



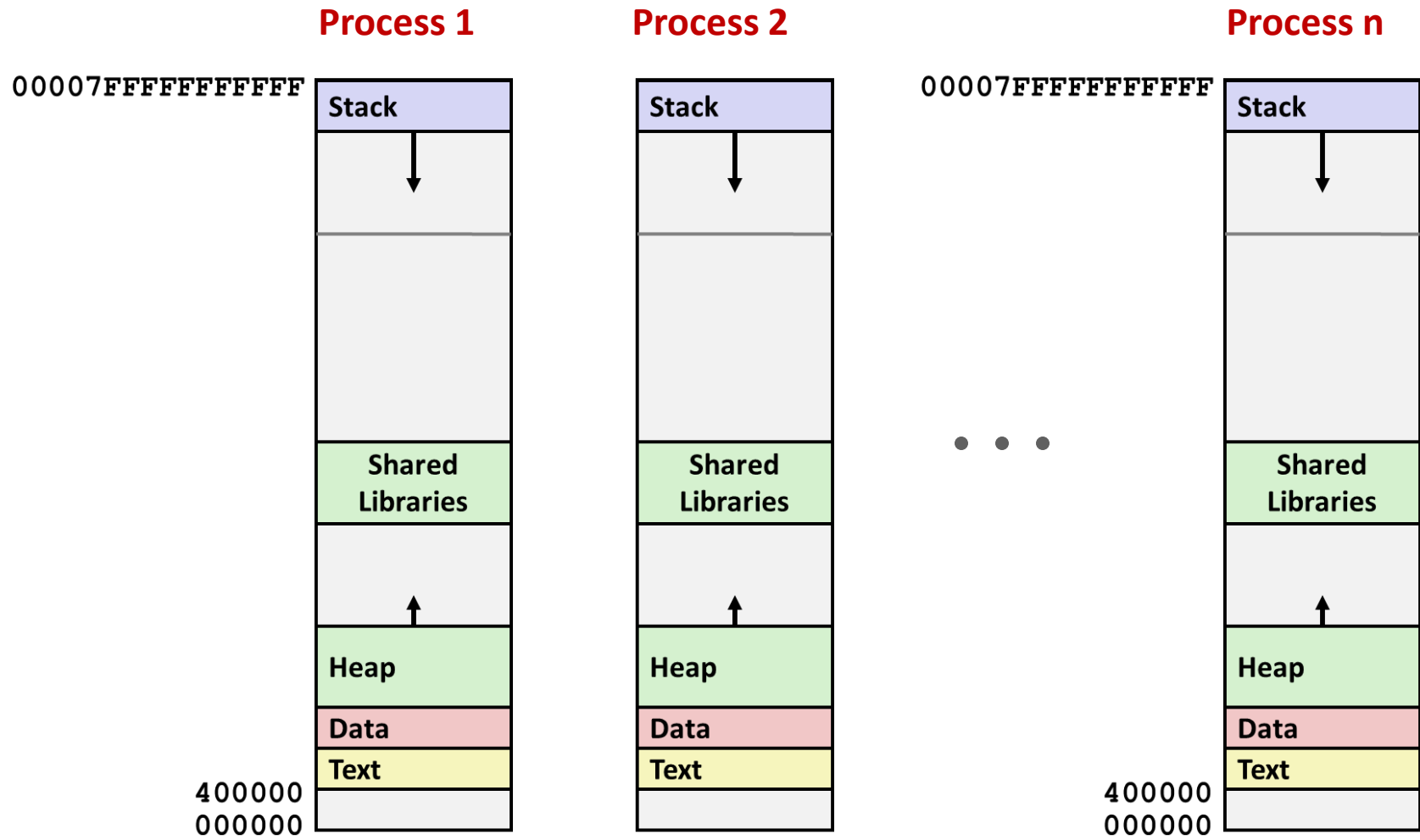
# Virtual Memory: Concepts

18-213/18-613: Introduction to Computer Systems  
12<sup>th</sup> Lecture, October 5, 2023

