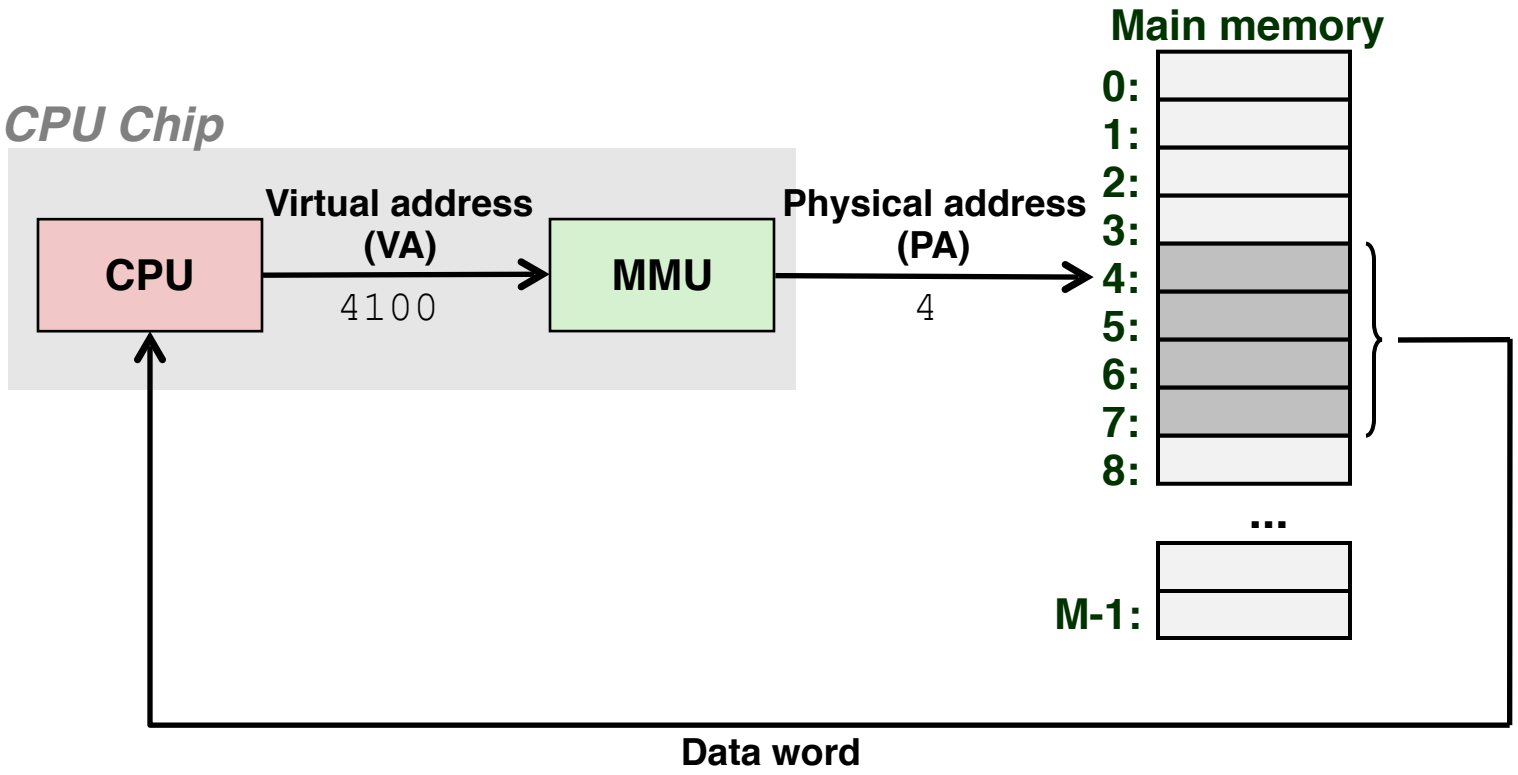
- Virtual memory (VM) illustration
- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

A System Using Physical Addressing



- Used in “simple” systems like embedded microcontrollers in devices like cars, elevators, and digital picture frames

A System Using Virtual Addressing



- Used in all modern servers, laptops, and smart phones
- One of the great ideas in computer science
- MMU: Memory Management Unit

Address Spaces

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- Virtual address space: Set of N = 2^n virtual addresses
  - Virtual address space is a linear address space, but limited

    {0, 1, 2, 3, …, N-1}

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- Physical address space: Set of $M = 2^m$ physical addresses
  - Physical address space is a also linear address space, but smaller than virtual address space

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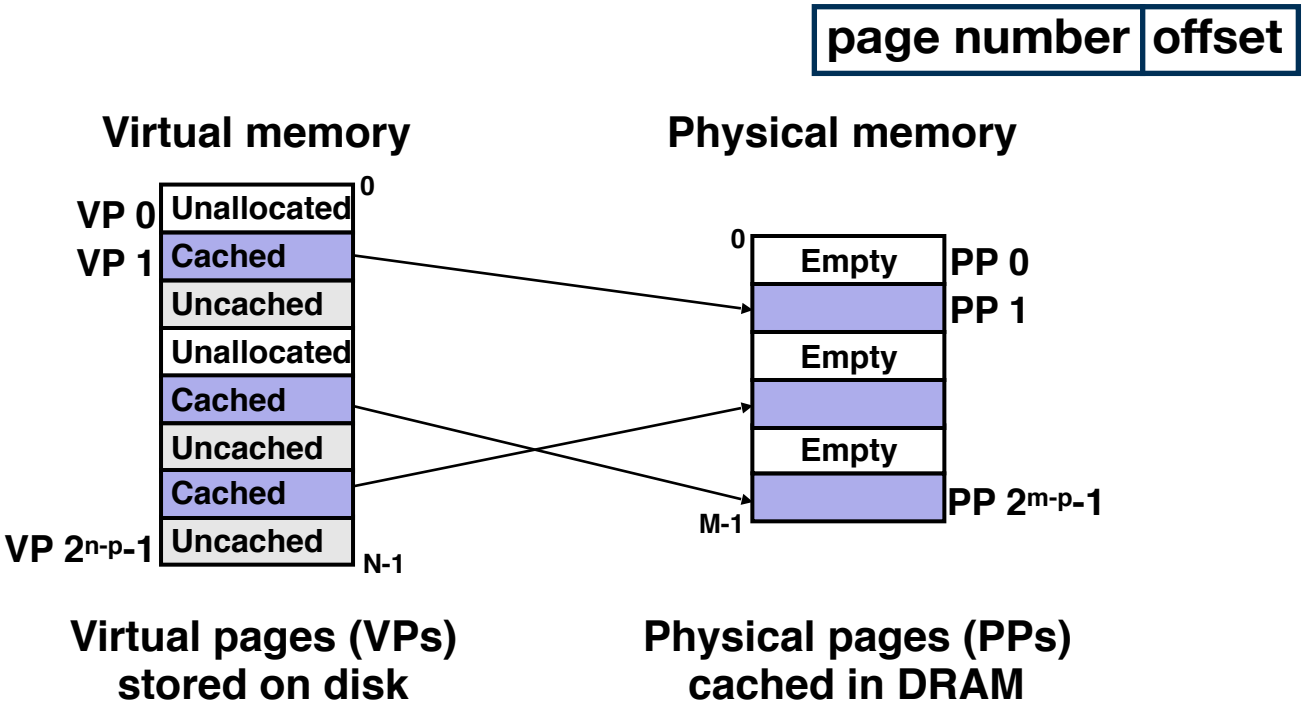
VM Concepts

- Conceptually, *virtual memory* is an array of N contiguous blocks stored on disk.
- The contents of the array on disk are “cached" in *physical memory*
- These blocks are called *pages* (size is P = 2^p bytes)



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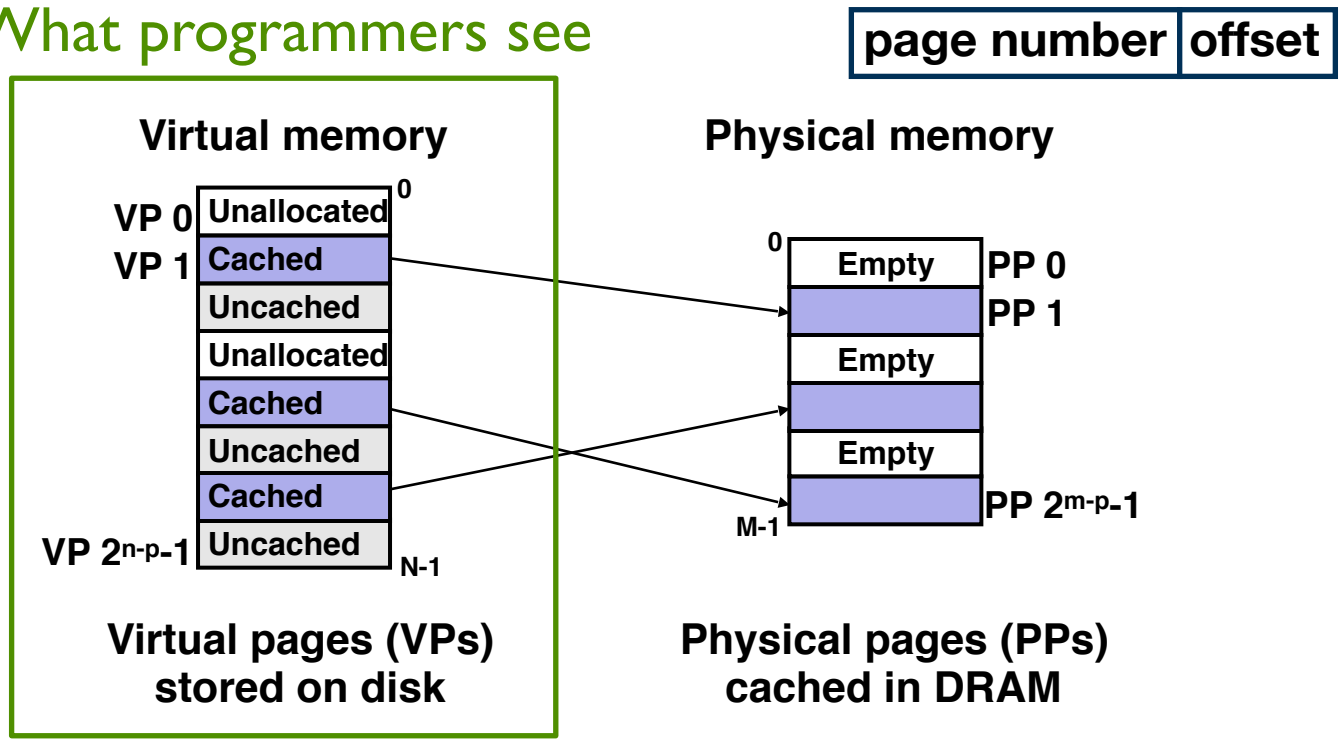

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- Call a hotel looking for a guest; what happens?
  - Front desk routes call to room, does not give out room number
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- Benefits
  - **Ease of management**: Guest could change rooms (physical address). You can still find her without knowing it
  - **Protection**: Guest could have block on calls, block on calls from specific callers (permissions)
  - **Sharing**: Multiple guests (virtual addresses) can share the same room (physical address)

Different Names in Different Places

Symbolic
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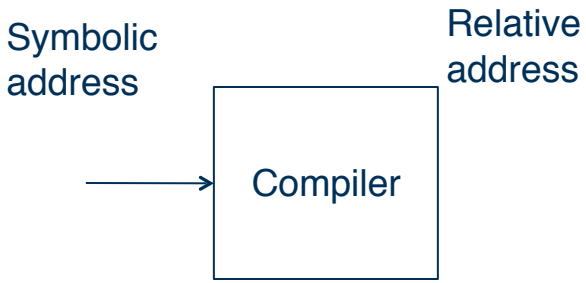

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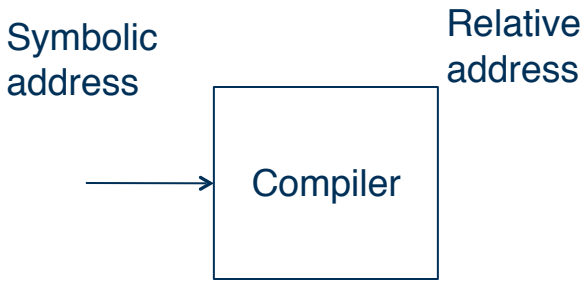

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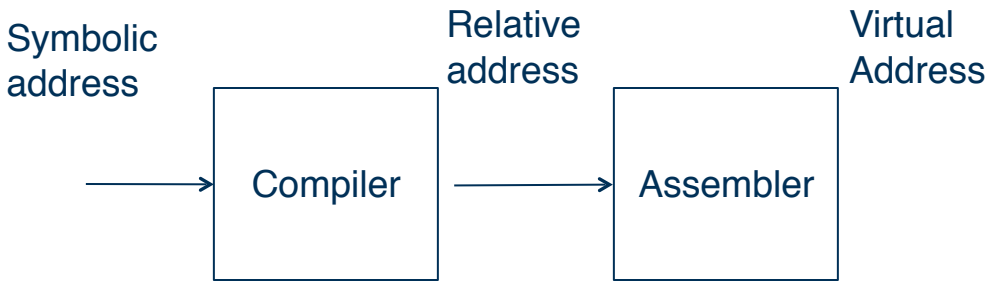

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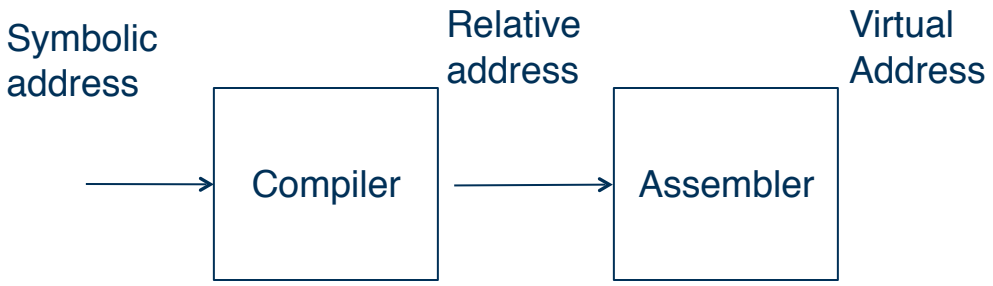

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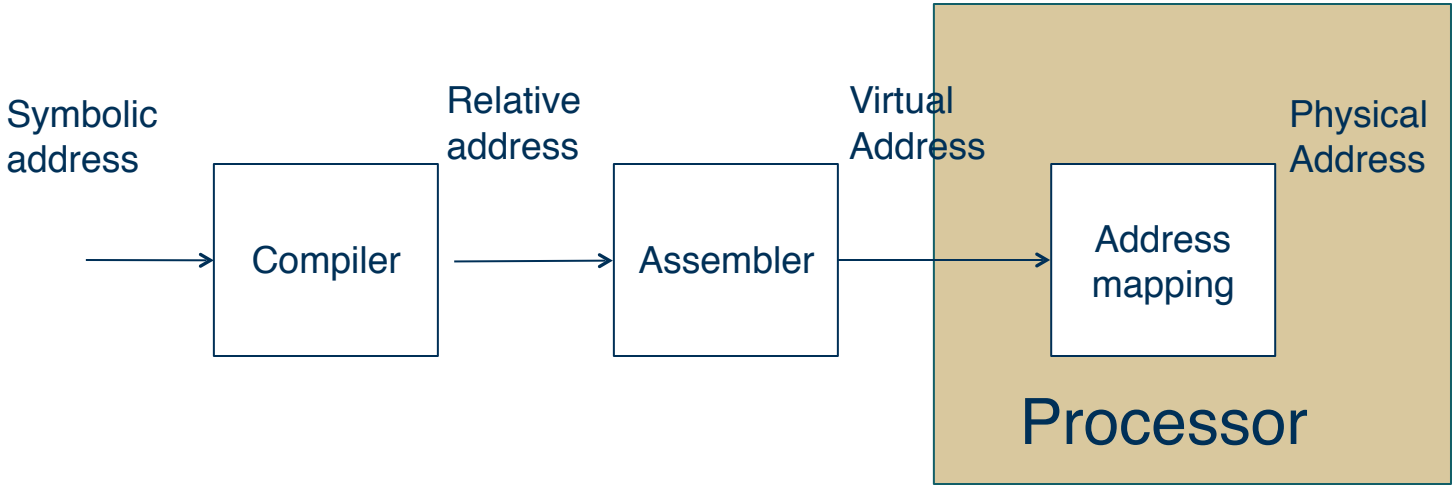

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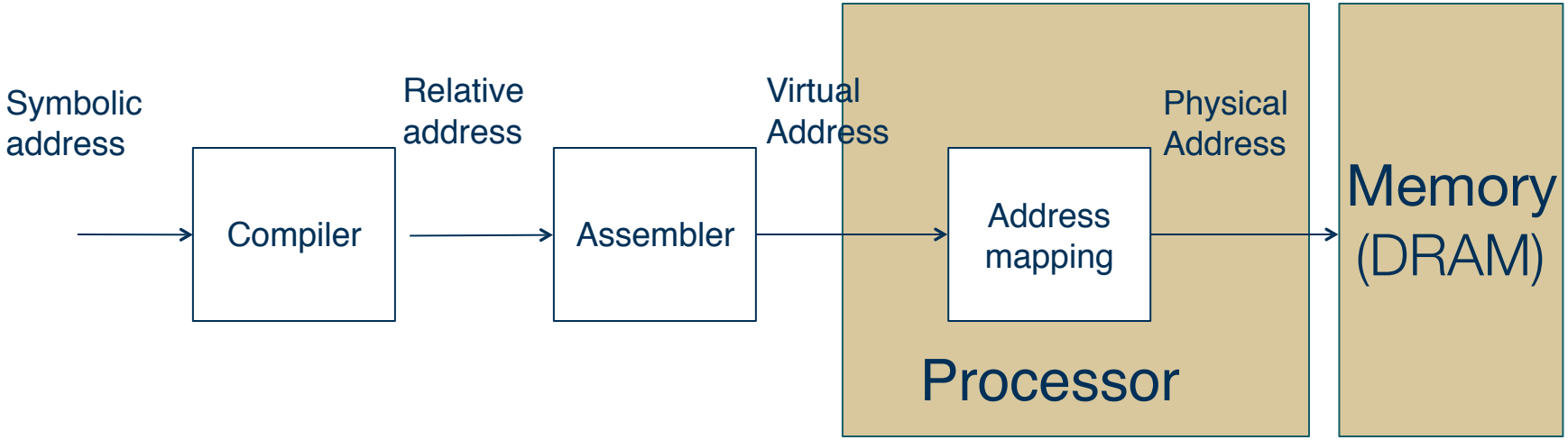

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  - Per-process data structure; managed by the OS kernel

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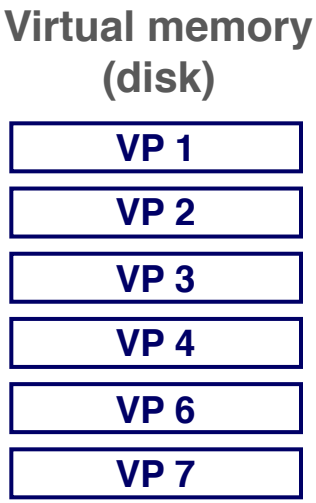

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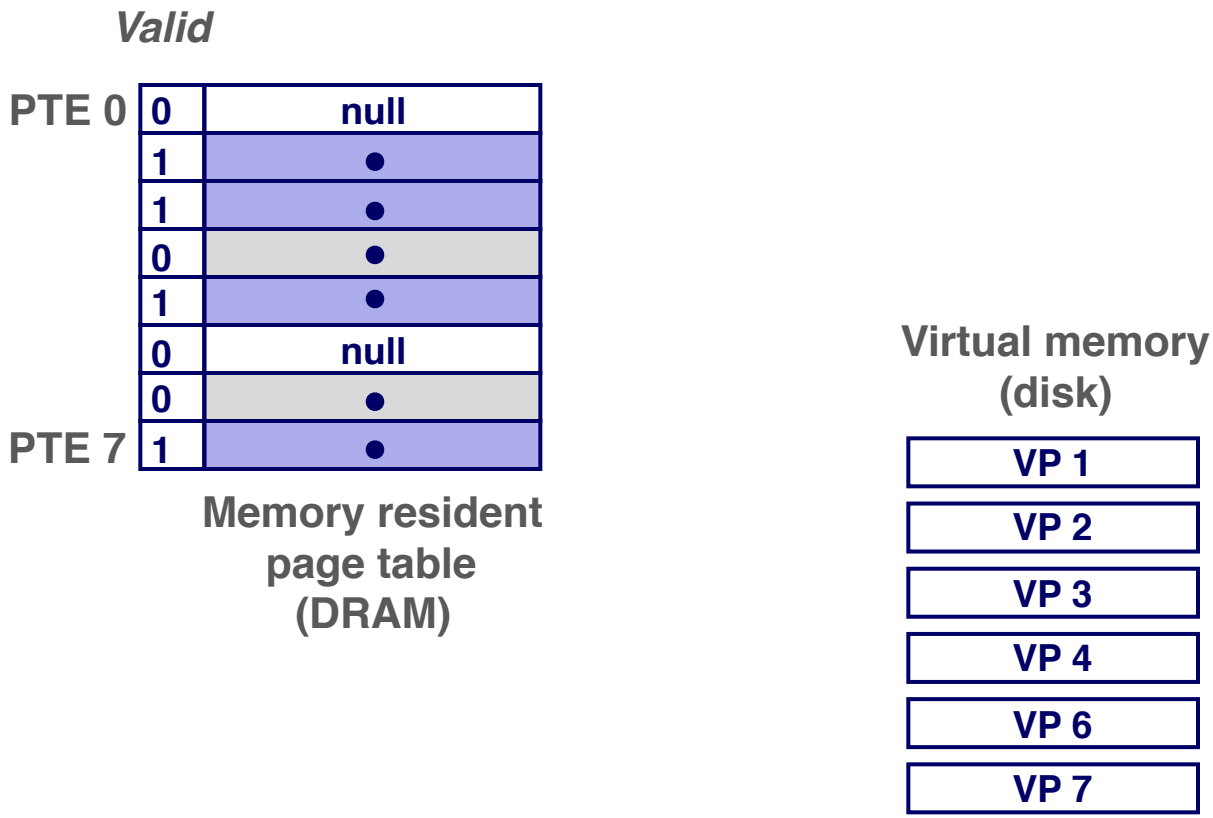

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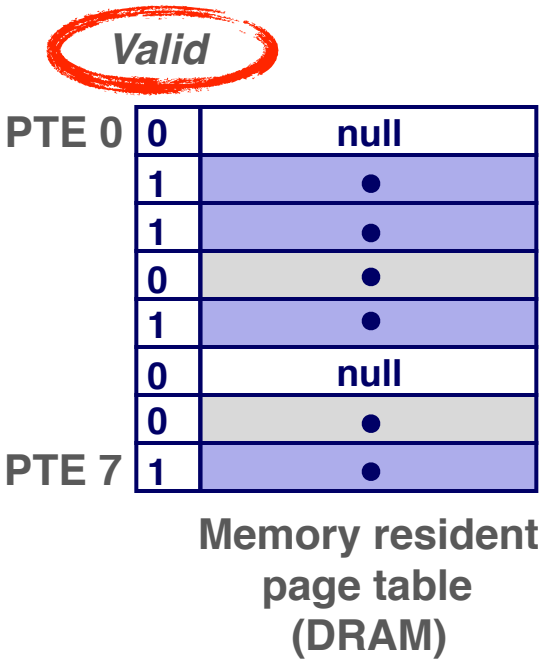

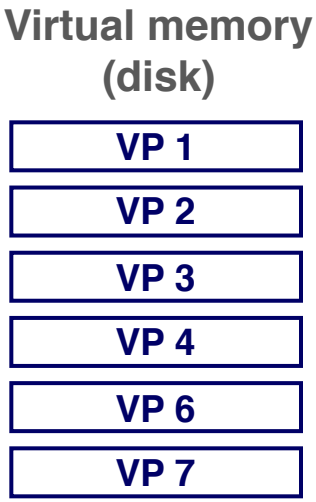

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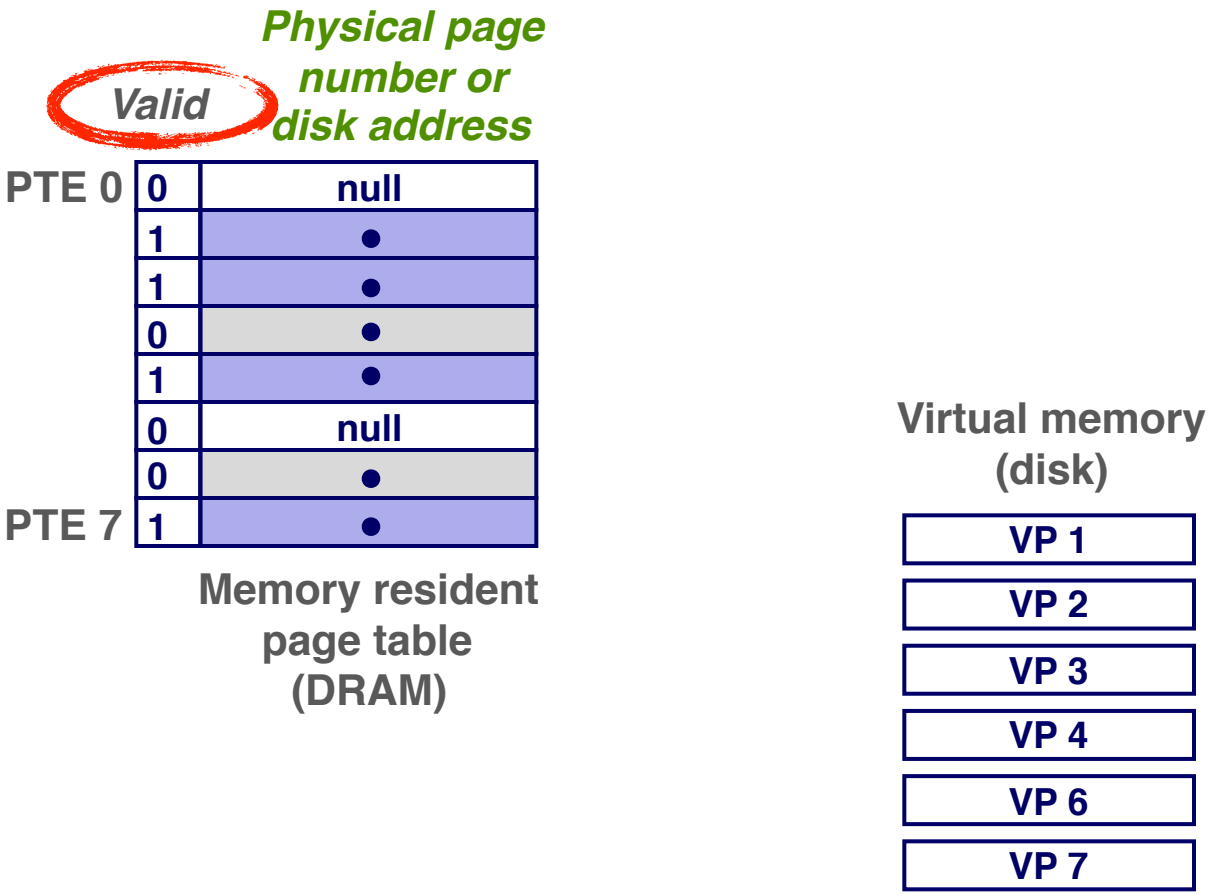

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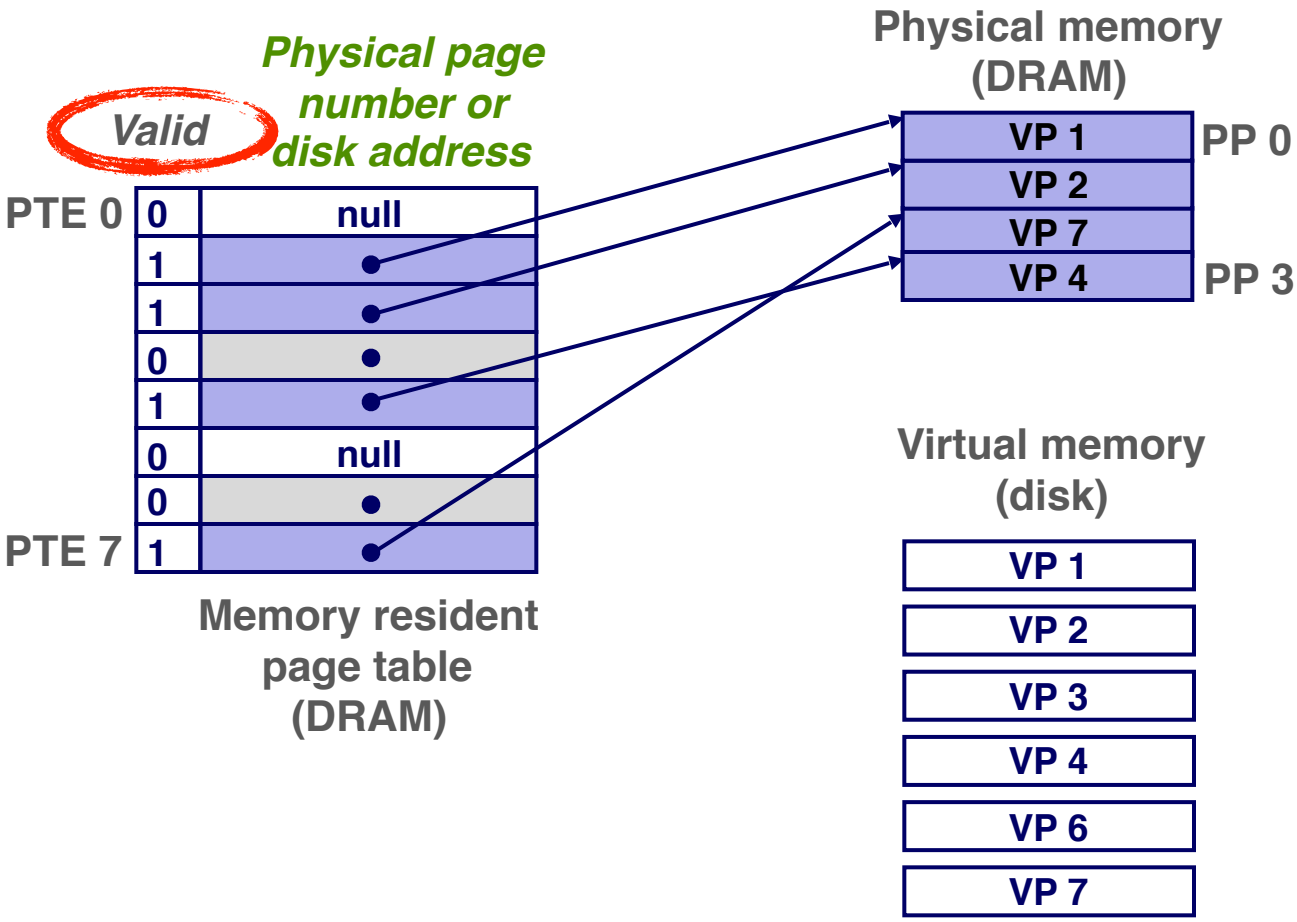

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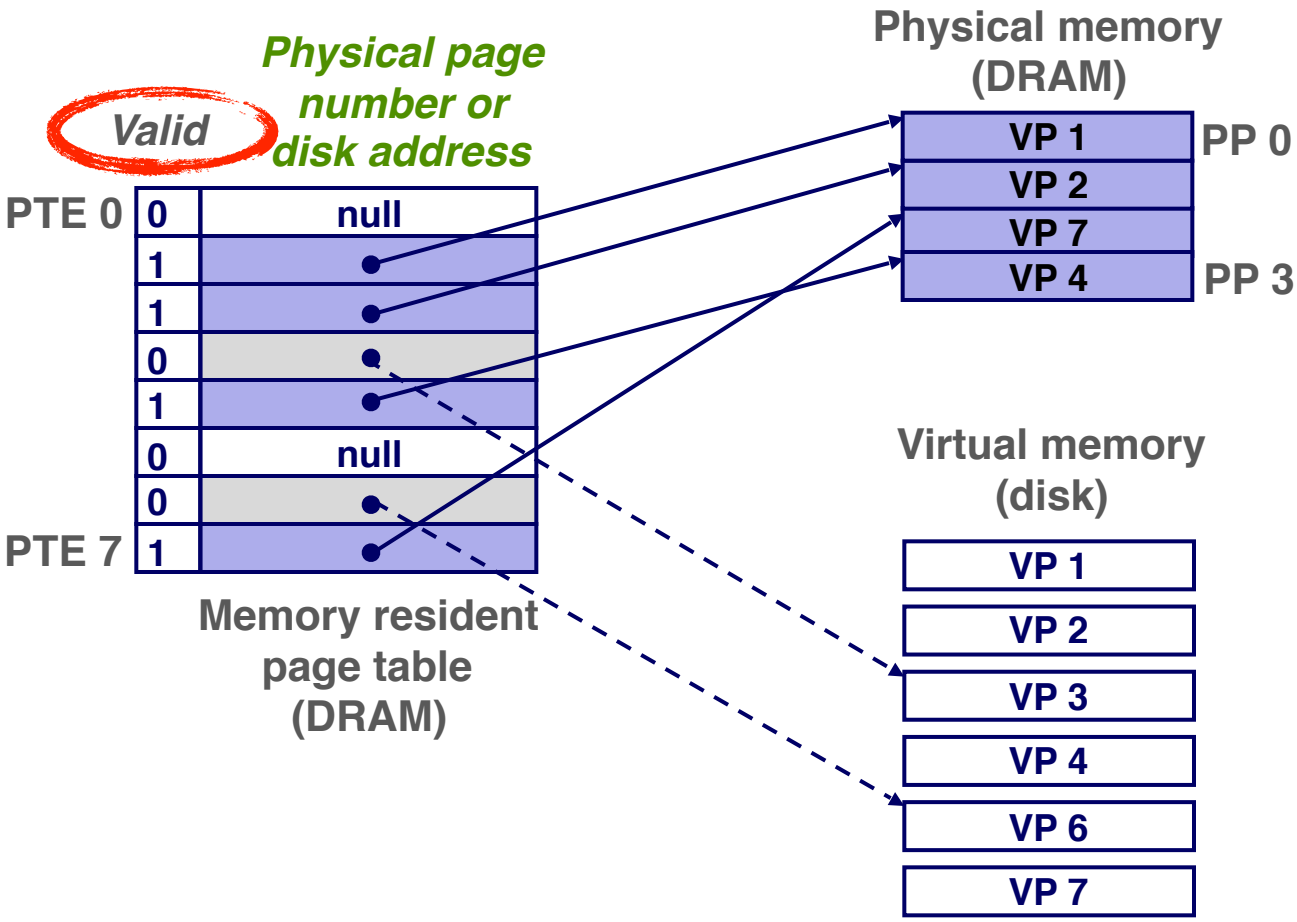

Page Hit

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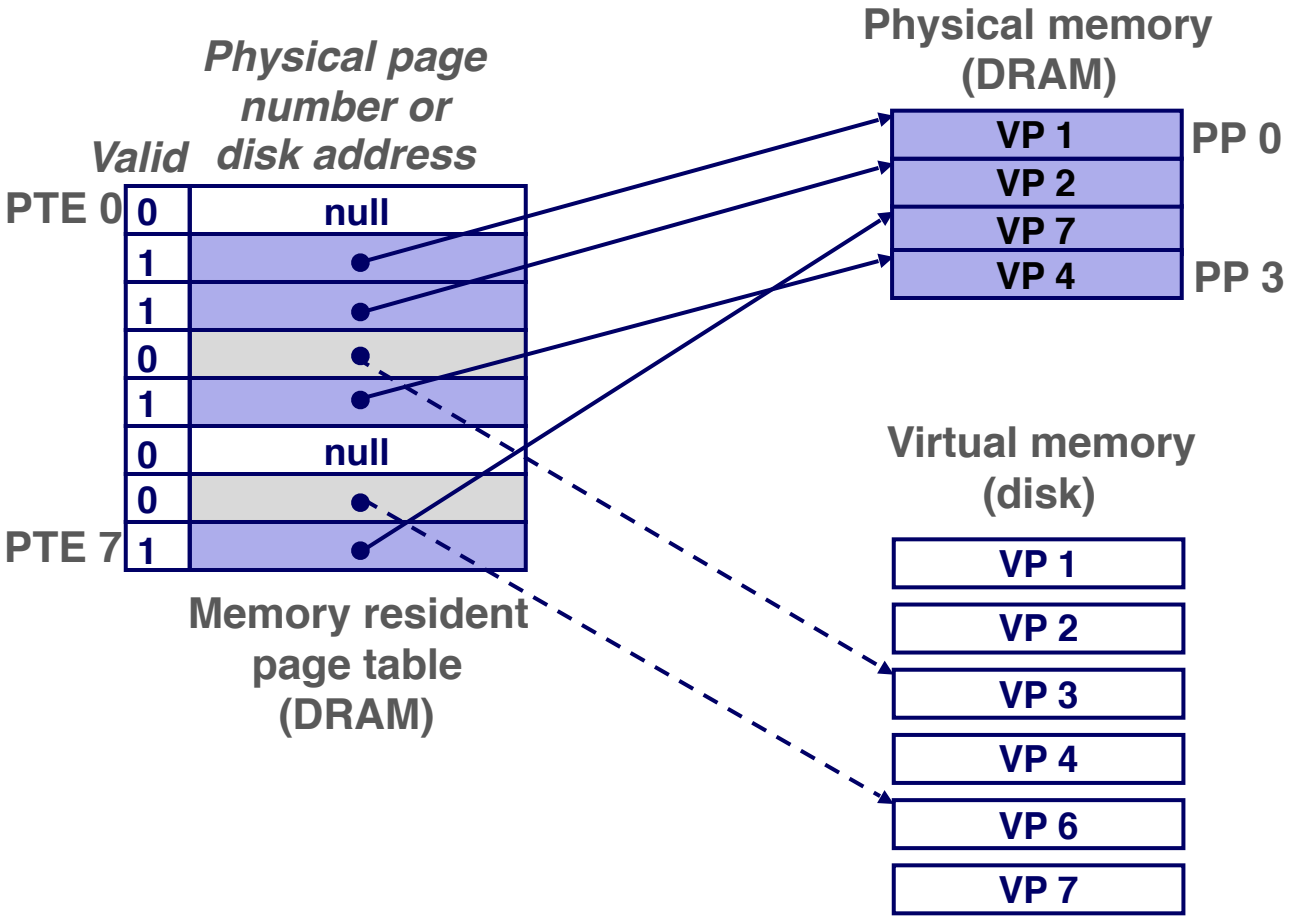

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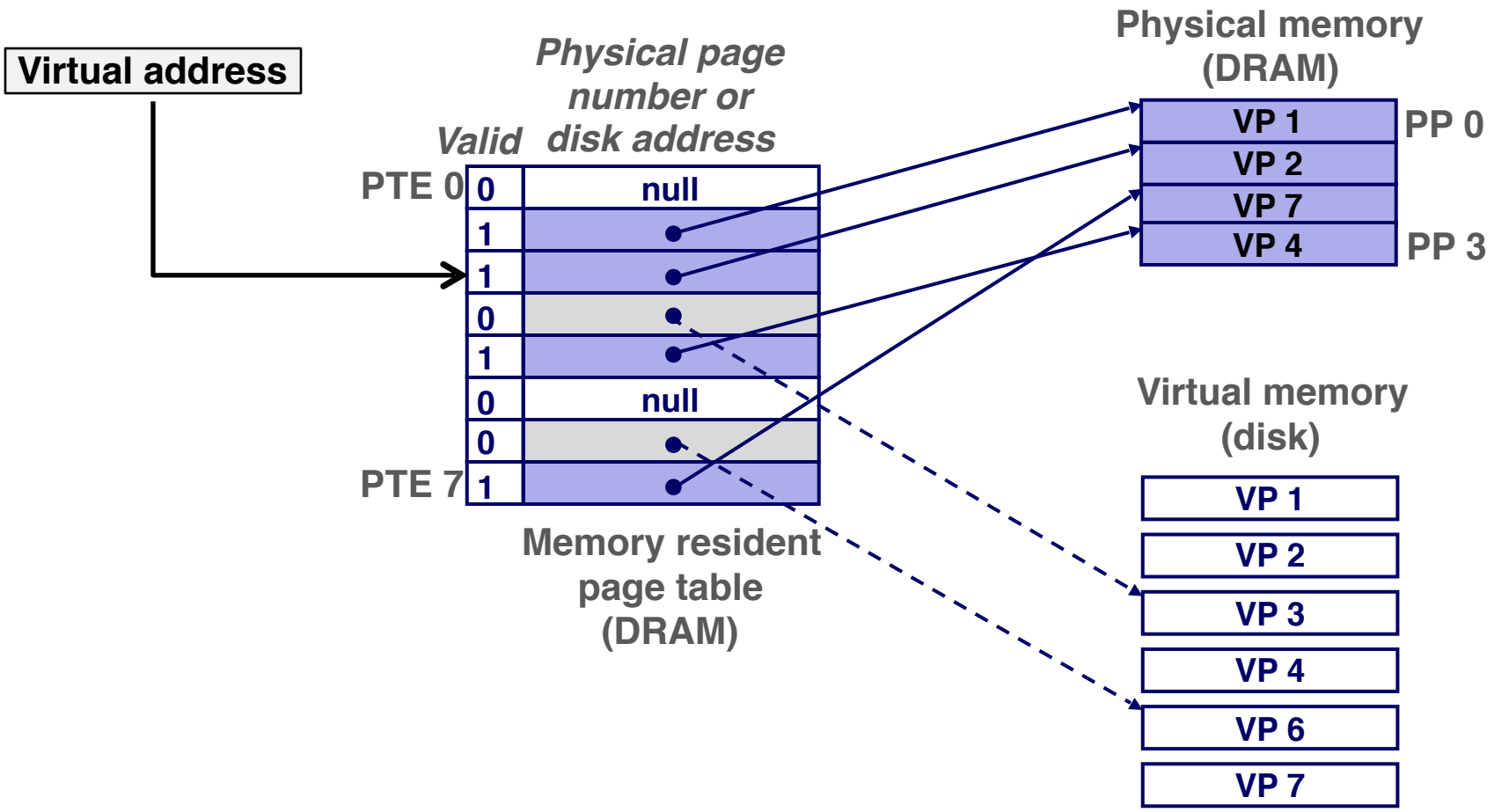

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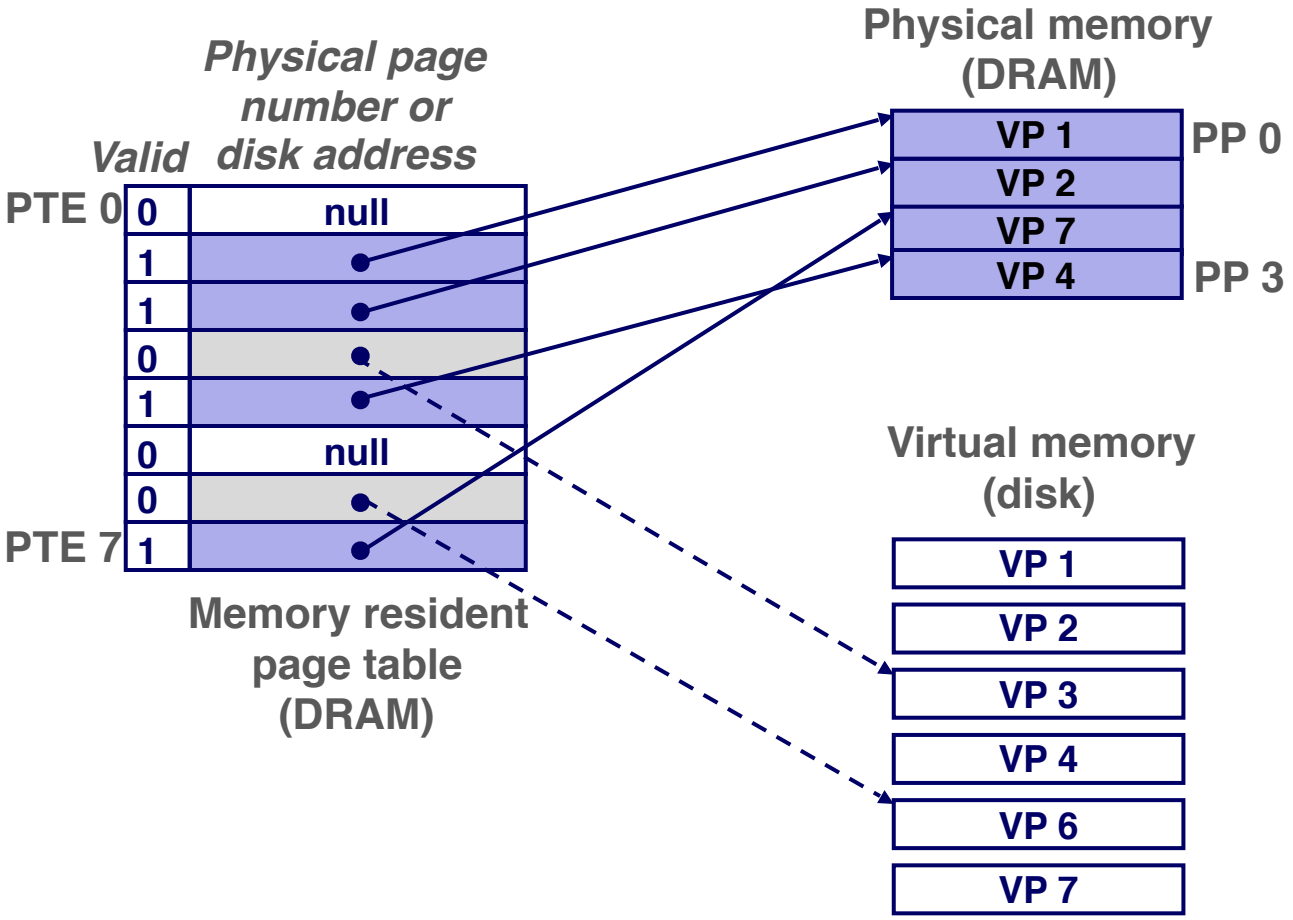

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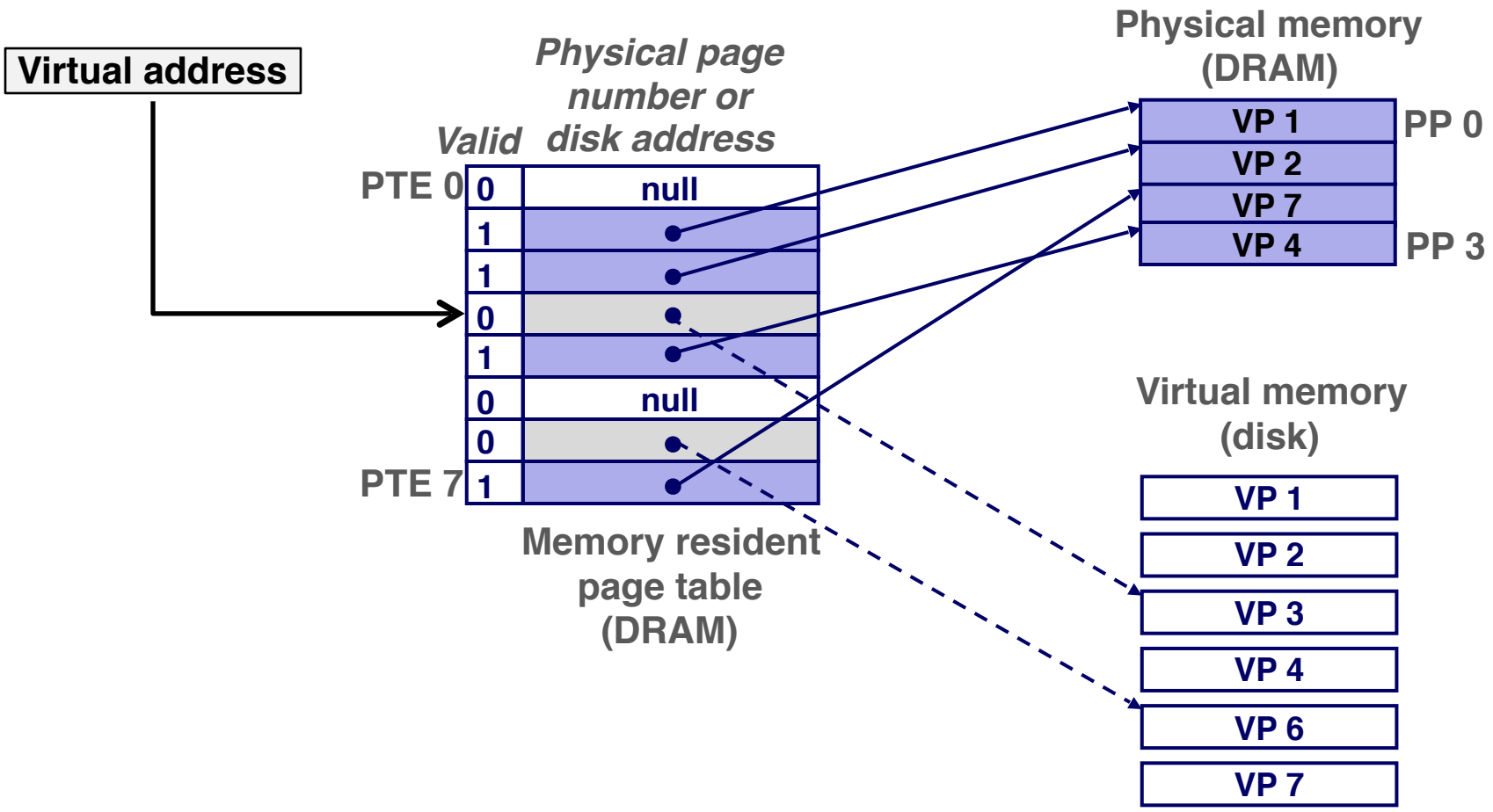
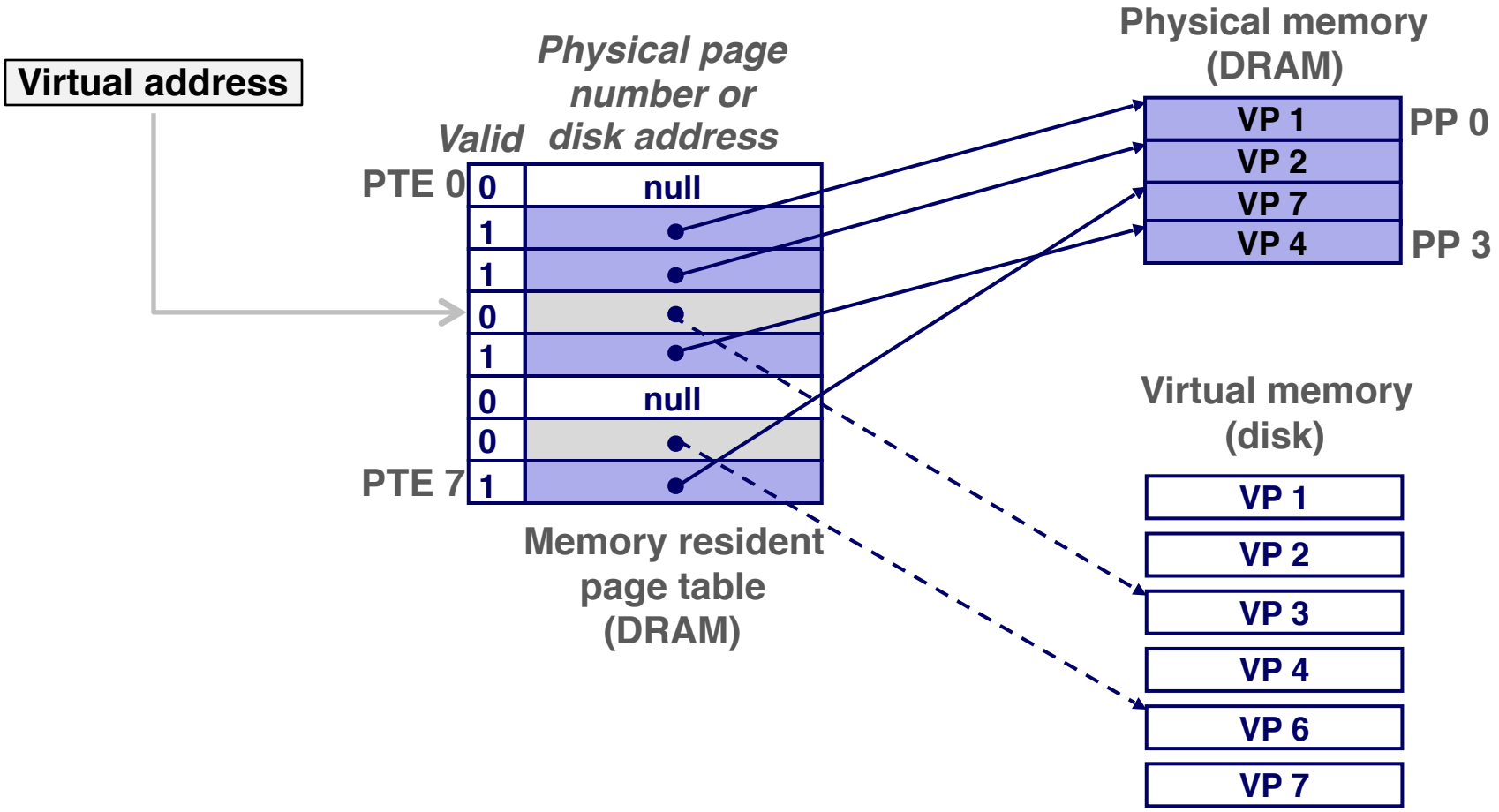


Handling Page Fault

- Page miss causes page fault (an exception)



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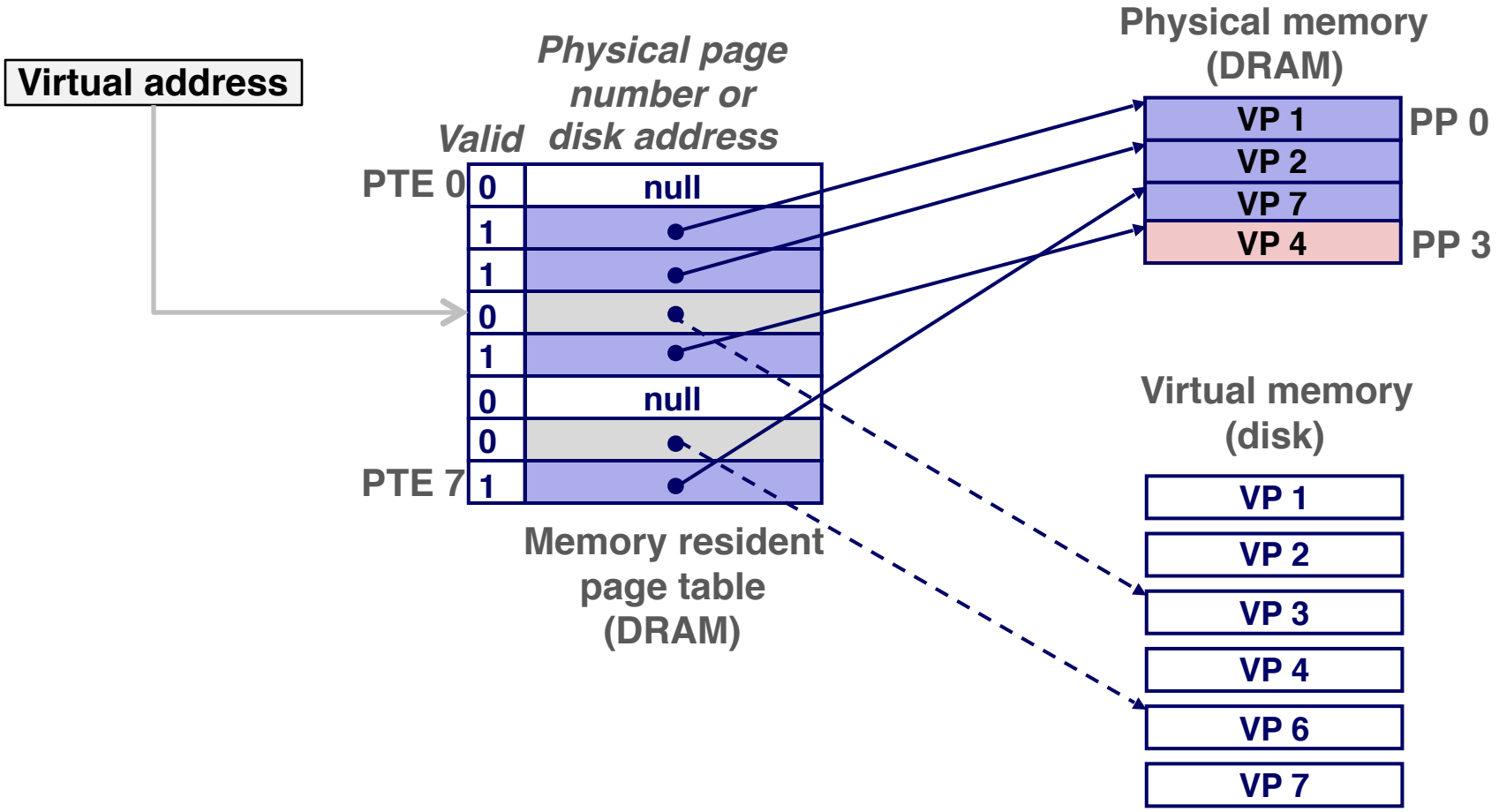

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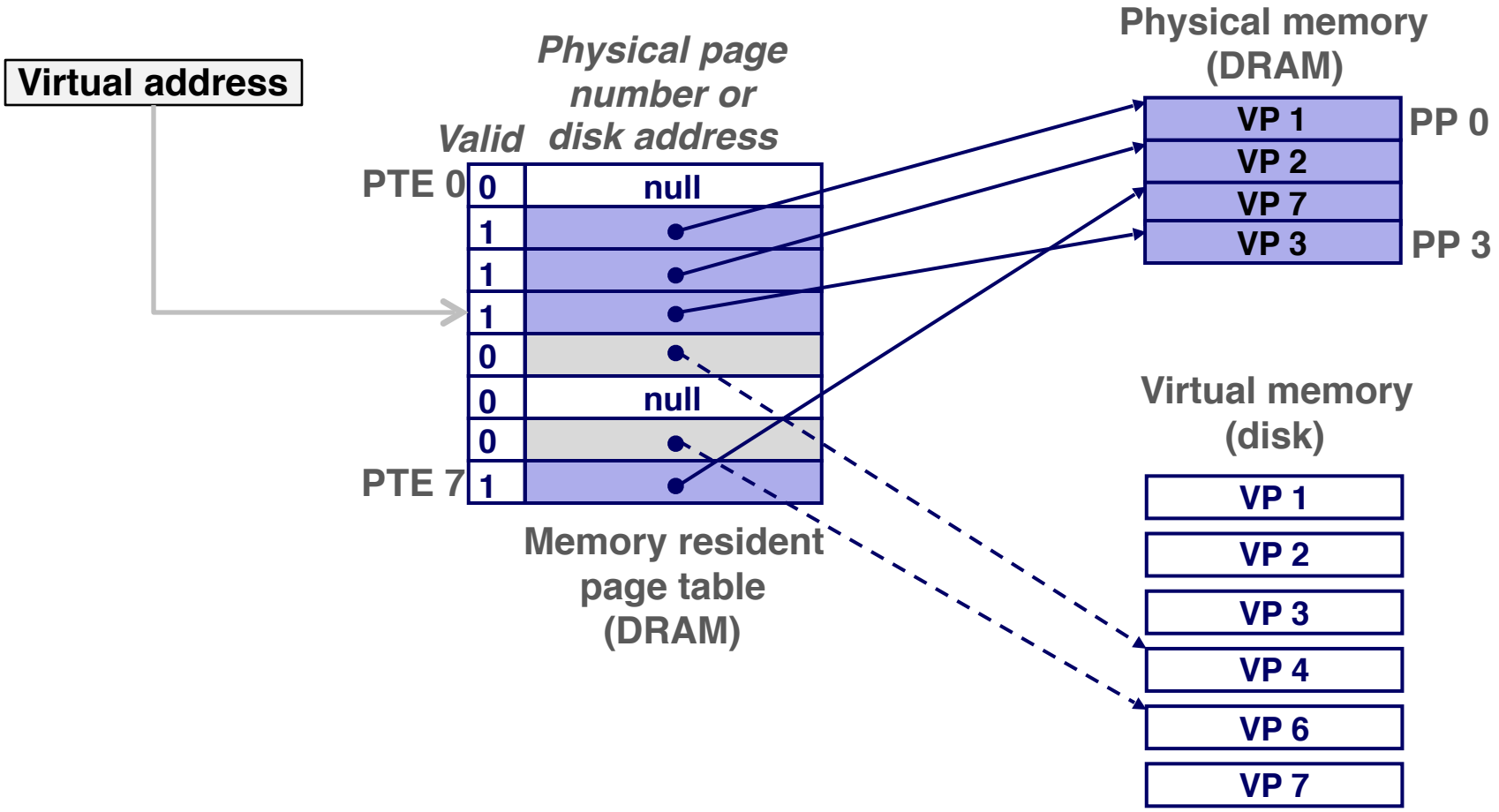

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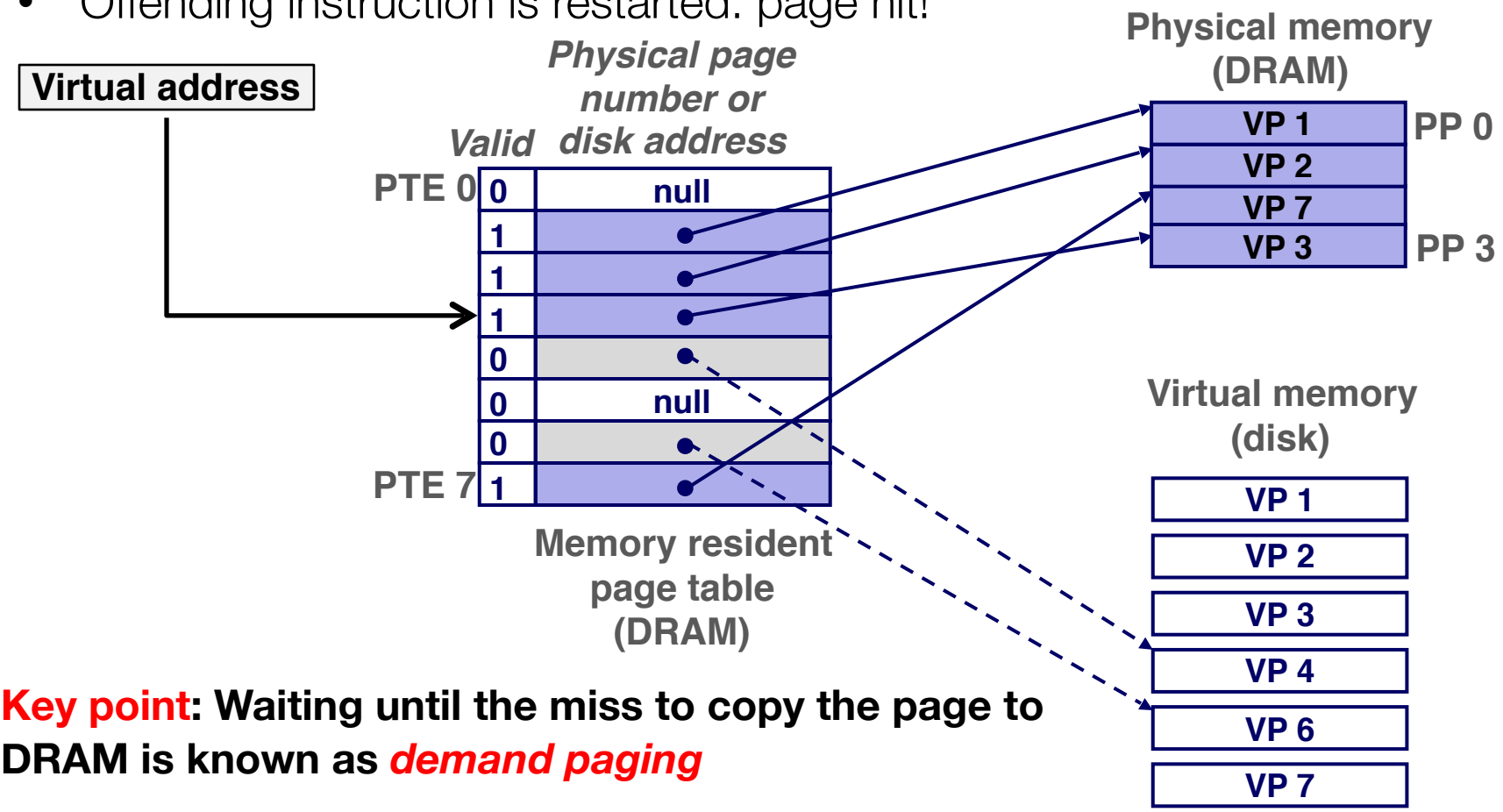
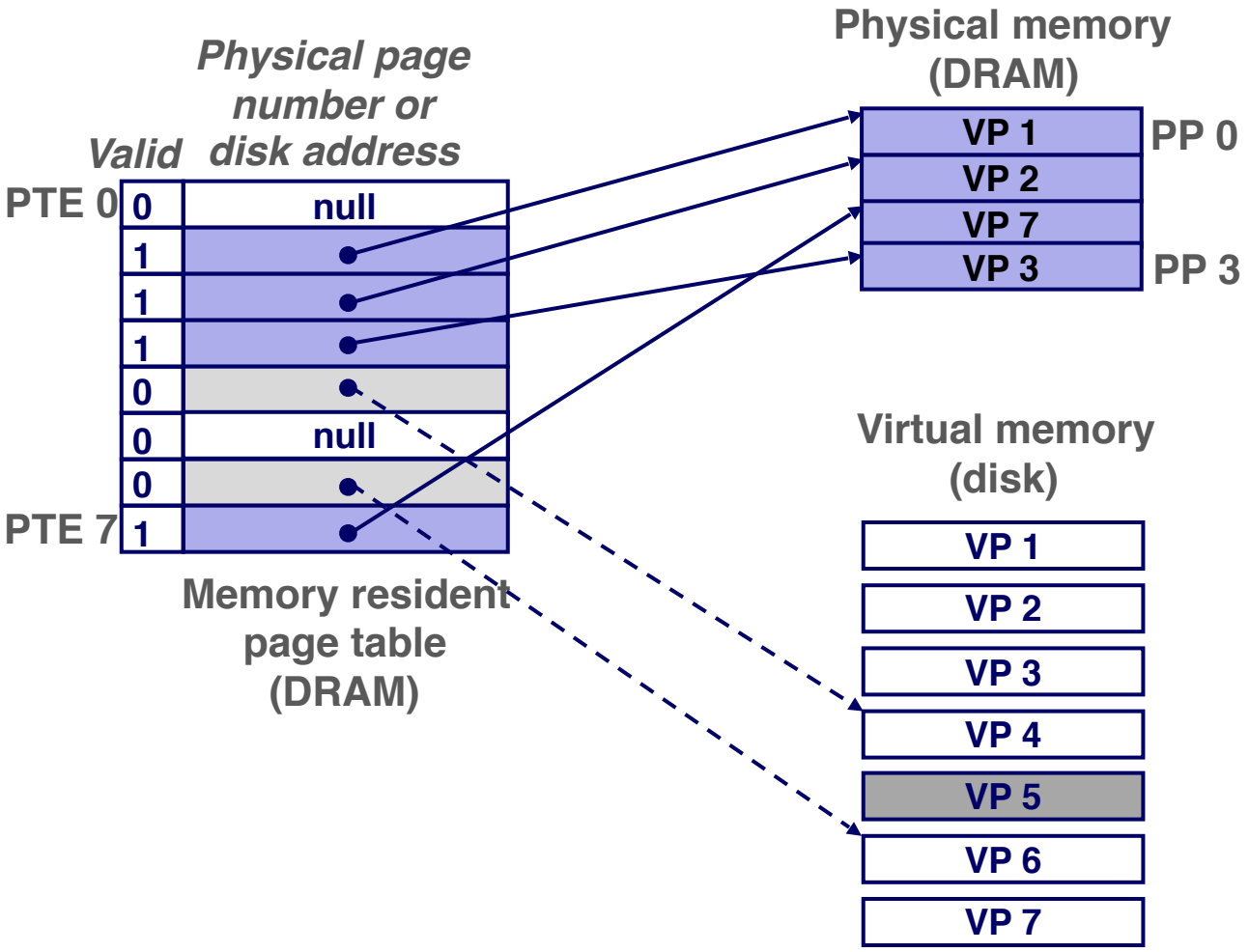
- Offending instruction is restarted: page hit!



Key point: Waiting until the miss to copy the page to DRAM is known as *demand paging*

Allocating Pages

- Allocating a new page (VP 5) of virtual memory.



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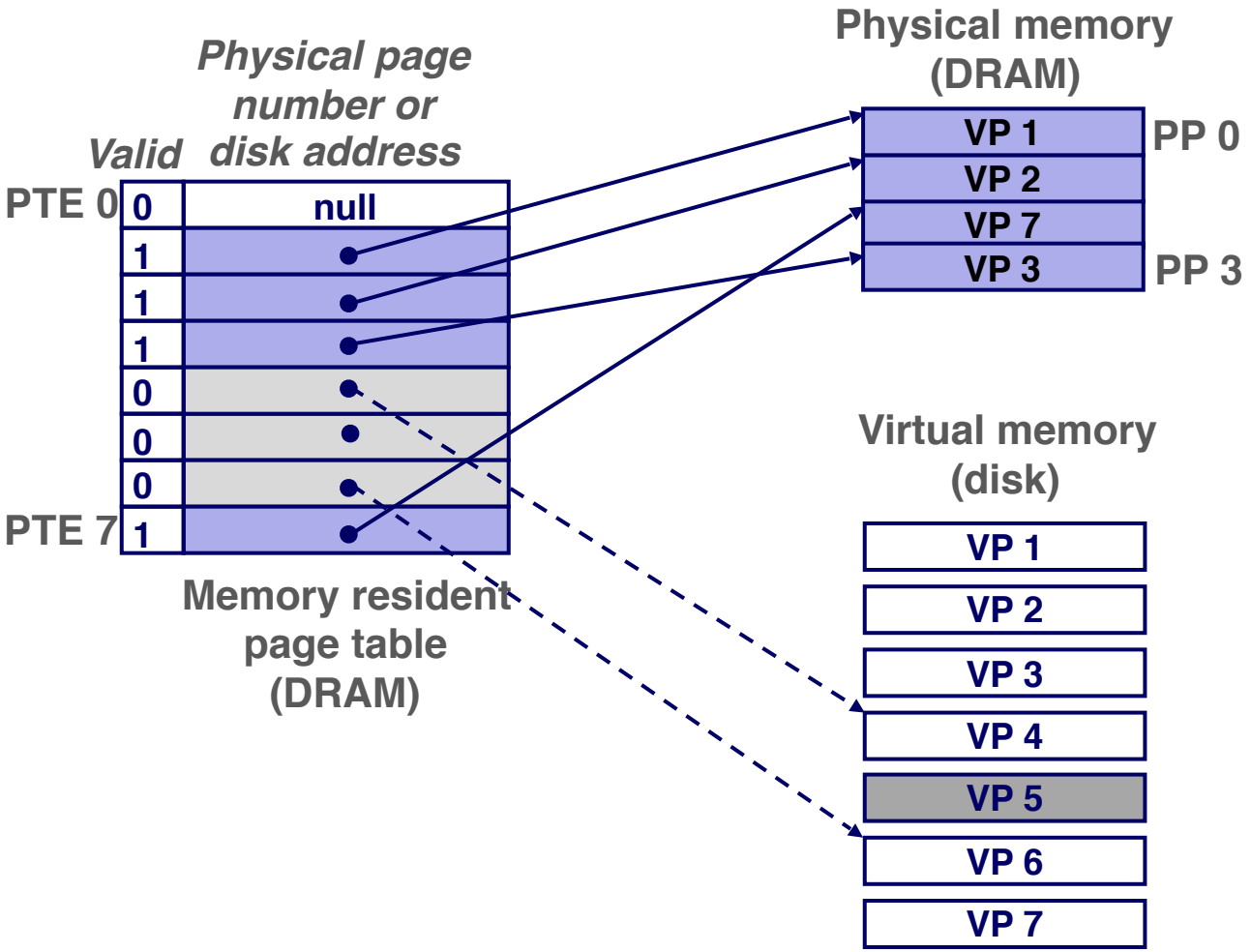

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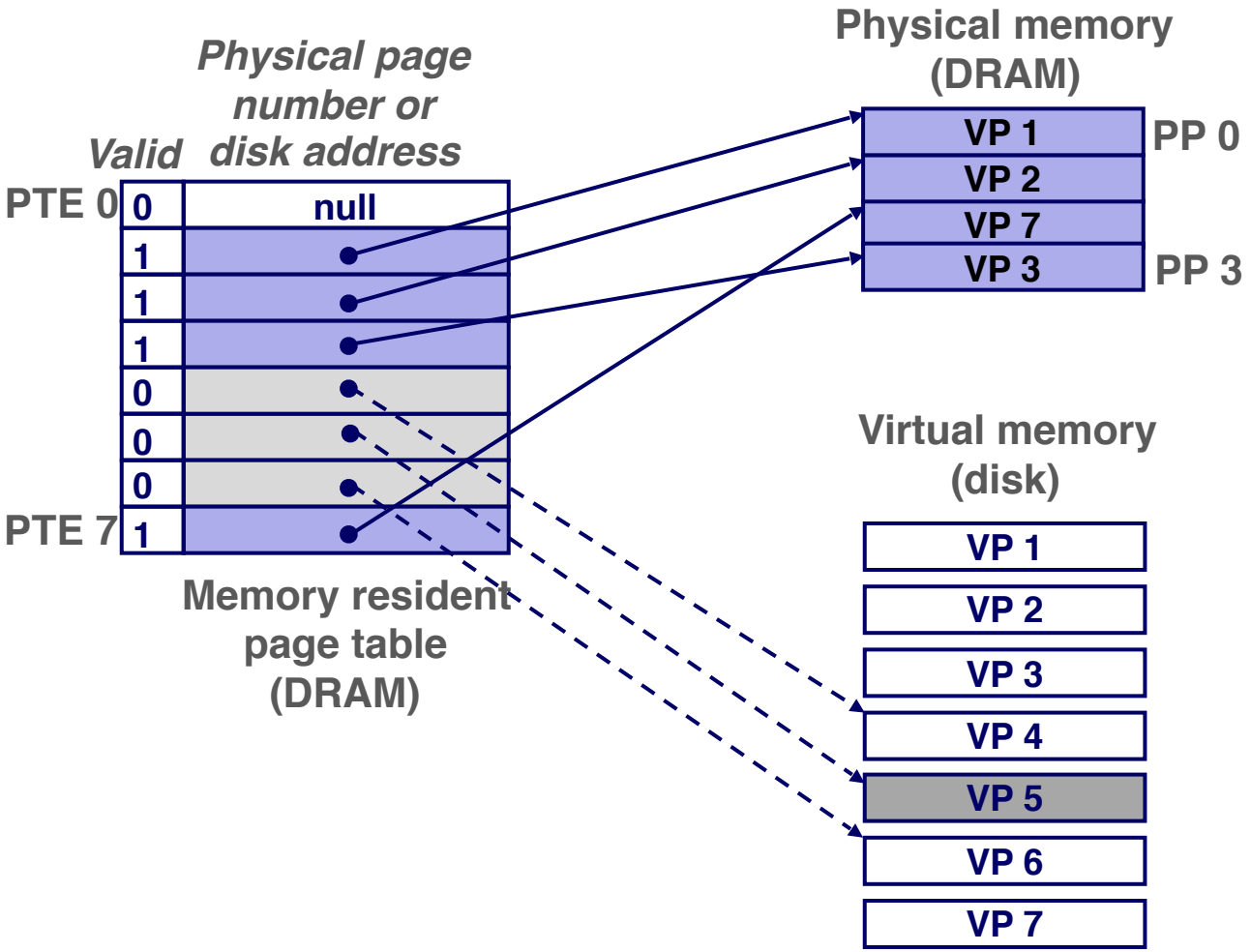

Virtual Memory Exploits Locality (Again!)

- Virtual memory seems terribly inefficient, but it works because of locality.

- At any point in time, programs tend to access a set of active virtual pages called the *working set*
  - Programs with better temporal locality will have smaller working sets

- If (working set size < main memory size)
  - Good performance for one process after initial misses

- If (SUM(working set sizes) > main memory size)
  - *Thrashing:* Performance meltdown where pages are swapped (copied) in and out continuously

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- Assume 4KB page, 4GB main memory, each PTE is 8 Bytes
  - 1M PTEs in a page table
  - 8MB total size per page table
  - Too big for on-chip SRAM
  - Too slow to access in disk
  - Put the page table in DRAM, with its start address stored in a special register (Page Table Base Register)

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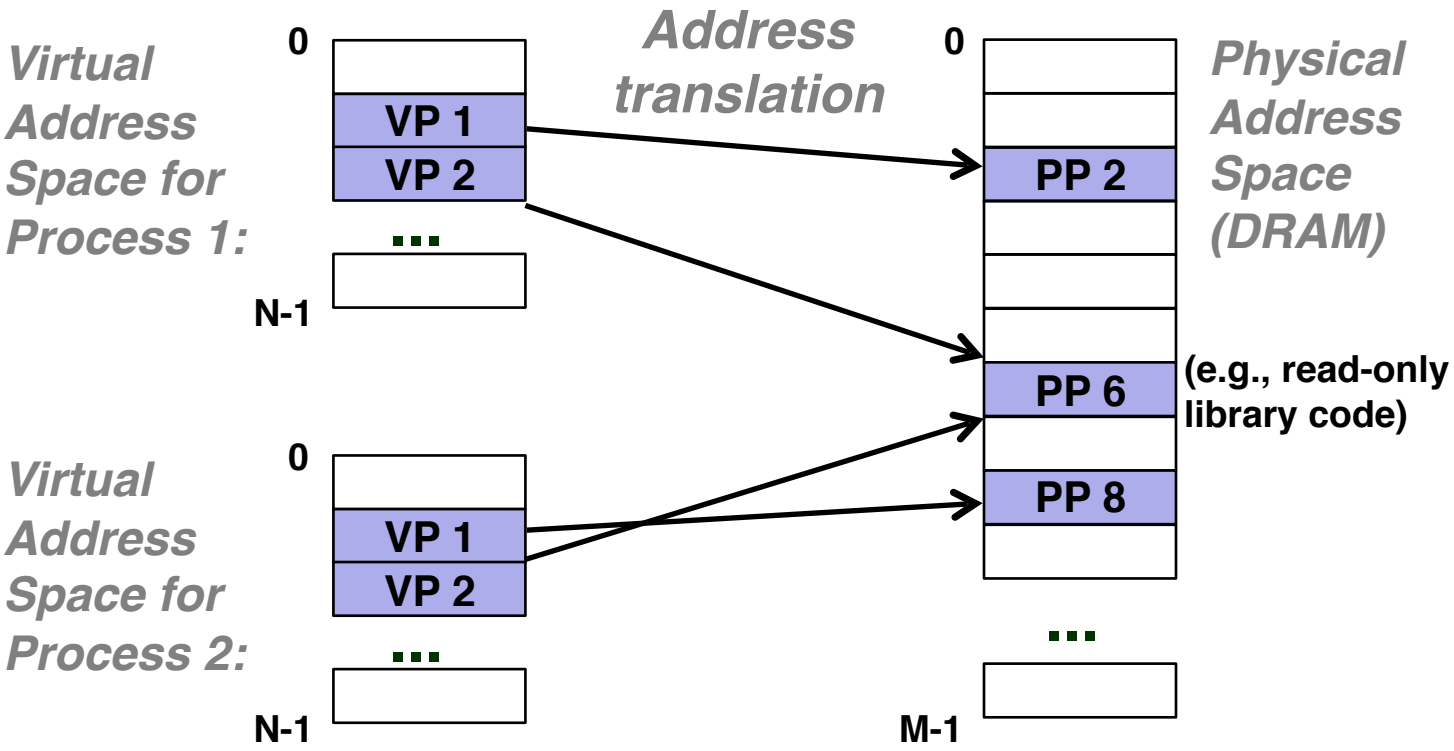
VM as a Tool for Memory Management

- Key idea: each process has its own virtual address space
  - It can view memory as a simple linear array
  - Mapping scatters addresses through physical memory
    - Well-chosen mappings can improve locality



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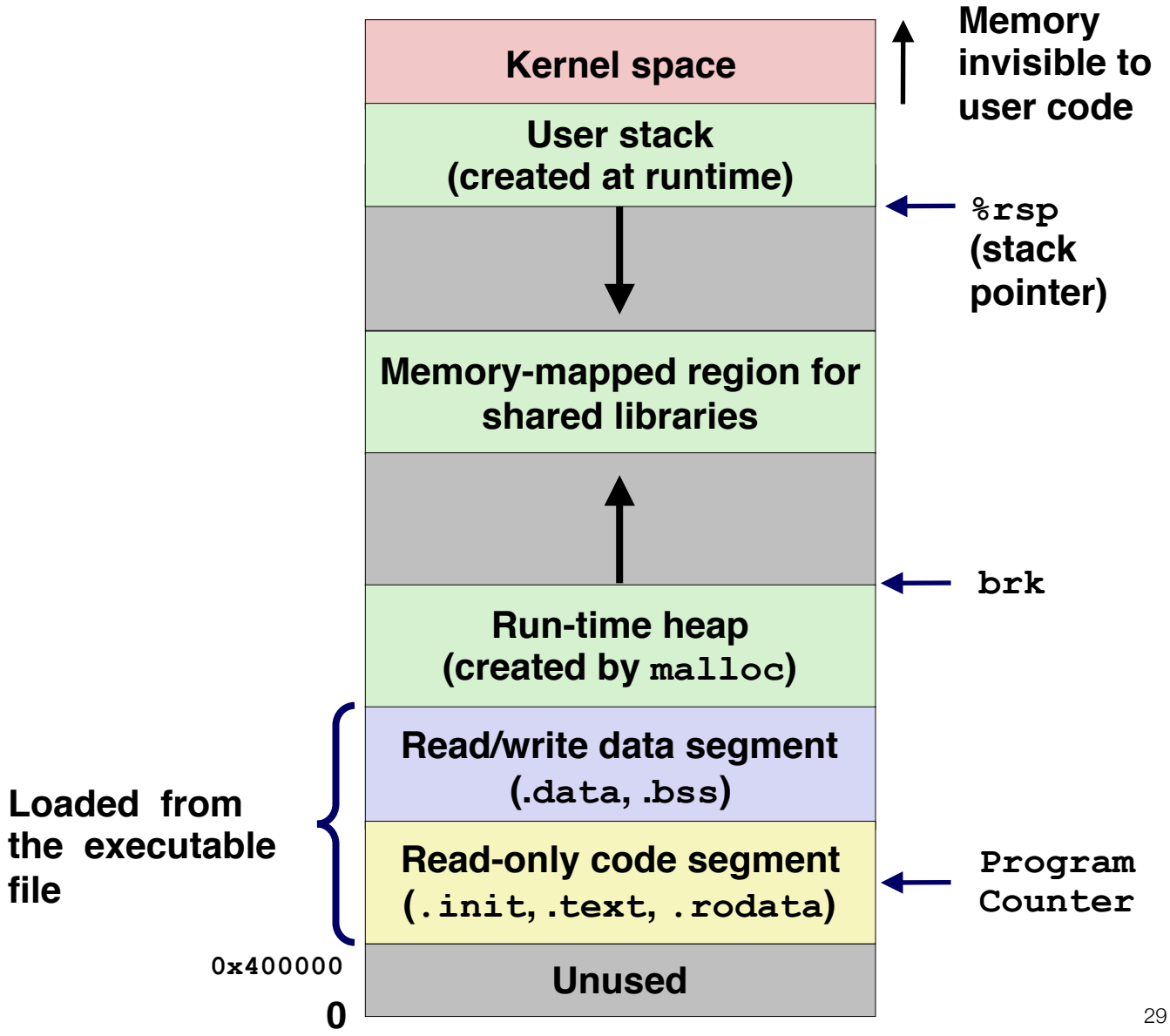
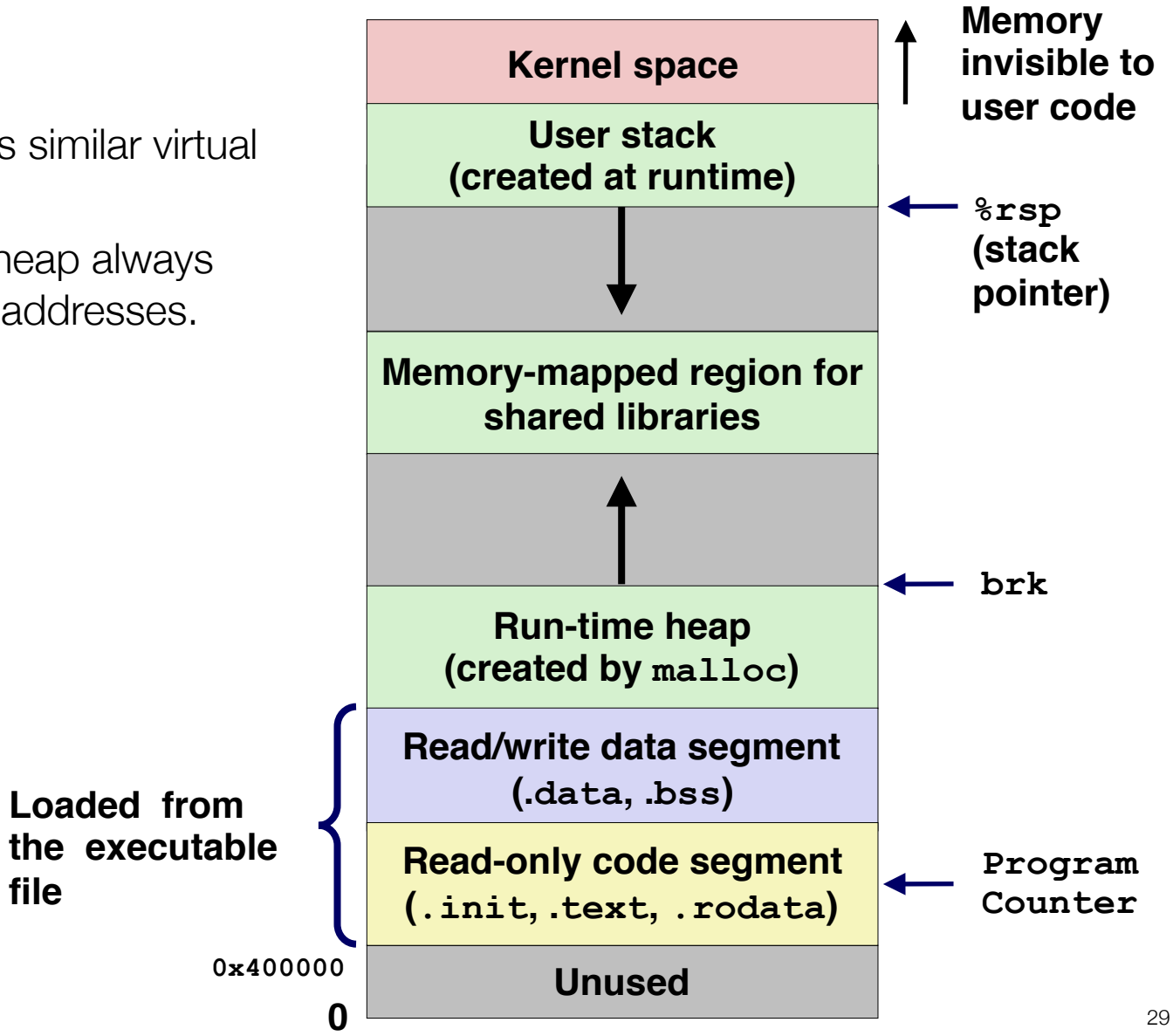
- With virtual memory, addresses used by program are not the same as what the processor uses to actually access memory. This naturally isolates/protect programs.

Simplifying Linking and Loading



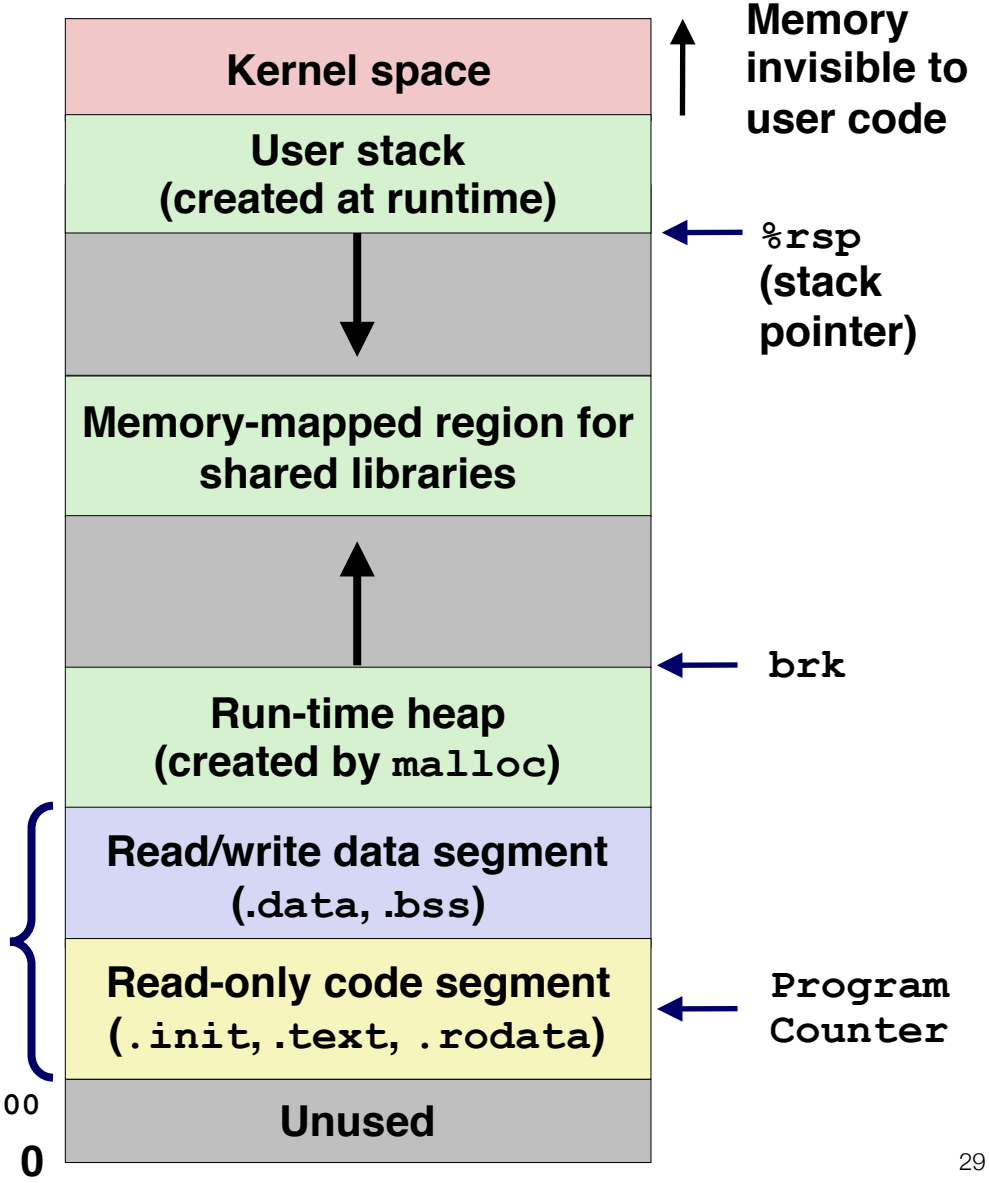
Simplifying Linking and Loading

- Linking
  - Each program has similar virtual address space
  - Code, data, and heap always start at the same addresses.



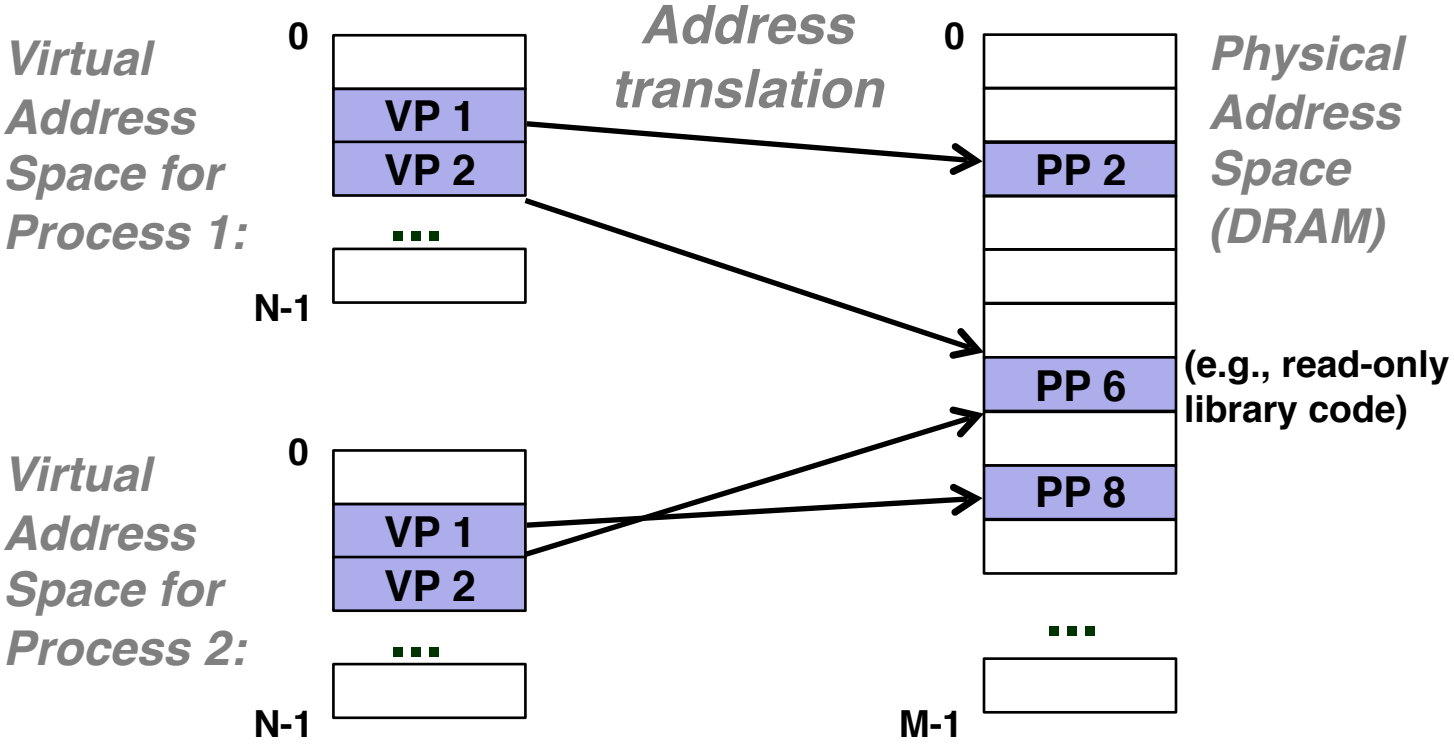
Simplifying Linking and Loading

- Linking
  - Each program has similar virtual address space
  - Code, data, and heap always start at the same addresses.
- Loading
  - `execve` allocates virtual pages for `.text` and `.data` sections & creates PTEs marked as invalid
  - The `.text` and `.data` sections are copied, page by page, on demand by the VM system



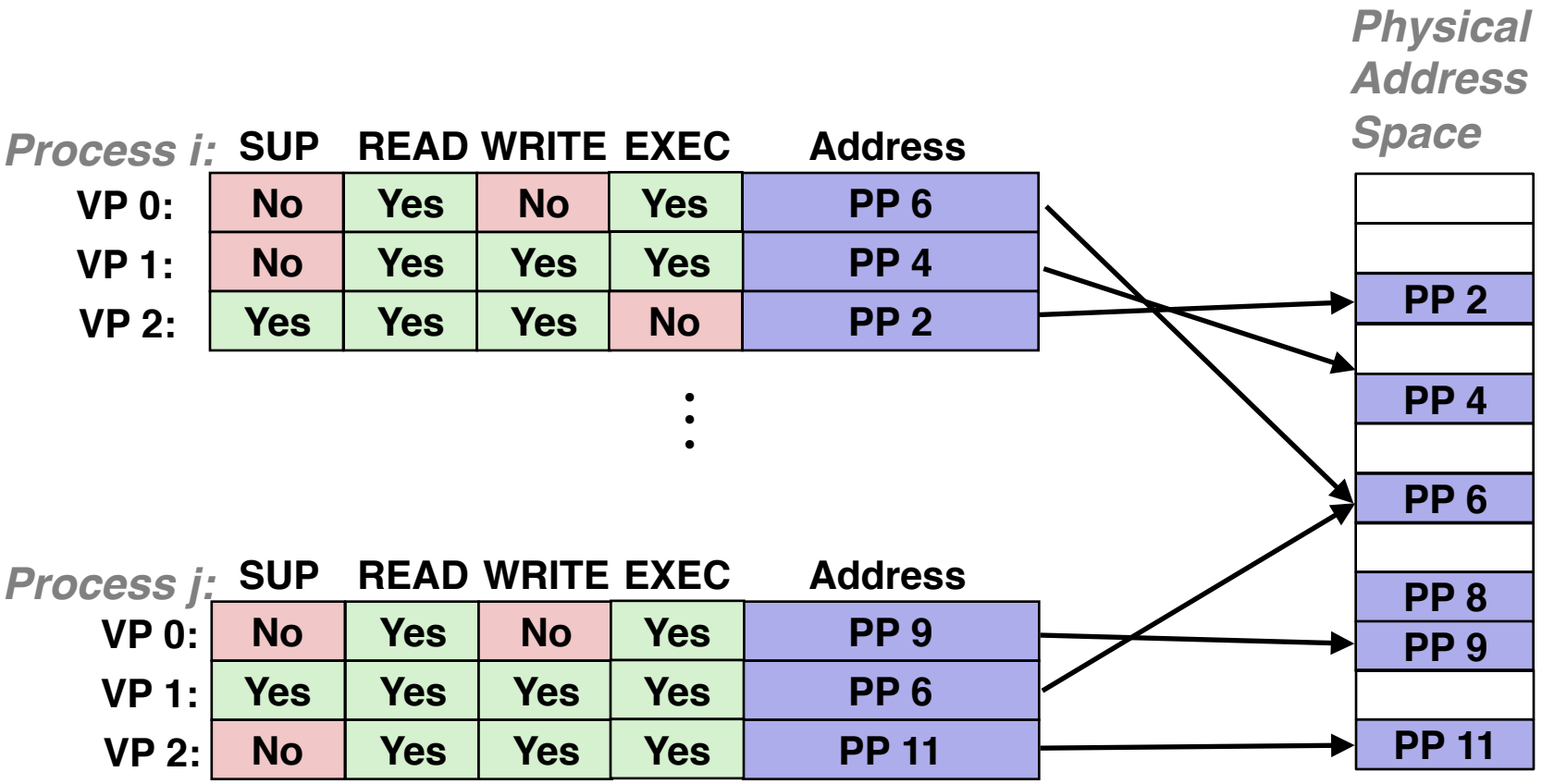
Virtual Memory Enables Sharing

- Simplifying memory allocation
  - Each virtual page can be mapped to any physical page
  - A virtual page can be stored in different physical pages at different times
- Sharing code and data among processes
  - Map virtual pages to the same physical page (here: PP 6)



VM Provides Further Protection Opportunities

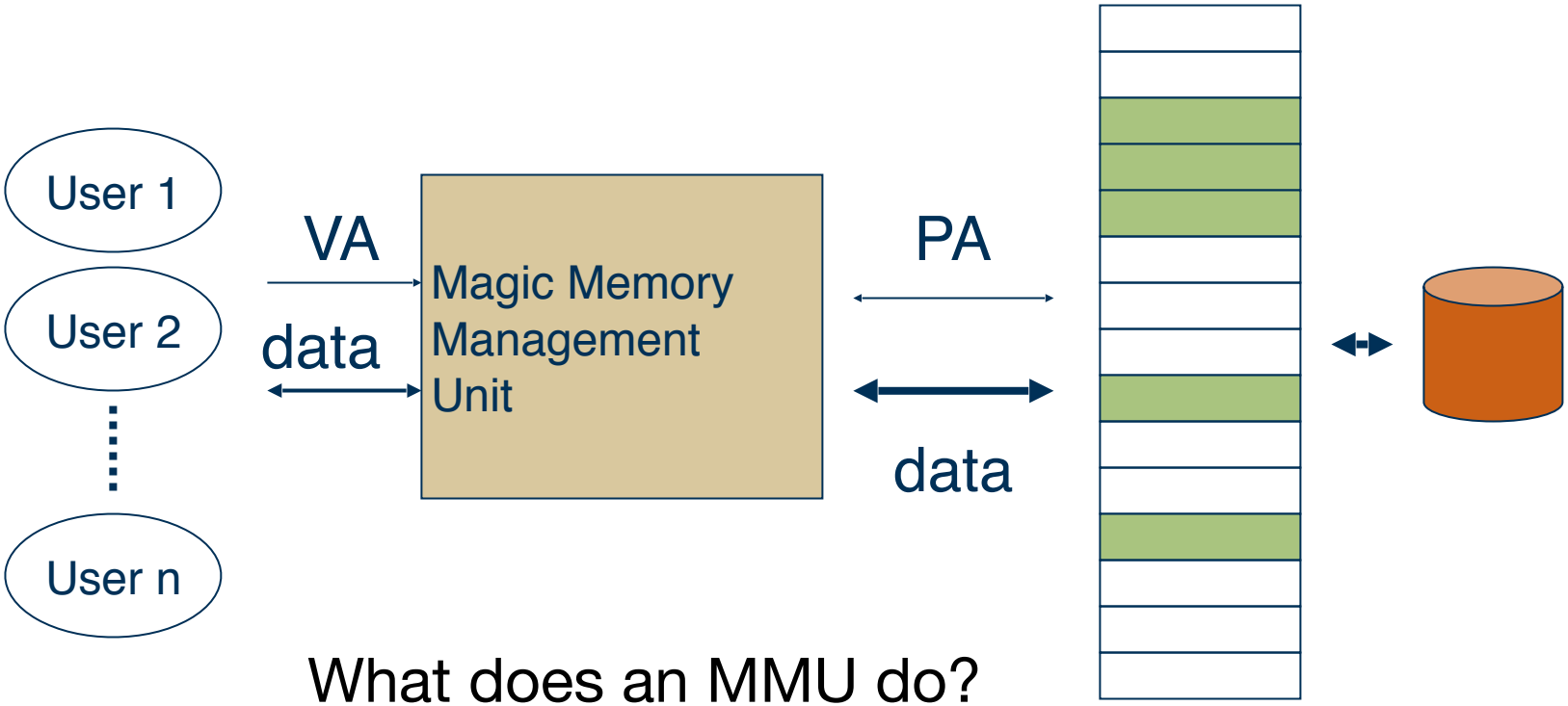
- Extend PTEs with permission bits
- MMU checks these bits on each access



Today

- Virtual memory (VM) illustration
- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

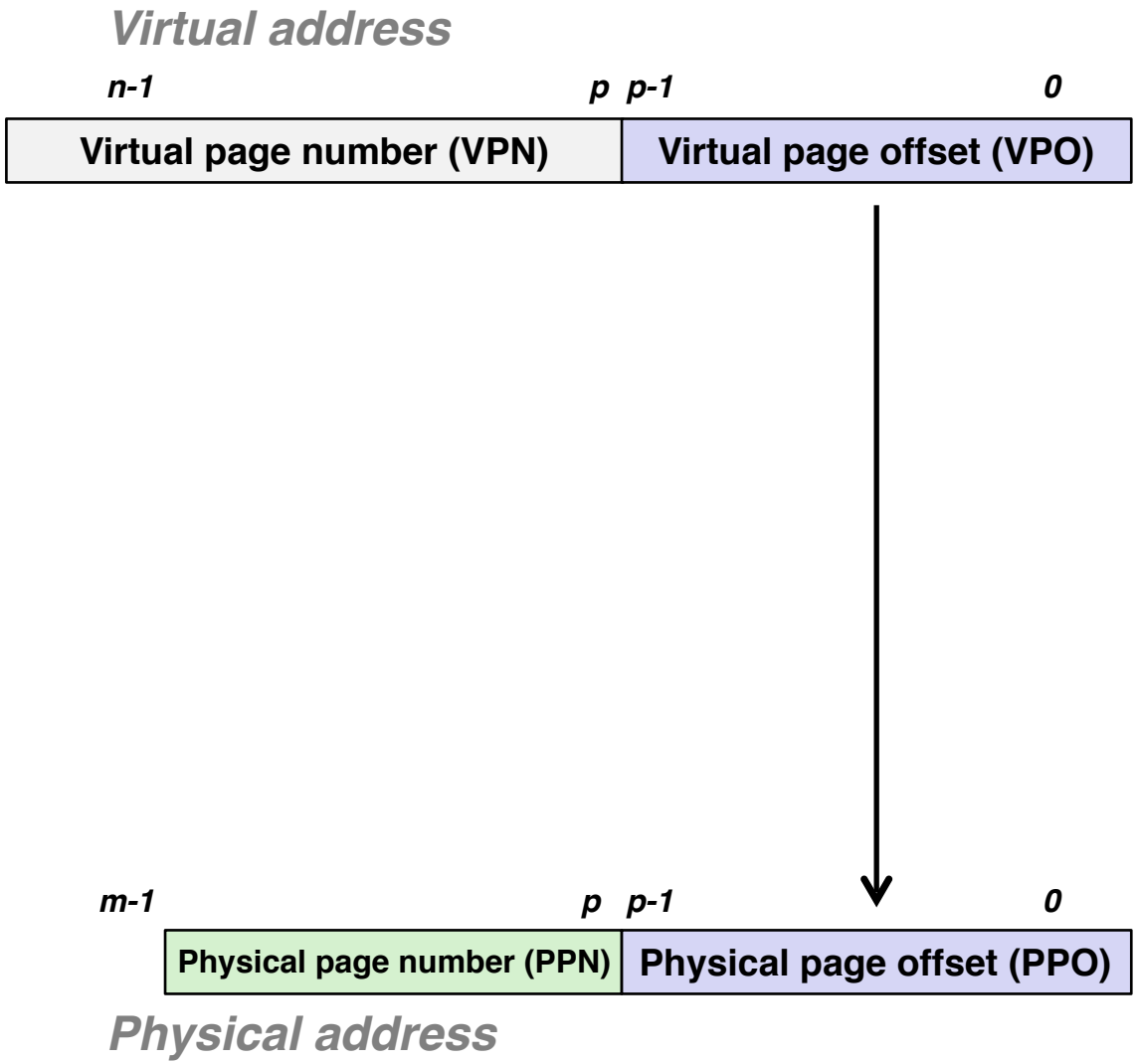
So Far…



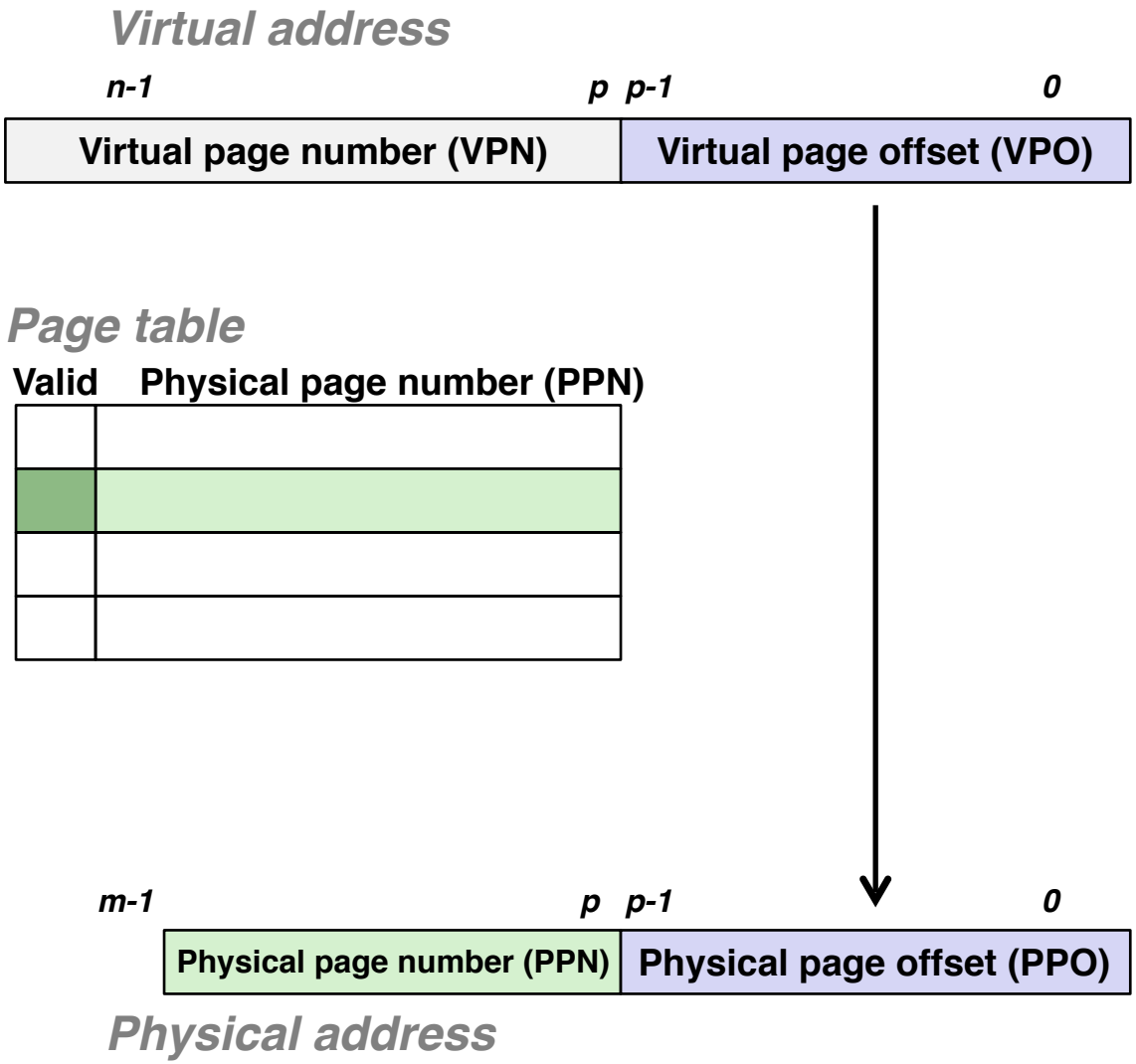
What does an MMU do?

- Translate address
  - Enforce permissions
  - Fetch from disk

Address Translation With a Page Table



Address Translation With a Page Table



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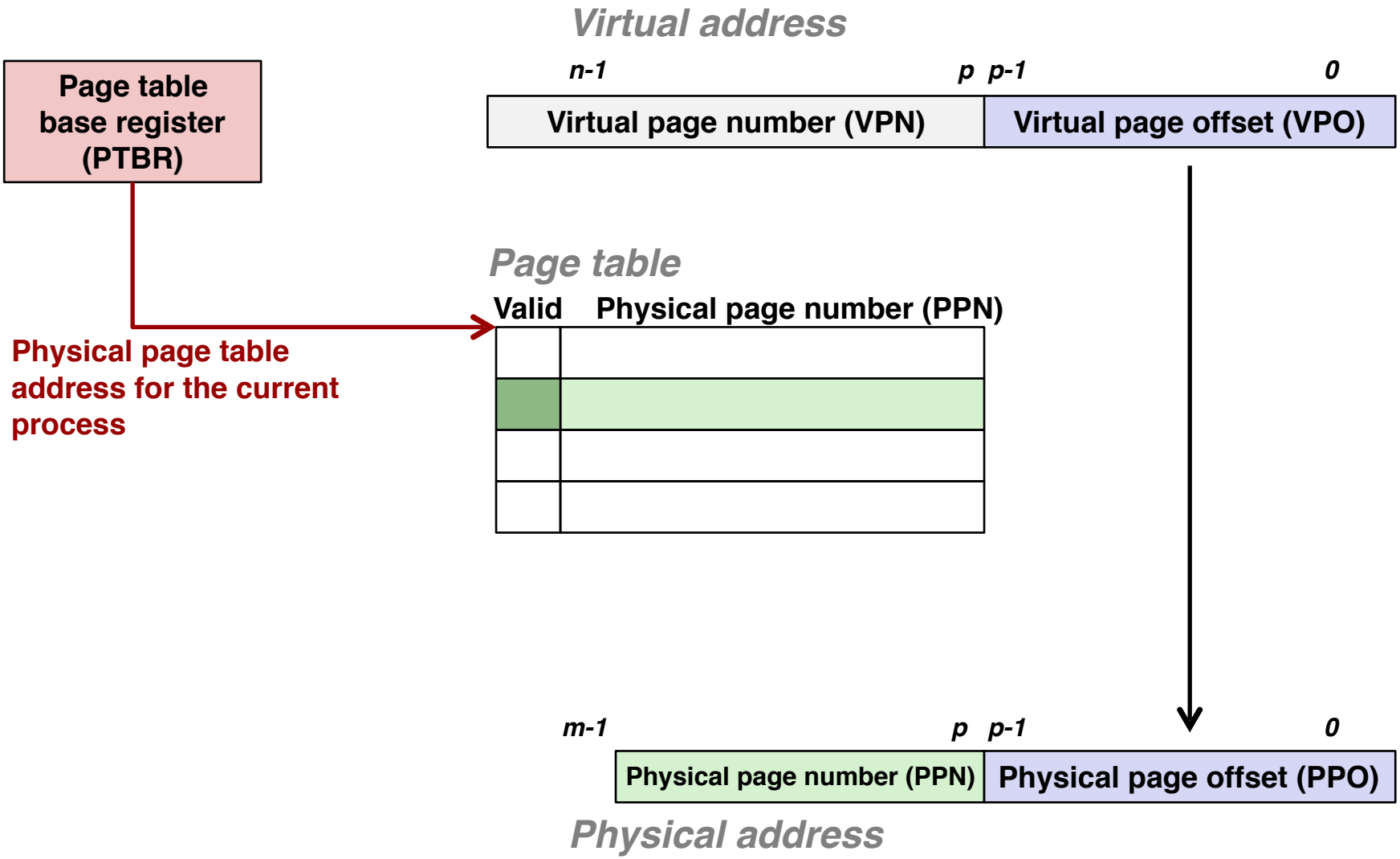

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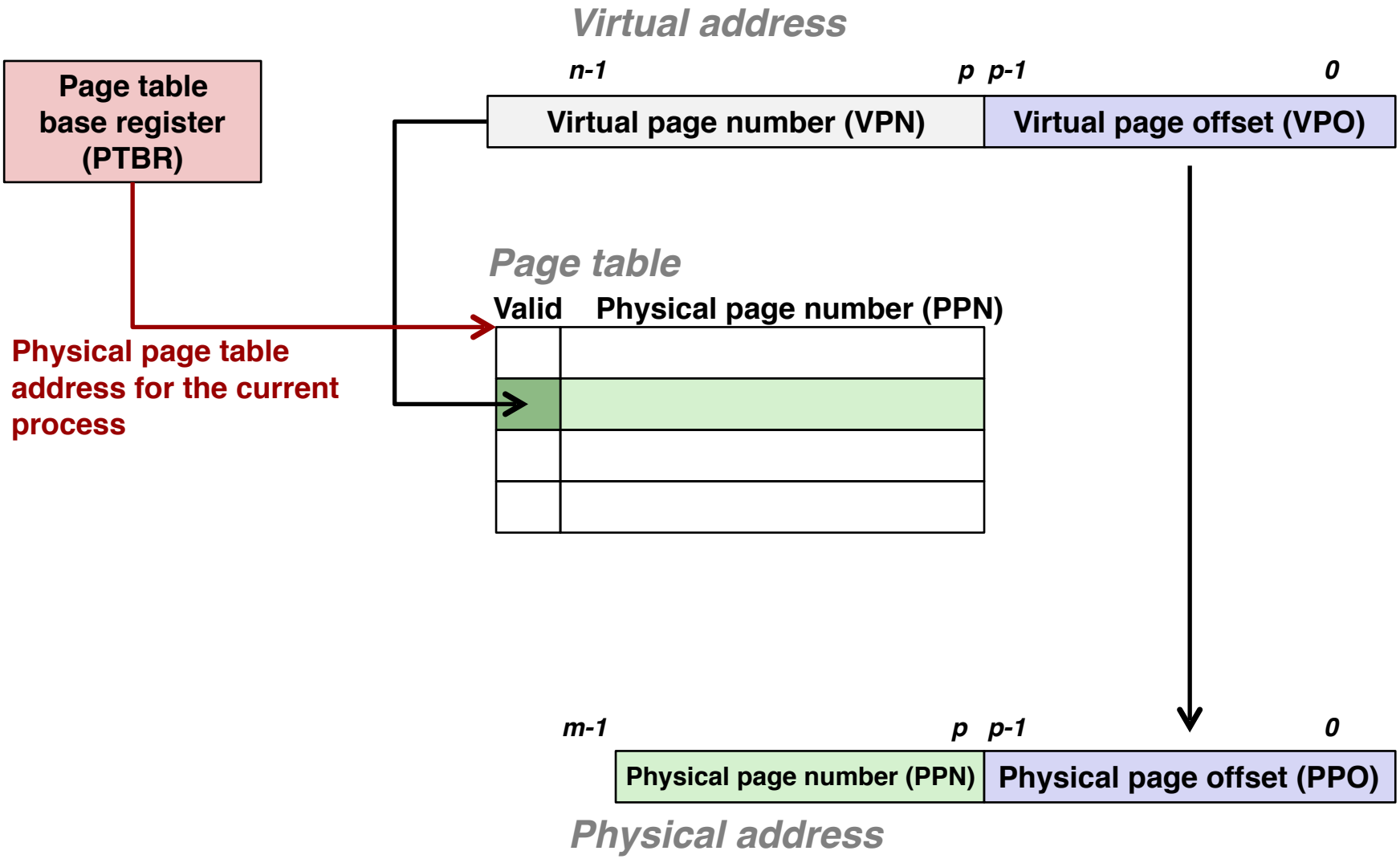

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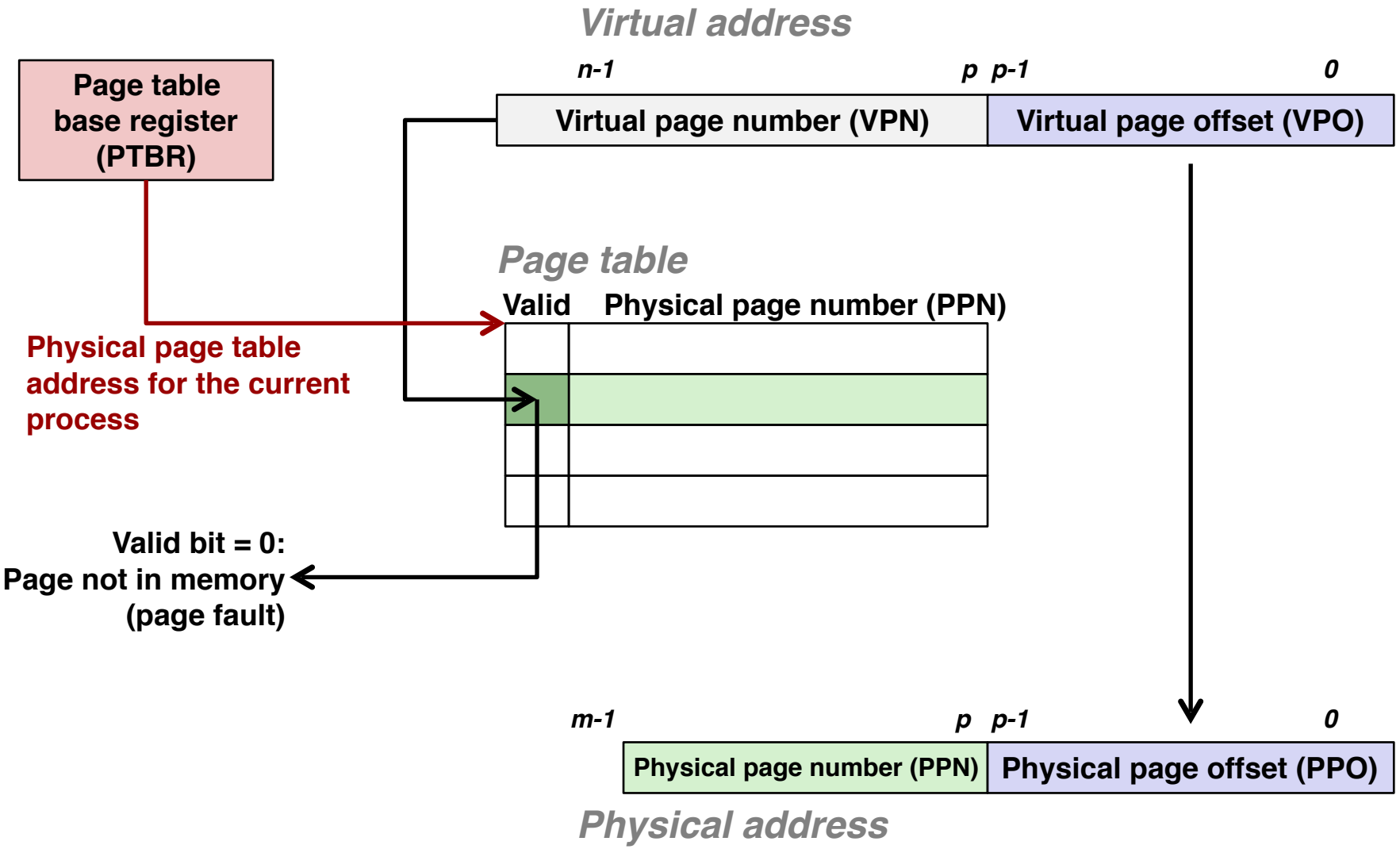

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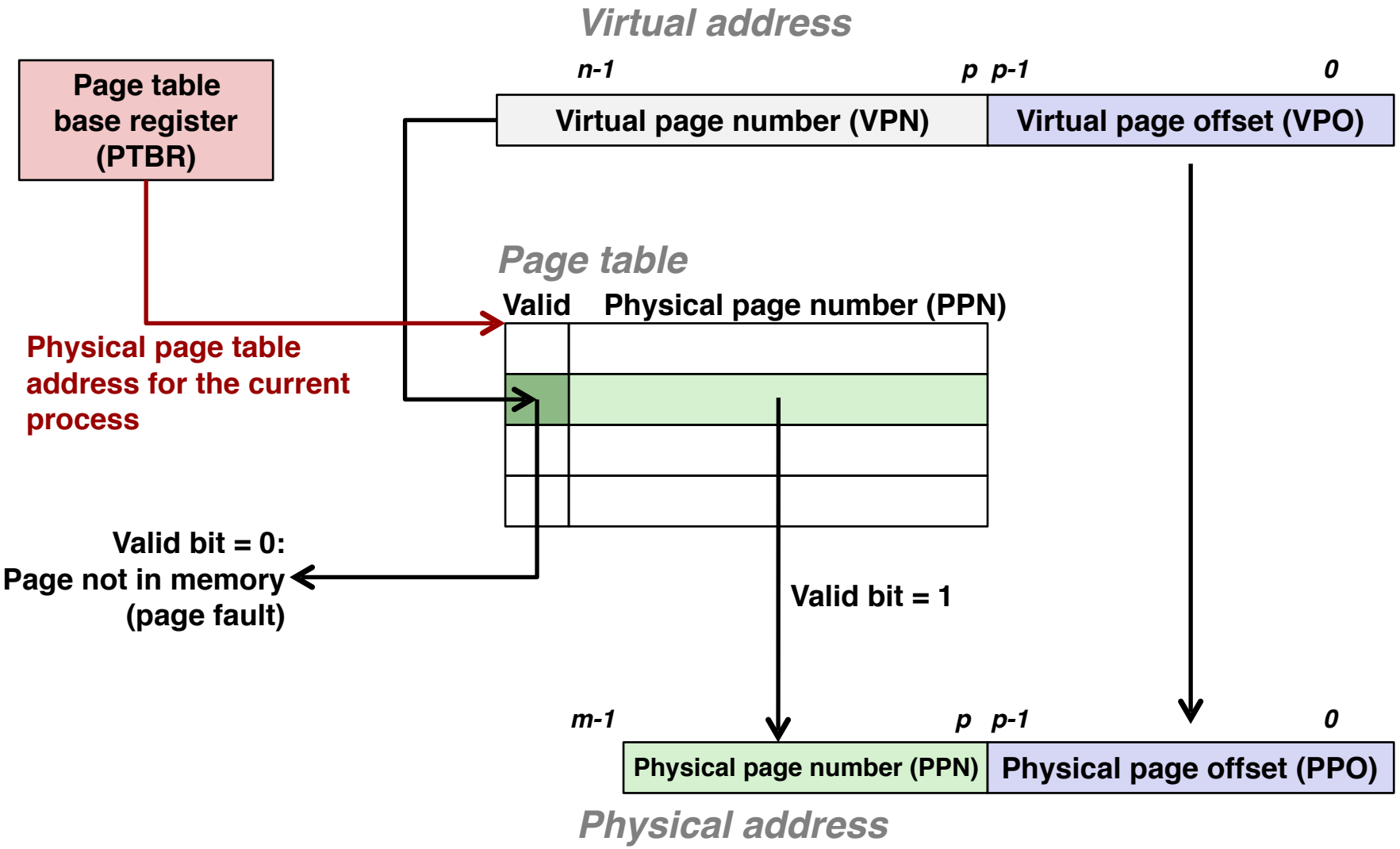
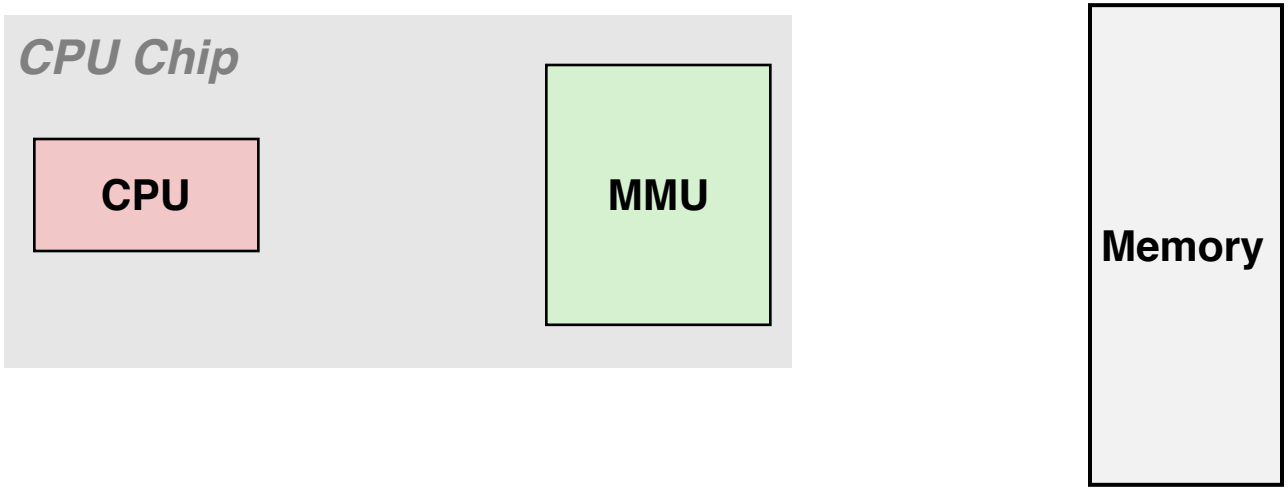
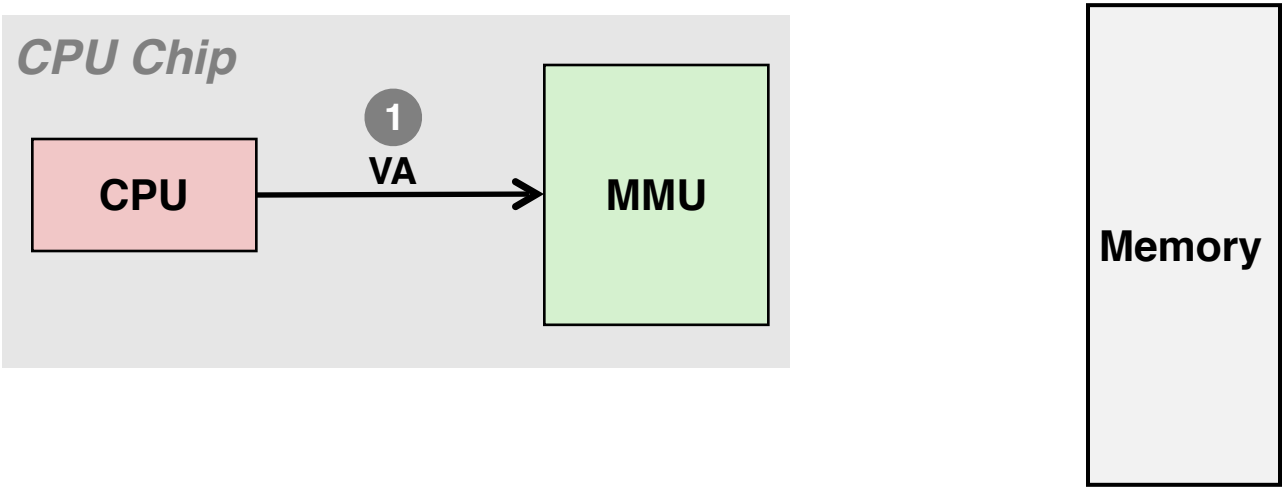


Address Translation: Page Hit



VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

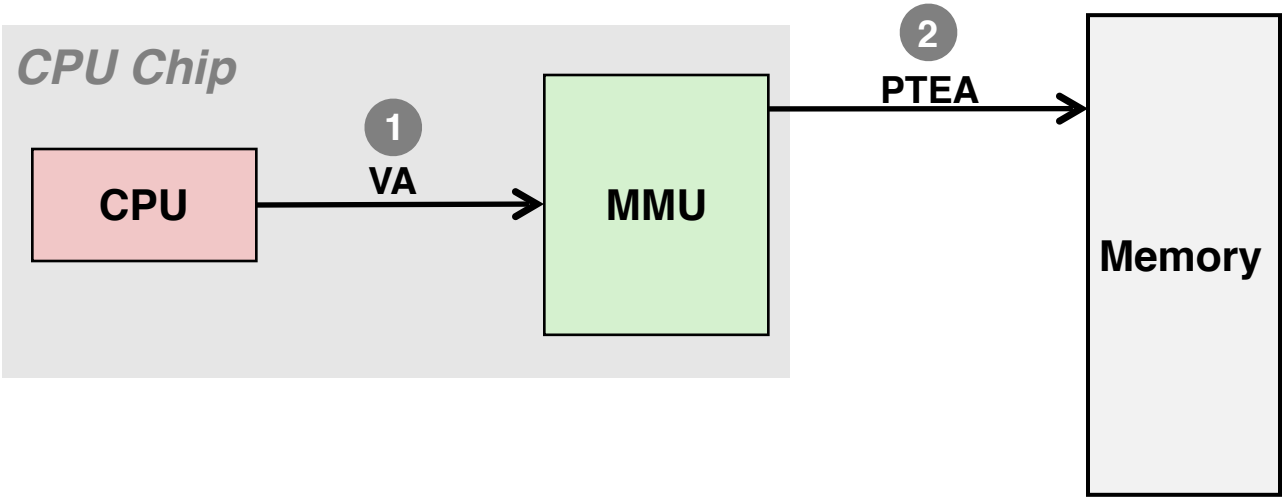
Address Translation: Page Hit



1) Processor sends virtual address to MMU

VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

Address Translation: Page Hit



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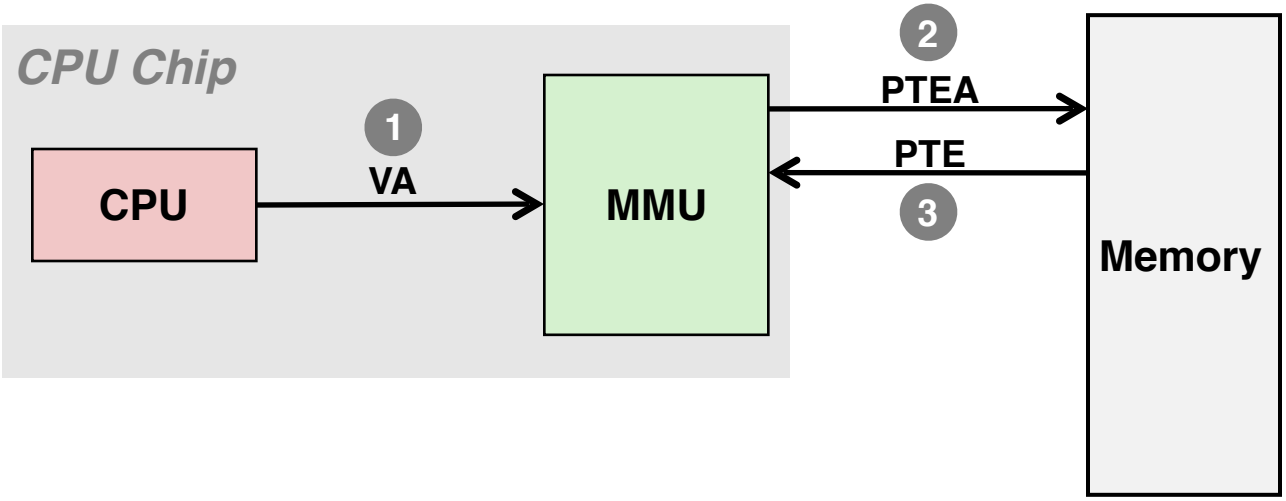
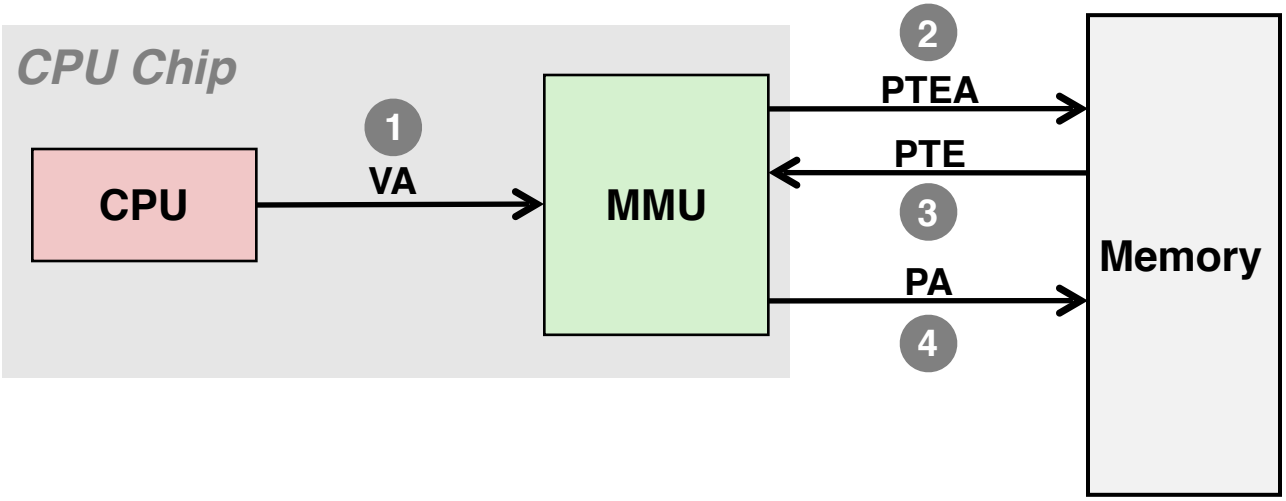


1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

Address Translation: Page Hit



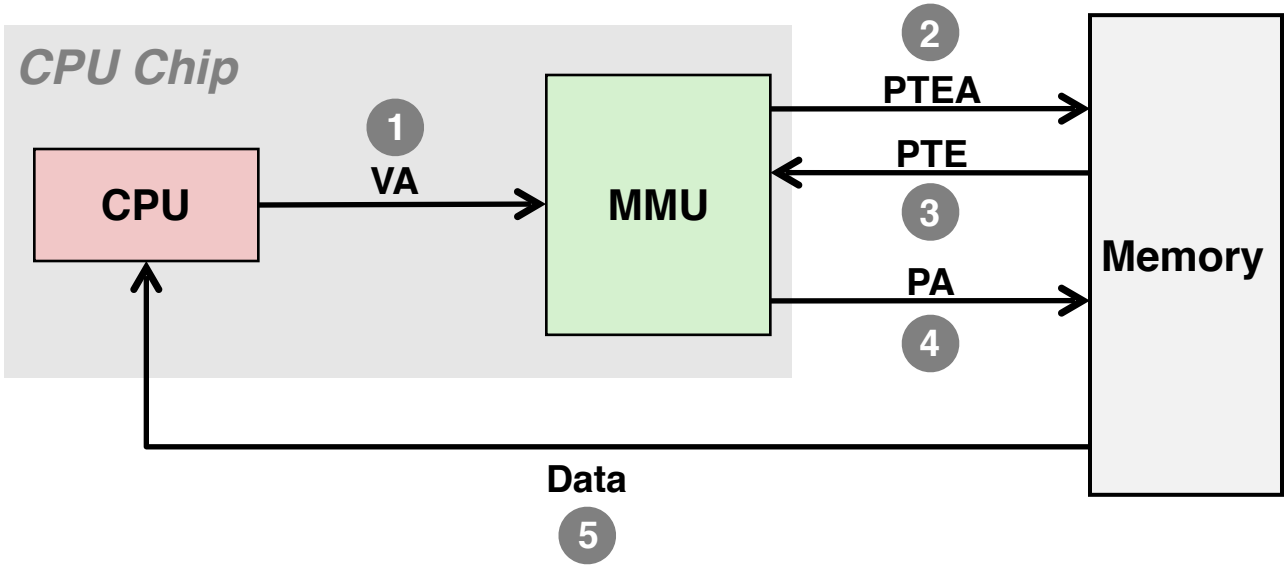
1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

4) MMU sends physical address to cache/memory

VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

Address Translation: Page Hit



1) Processor sends virtual address to MMU

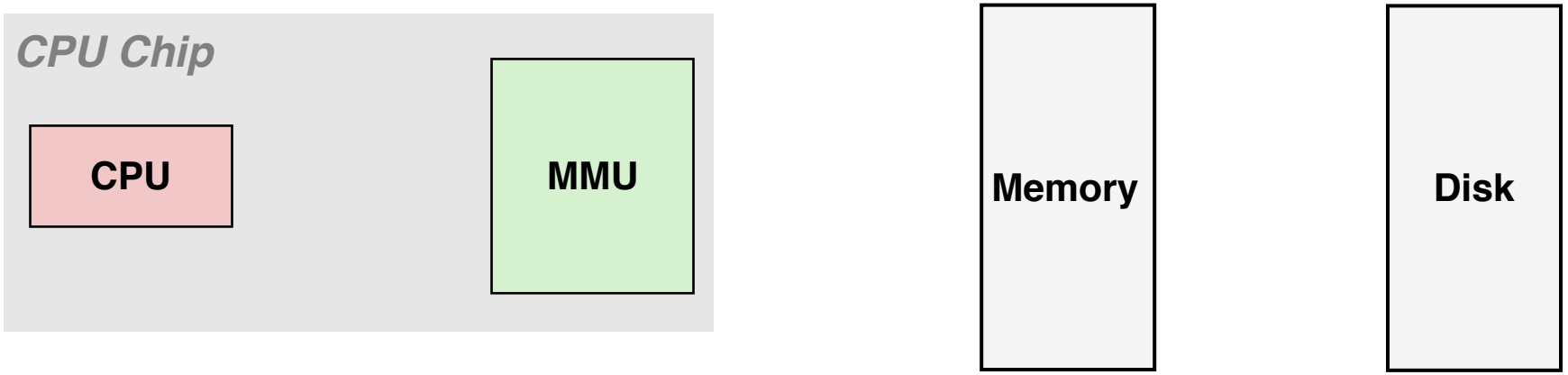
2-3) MMU fetches PTE from page table in memory

4) MMU sends physical address to cache/memory

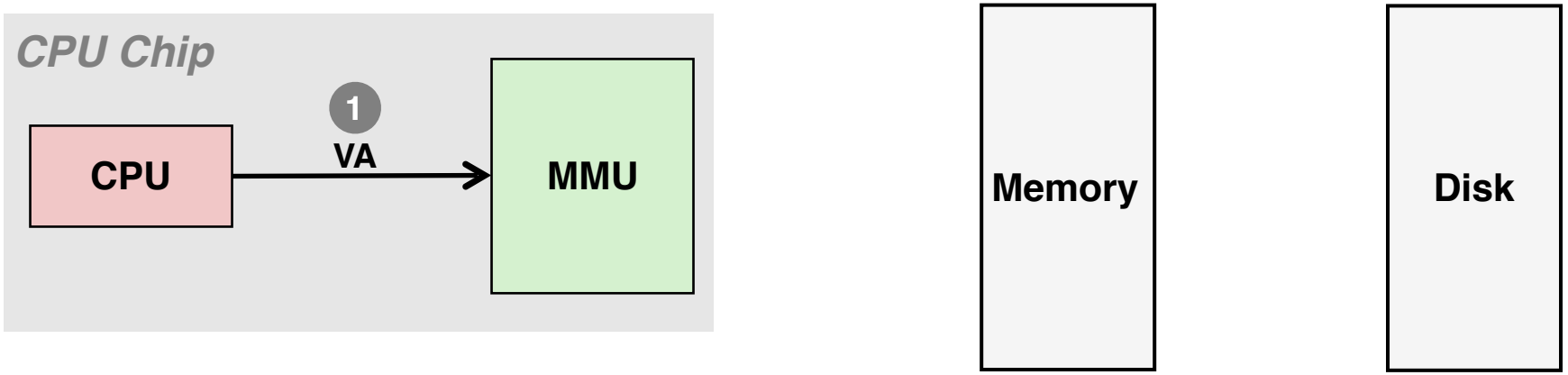
5) Cache/memory sends data word to processor

VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

Address Translation: Page Fault



Address Translation: Page Fault



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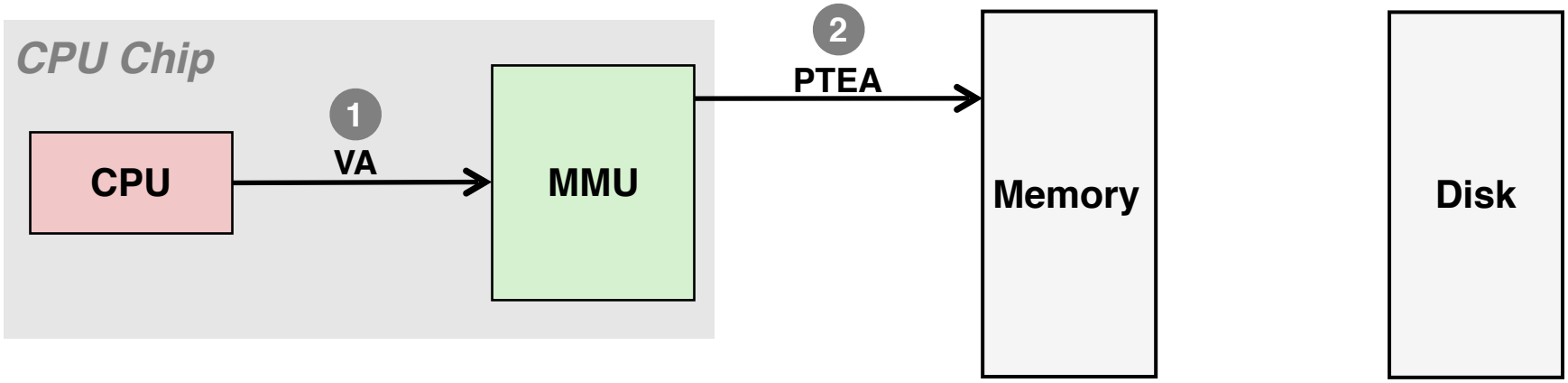
Address Translation: Page Fault



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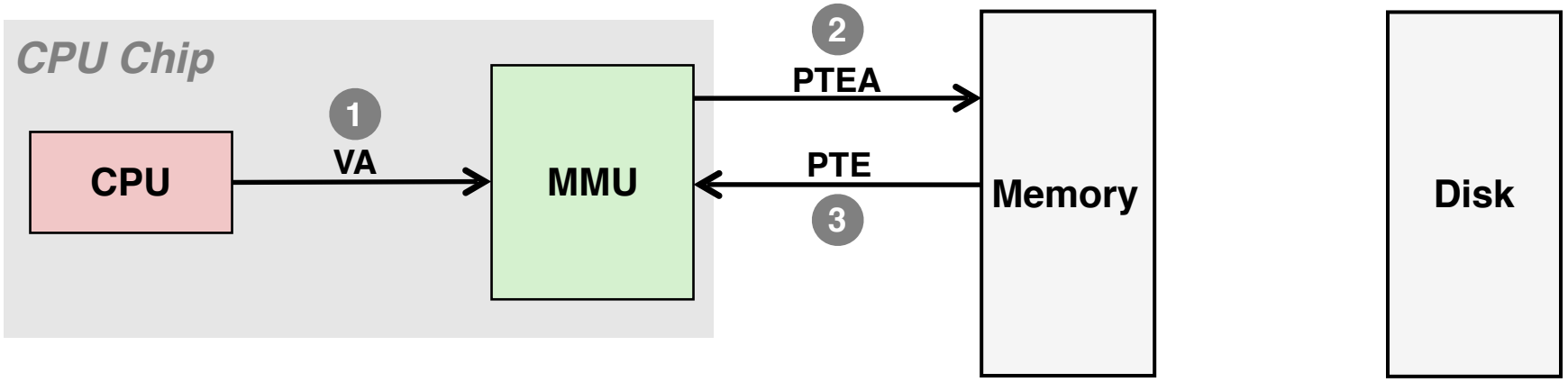
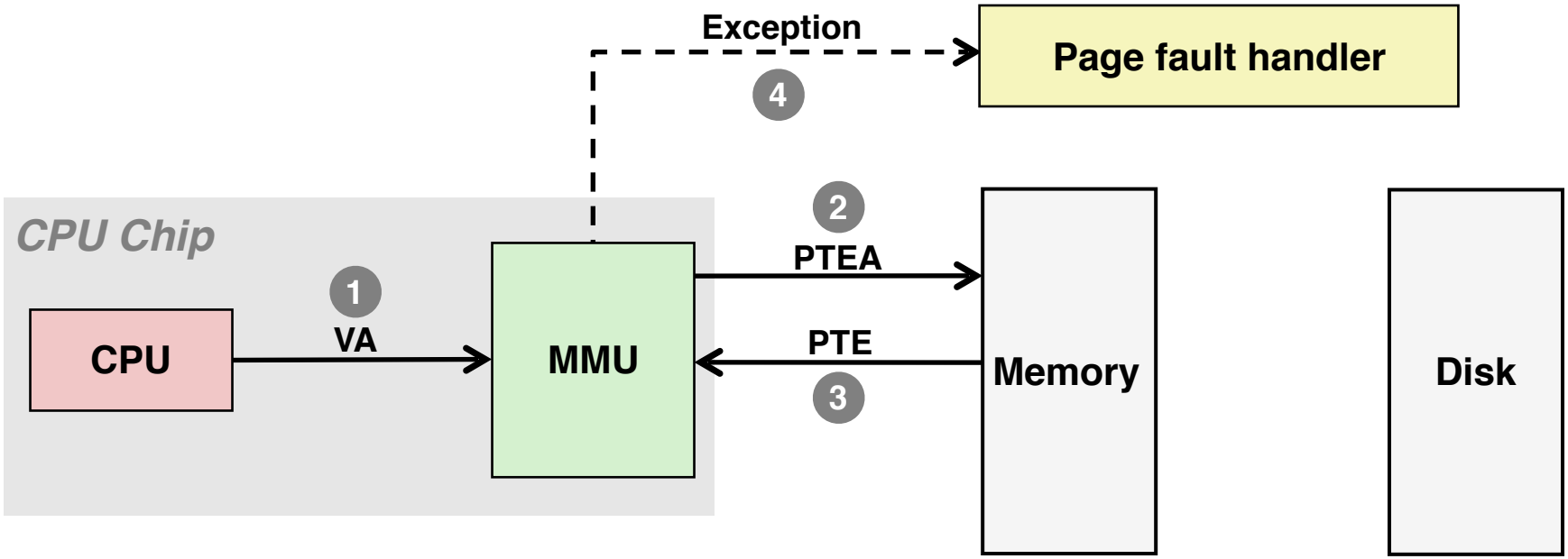
Address Translation: Page Fault



1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

Address Translation: Page Fault

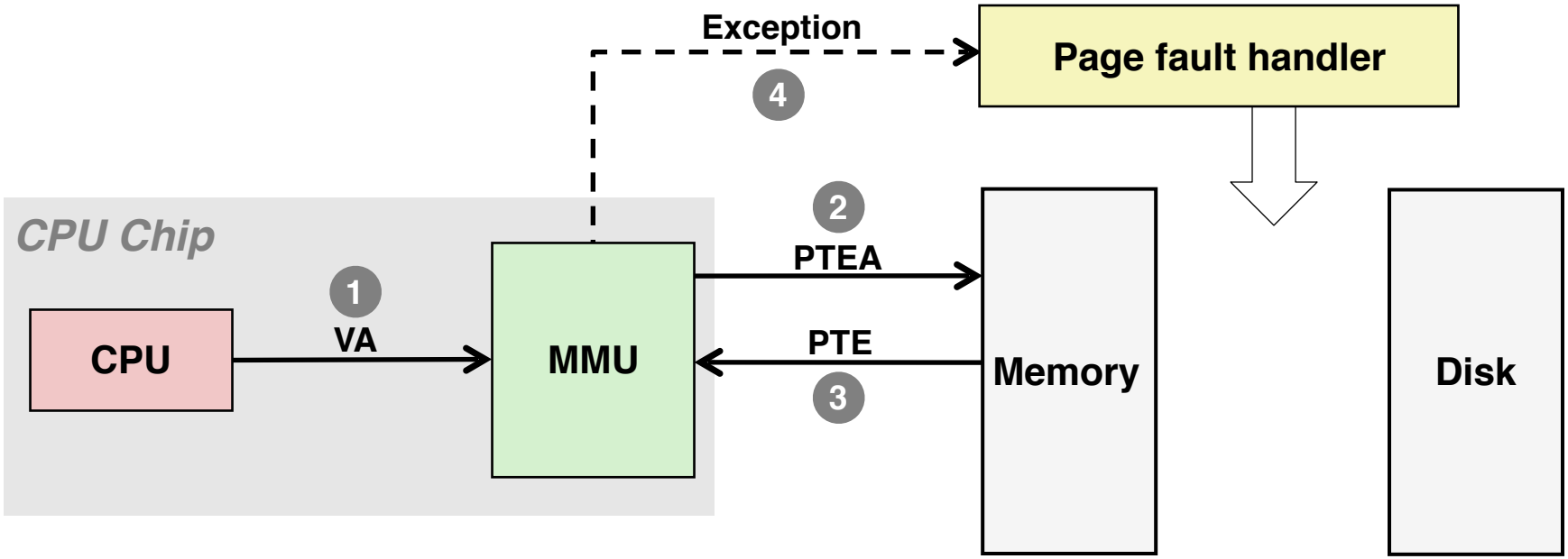


1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

4) Valid bit is zero, so MMU triggers page fault exception

Address Translation: Page Fault



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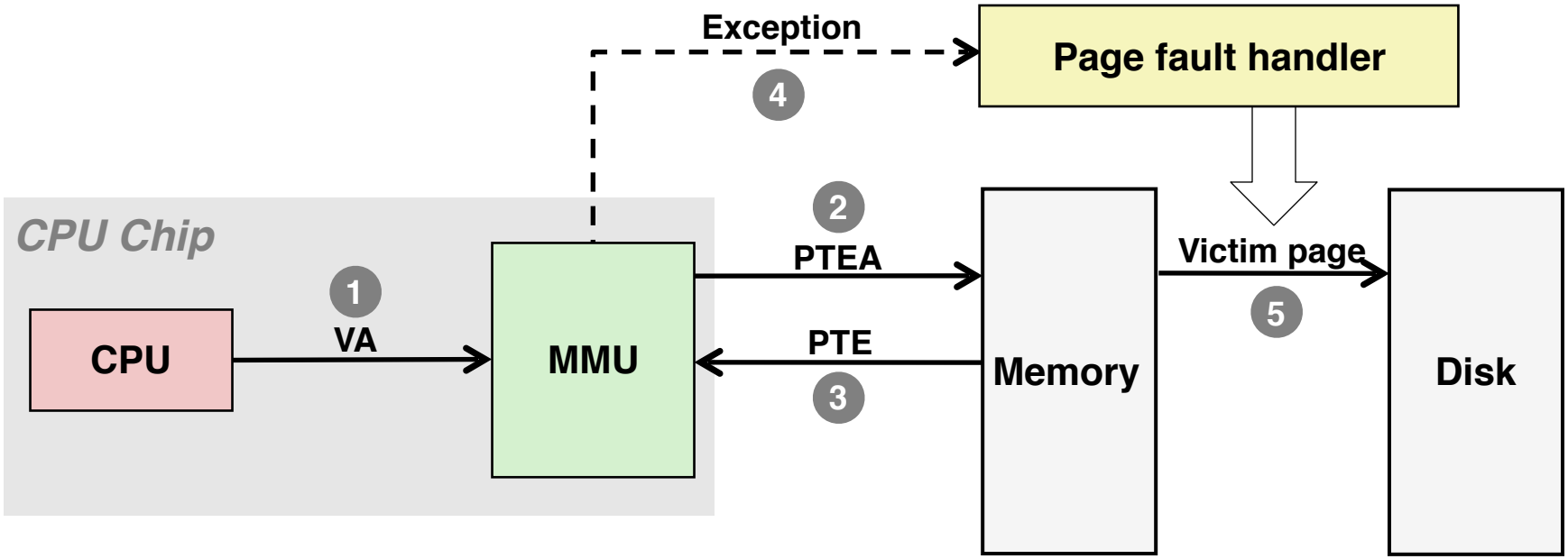

1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

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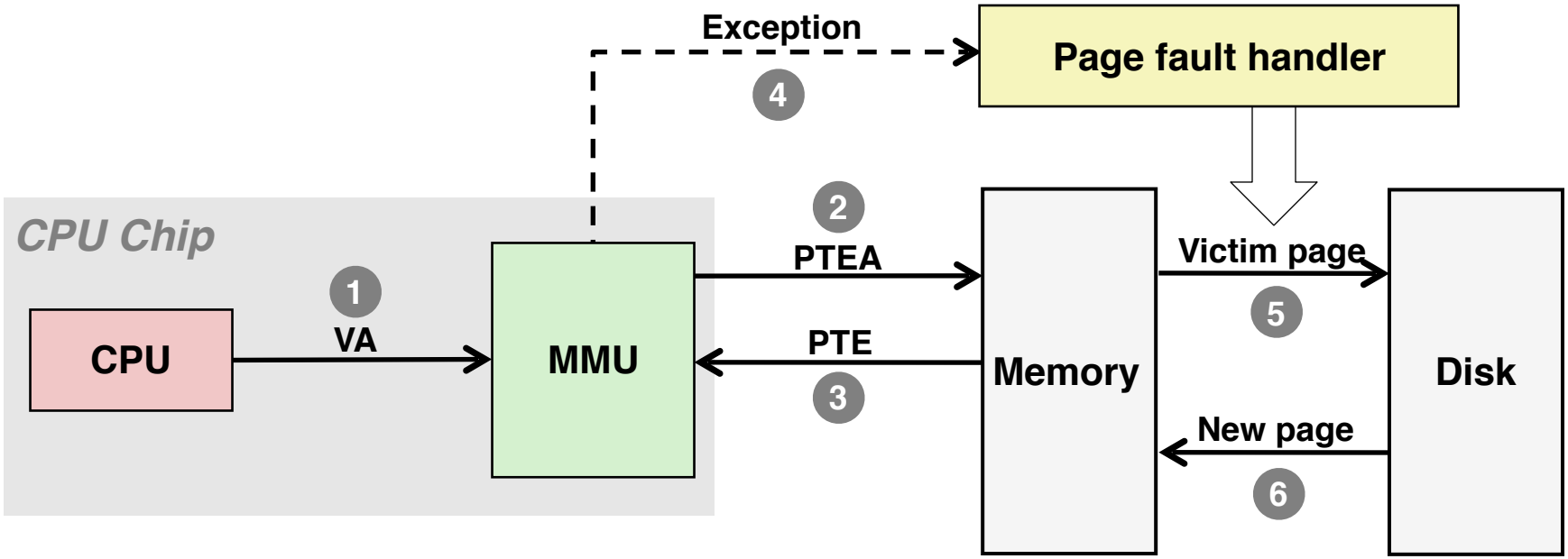
5) Handler identifies victim (and, if dirty, pages it out to disk)

Address Translation: Page Fault



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2-3) MMU fetches PTE from page table in memory

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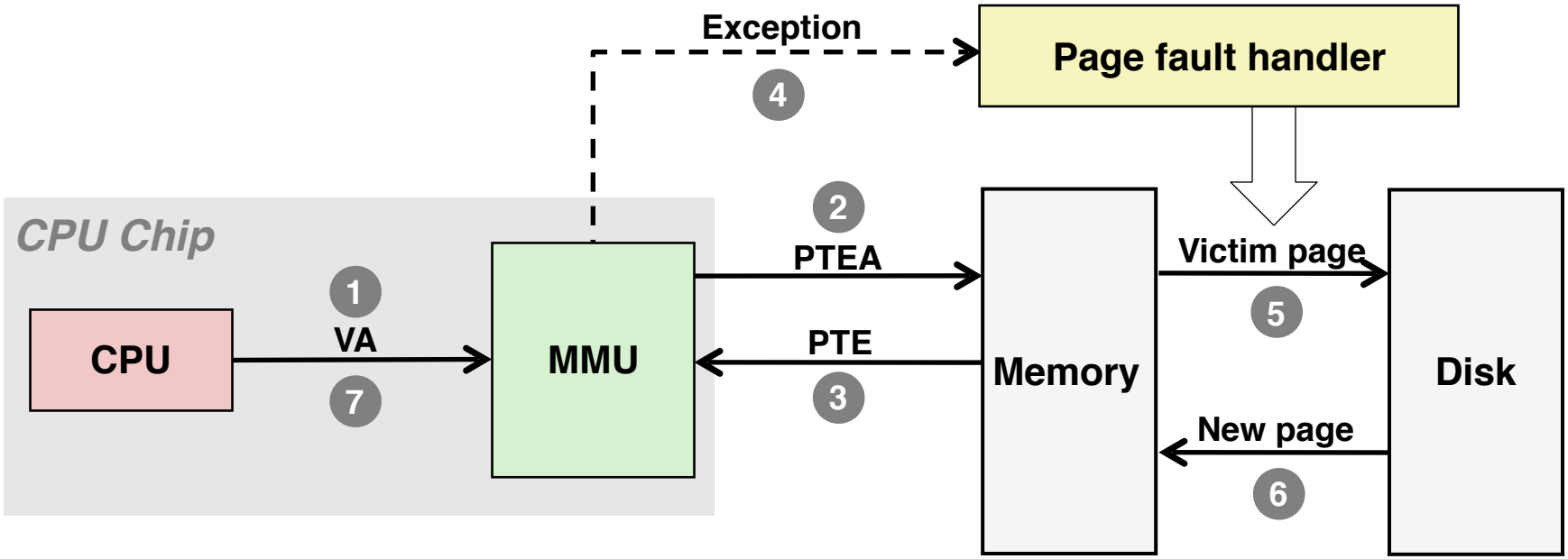
6) Handler pages in new page and updates PTE in memory

Address Translation: Page Fault



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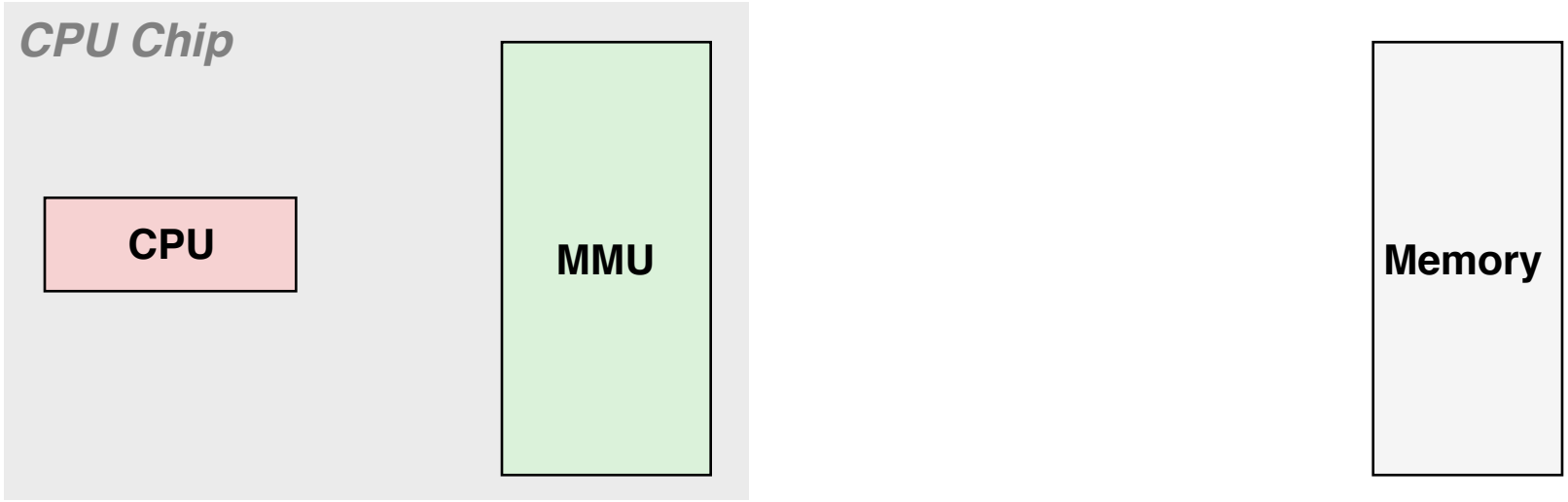
6) Handler pages in new page and updates PTE in memory

7) Handler returns to original process, restarting faulting instruction

Integrating VM and Cache



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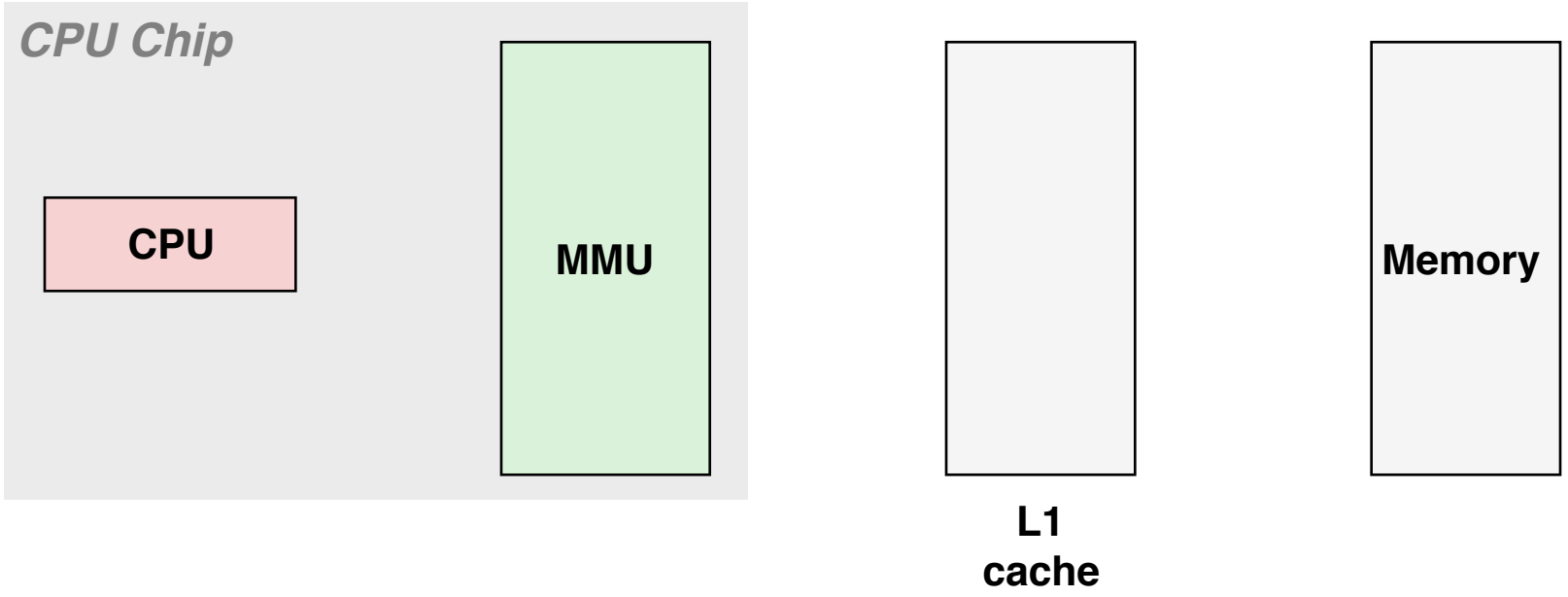

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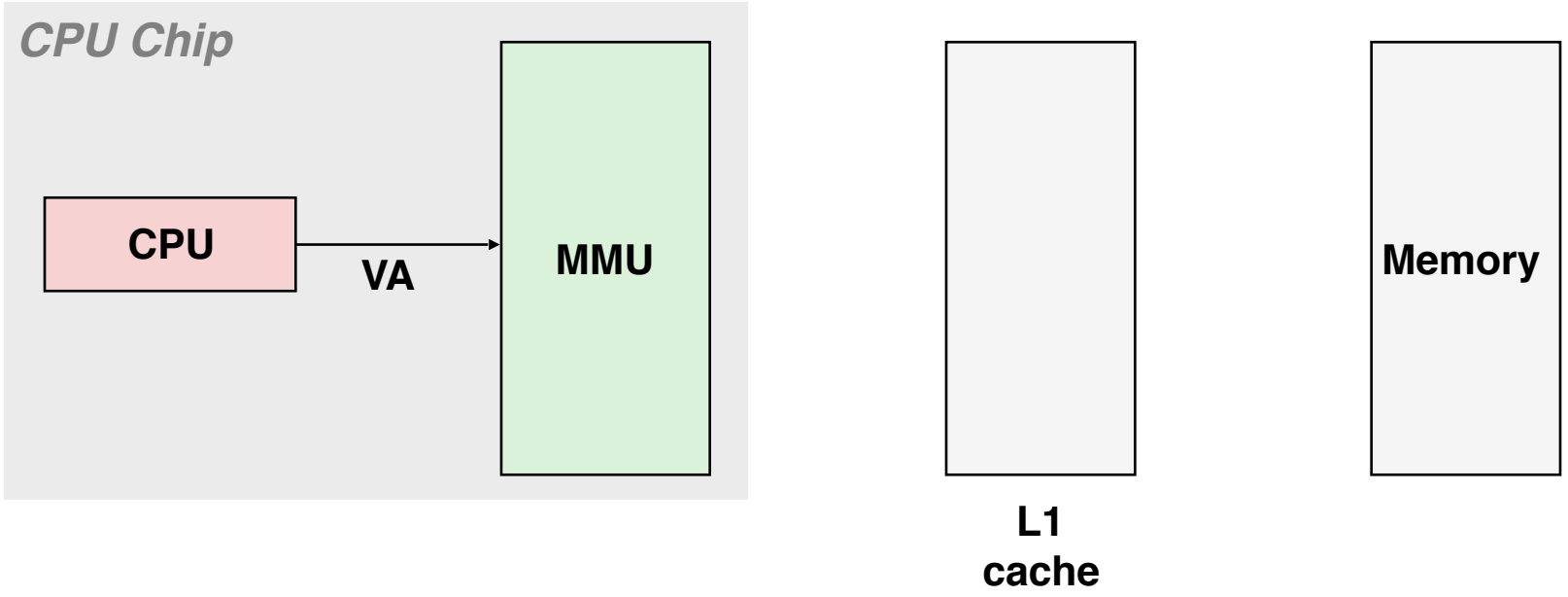

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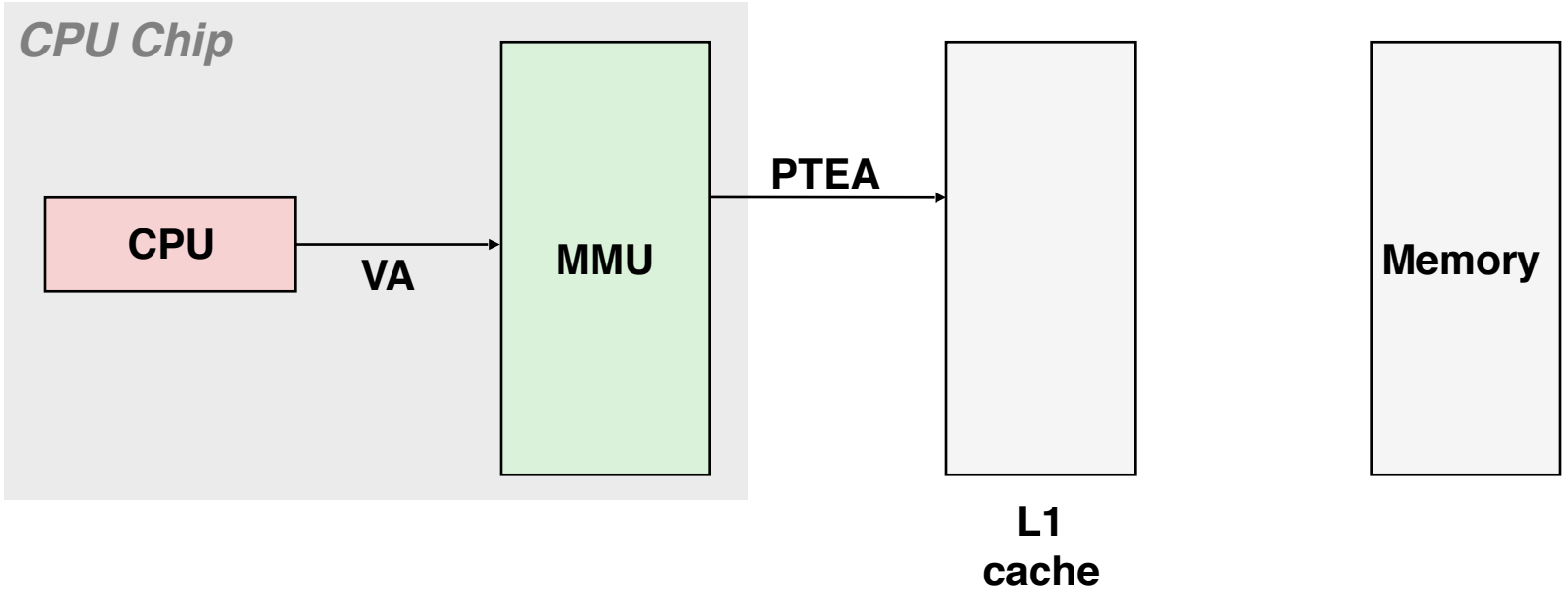

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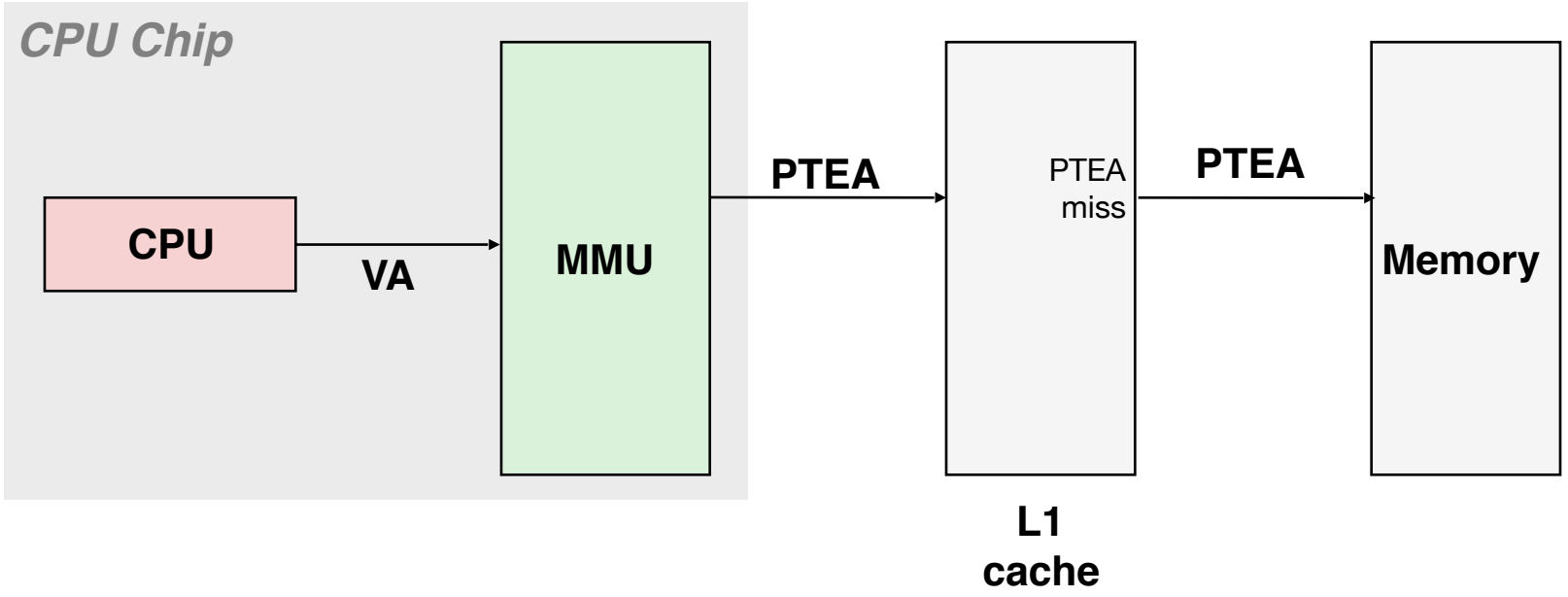

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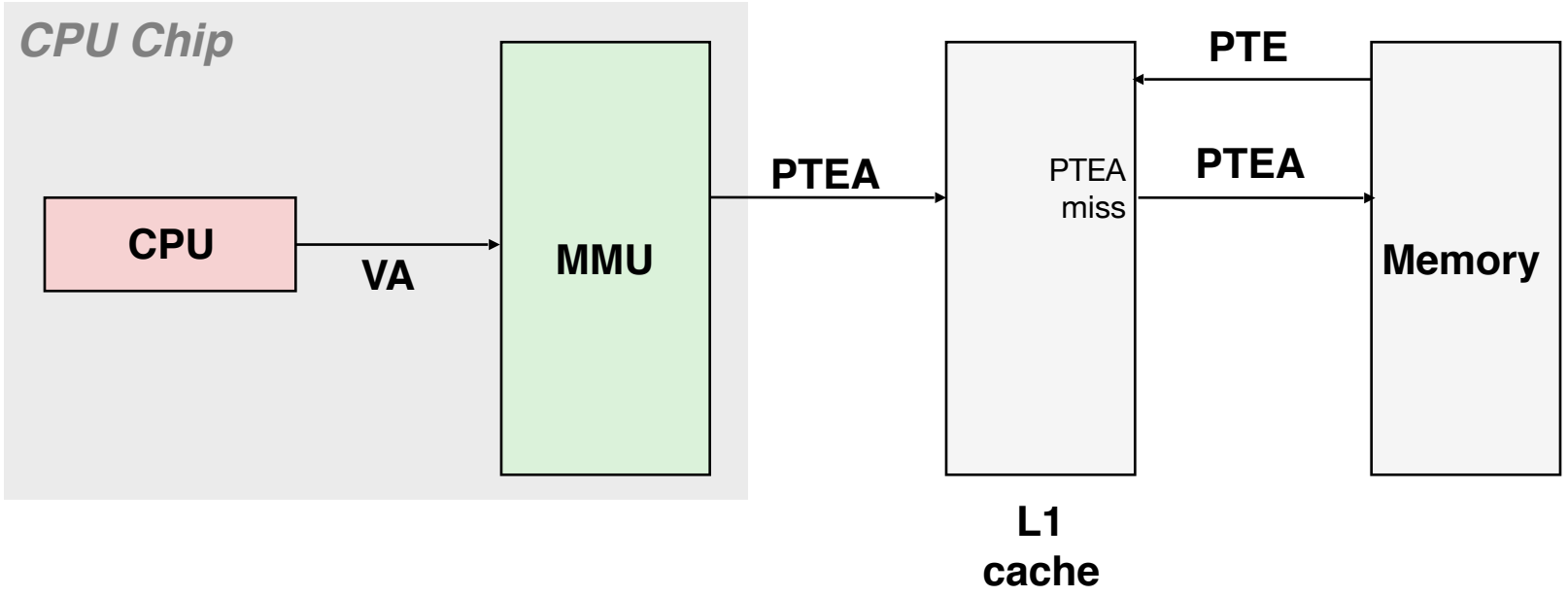

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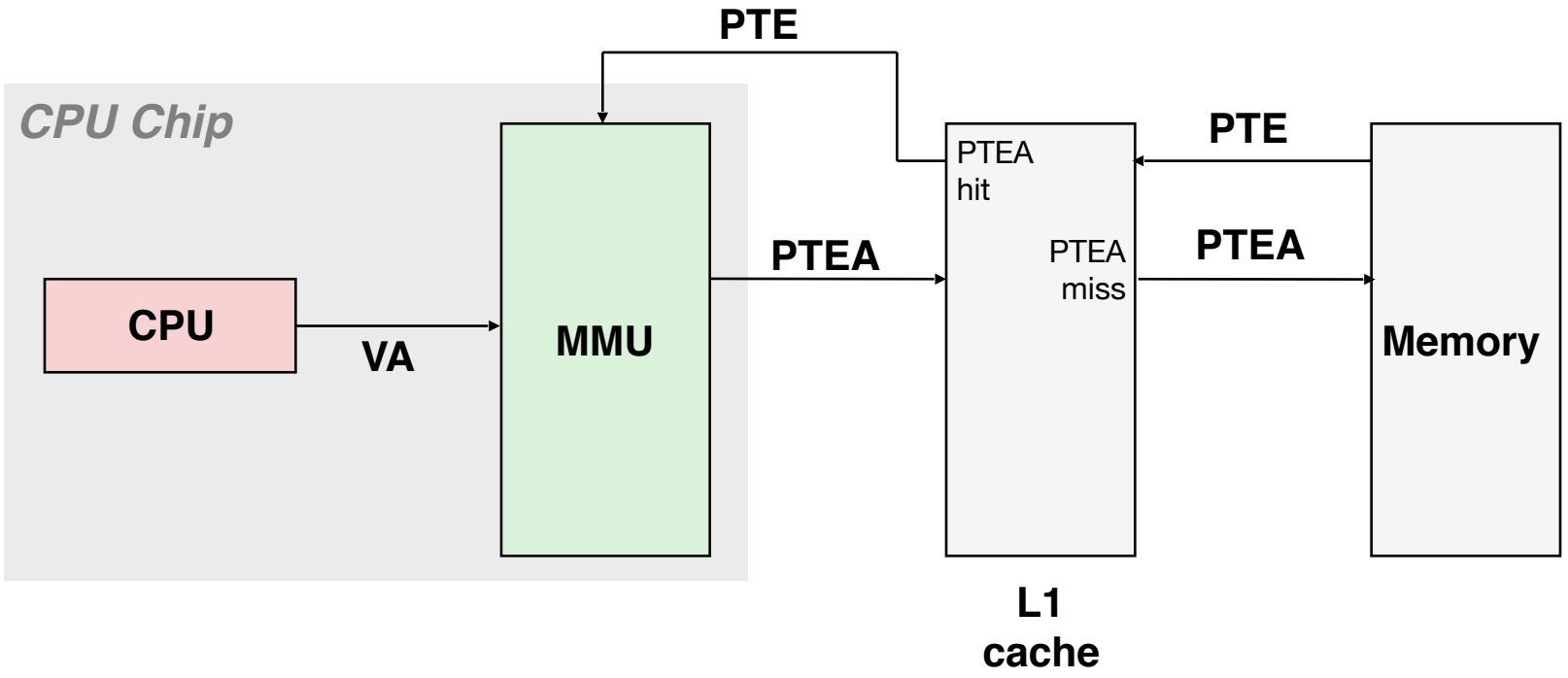

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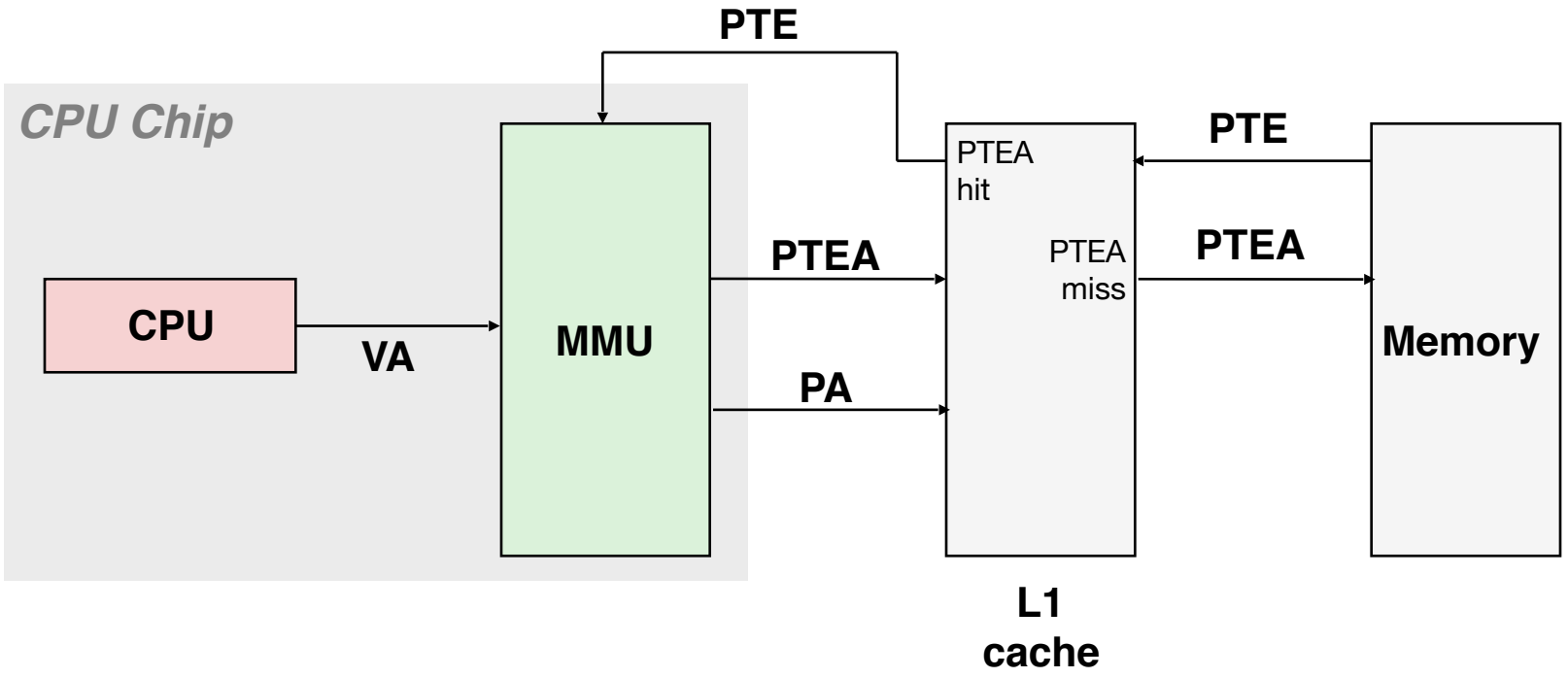

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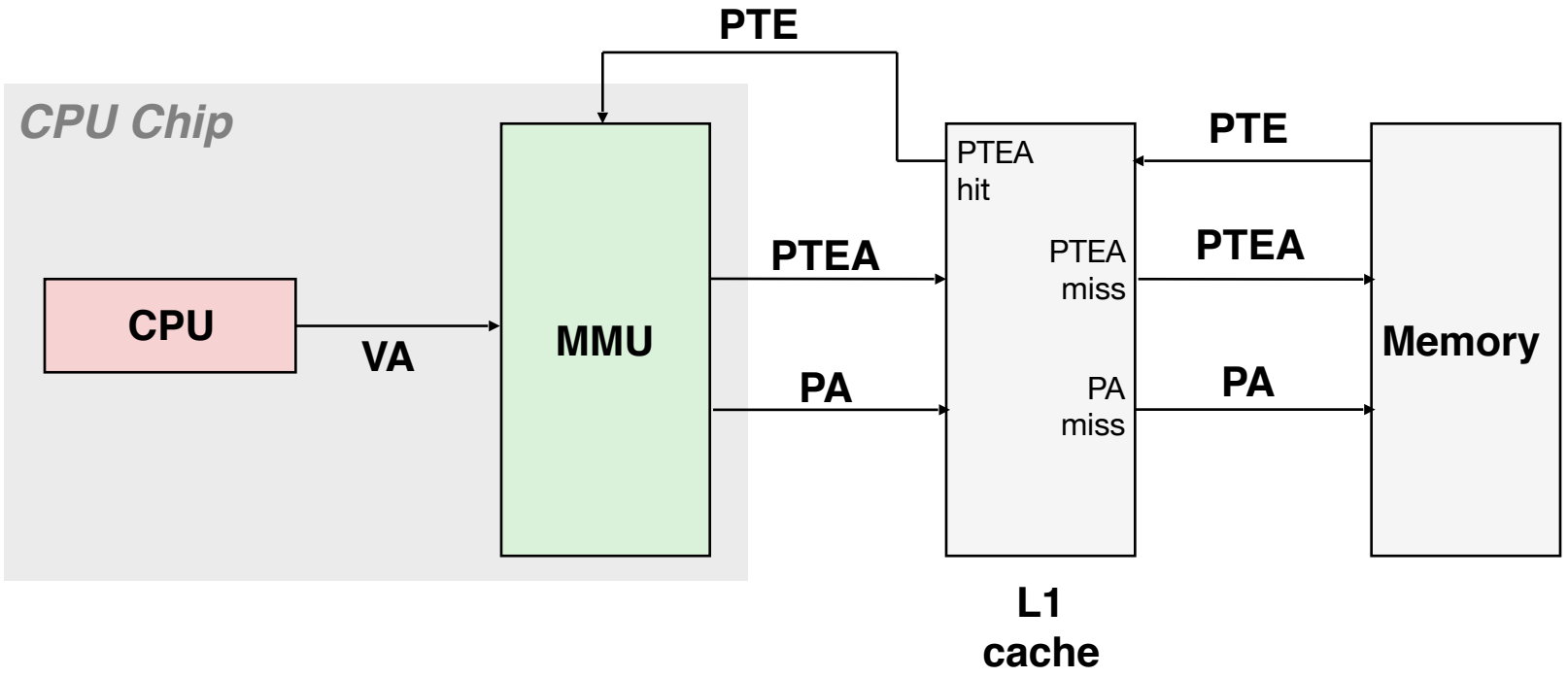

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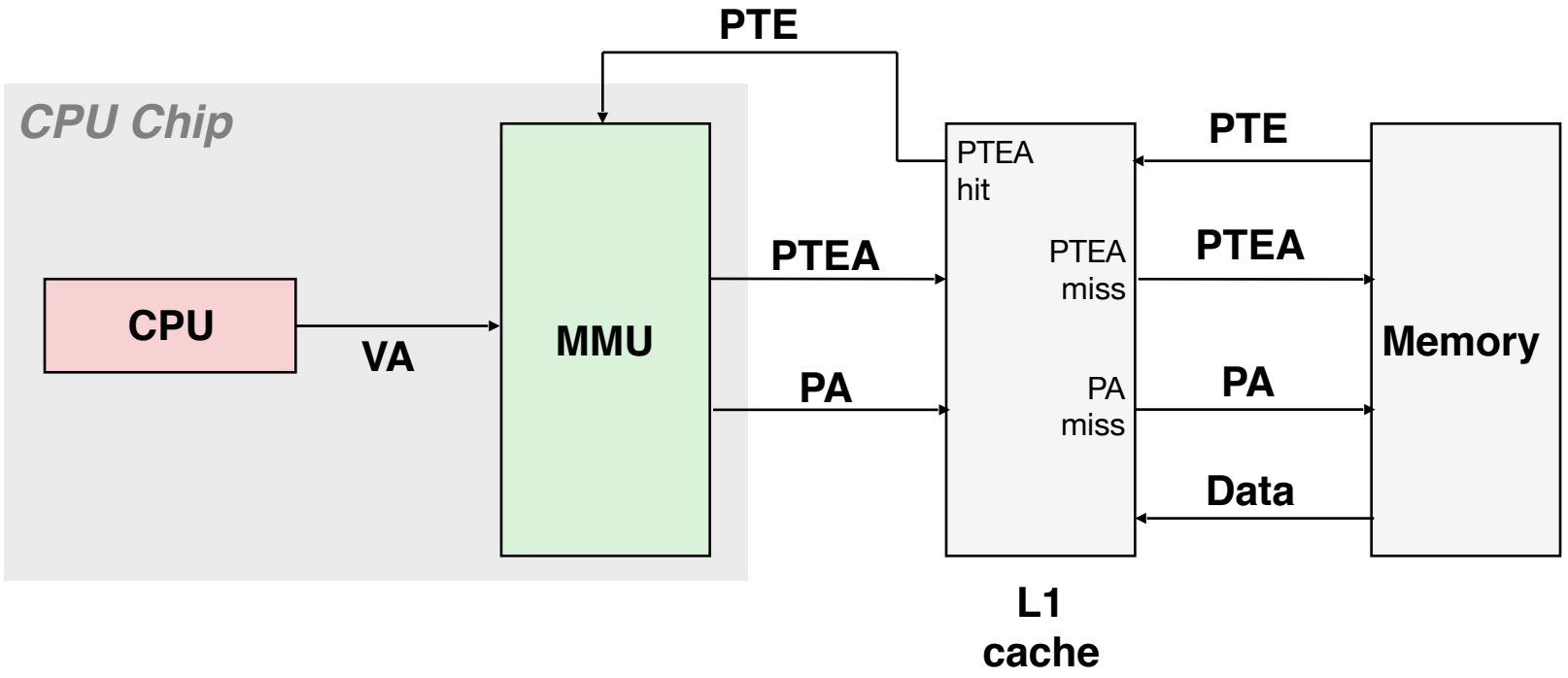

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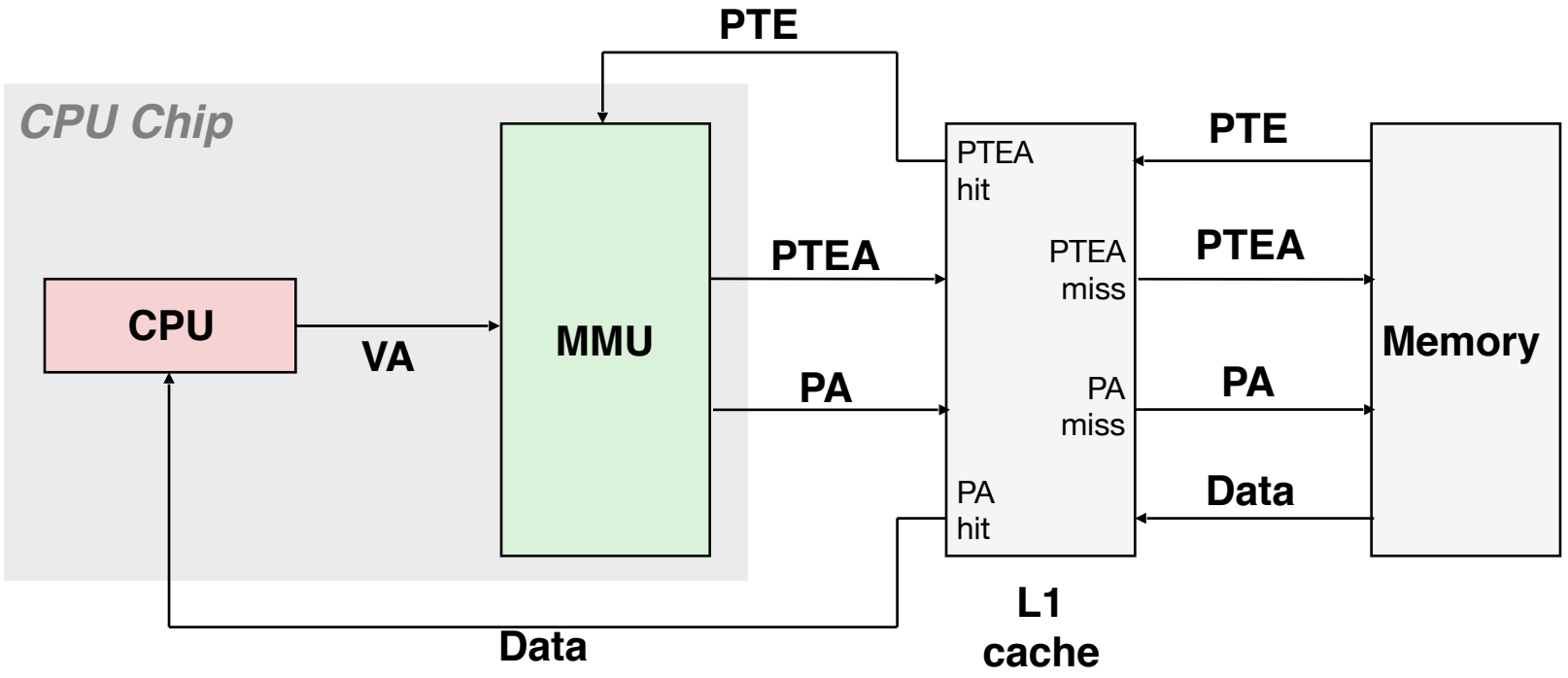

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