# Announcements

- Homework #5 due today
- No new HW released this week
- Low-stakes Midterm Review in Small Groups Mon Oct 9
- Lab 4 (cachelab) due Thurs Oct 12
- Homework #6/#7 (low-stakes take-home midterm) goes out Mon Oct 9 at 10 pm ET, due Fri Oct 13 at 11:59 pm
  - 80 minutes self-timed. Covers through 9/29 lecture. Questions similar to homeworks, but **only one attempt**. Closed book.
  - Tests what you've learned, as in a real midterm (and as in the Final).
  - Low-stakes: Only 4% of grade (could even be ½ HW dropped).

# Hmmm, How Does This Work?!

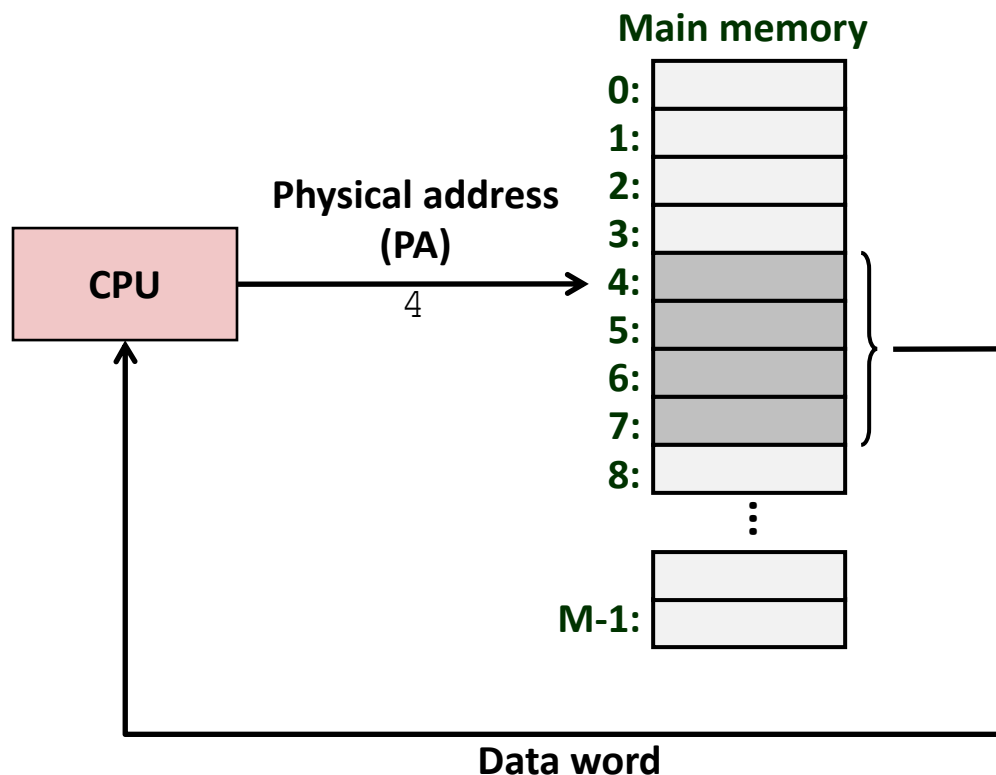


***Solution: Virtual Memory (today and next lecture)***

# Today

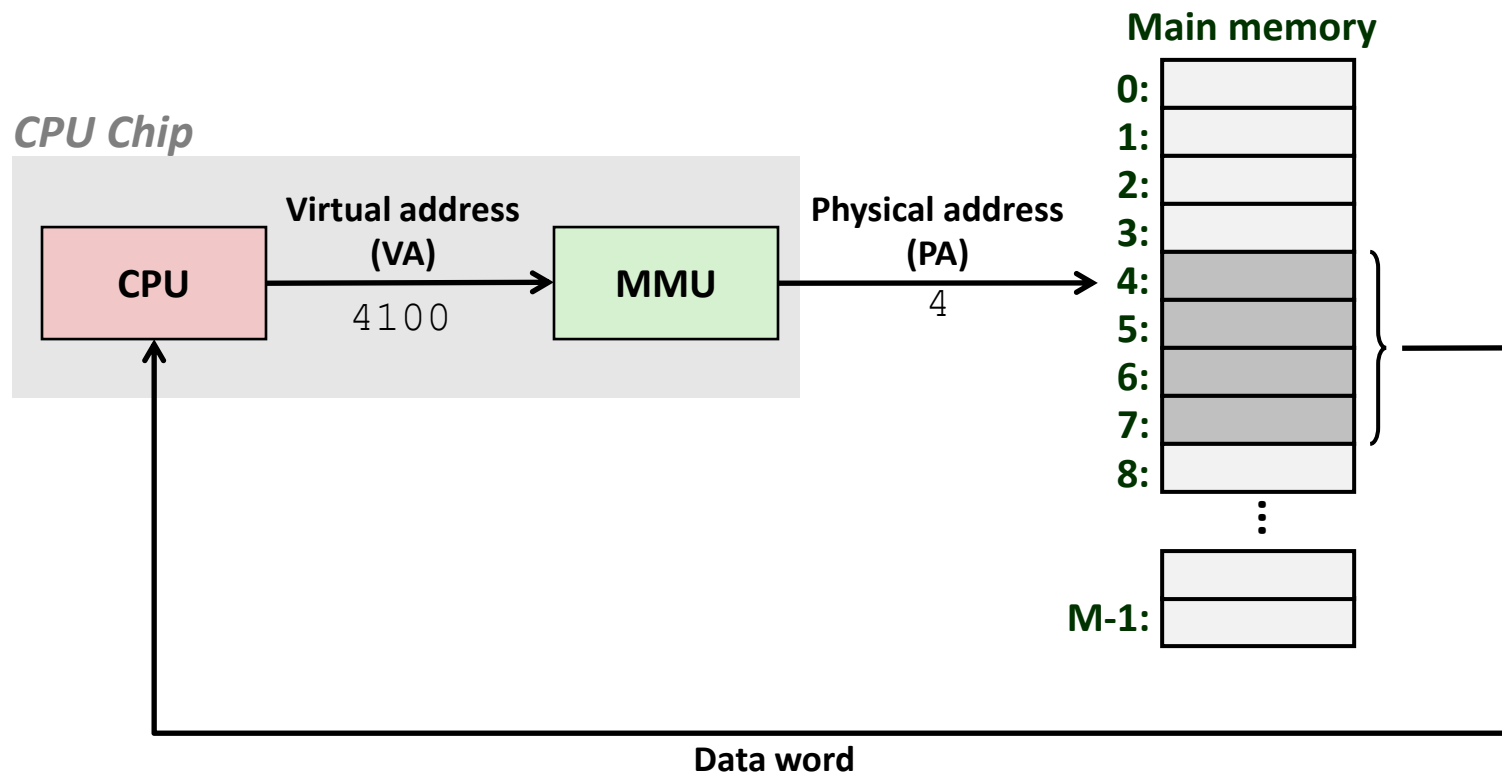
- **Address spaces** CSAPP 9.1-9.2
- VM as a tool for caching CSAPP 9.3
- VM as a tool for memory management CSAPP 9.4
- VM as a tool for memory protection CSAPP 9.5
- Address translation CSAPP 9.6

# A System Using Physical Addressing



- Used in “simple” systems like embedded microcontrollers in devices like 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

# Address Spaces

- **Linear address space:** Ordered set of contiguous non-negative integer addresses:

$\{0, 1, 2, 3 \dots \}$

- **Virtual address space:** Set of  $N = 2^n$  virtual addresses

$\{0, 1, 2, 3, \dots, N-1\}$

- **Physical address space:** Set of  $M = 2^m$  physical addresses

$\{0, 1, 2, 3, \dots, M-1\}$



# Why Virtual Memory (VM)?

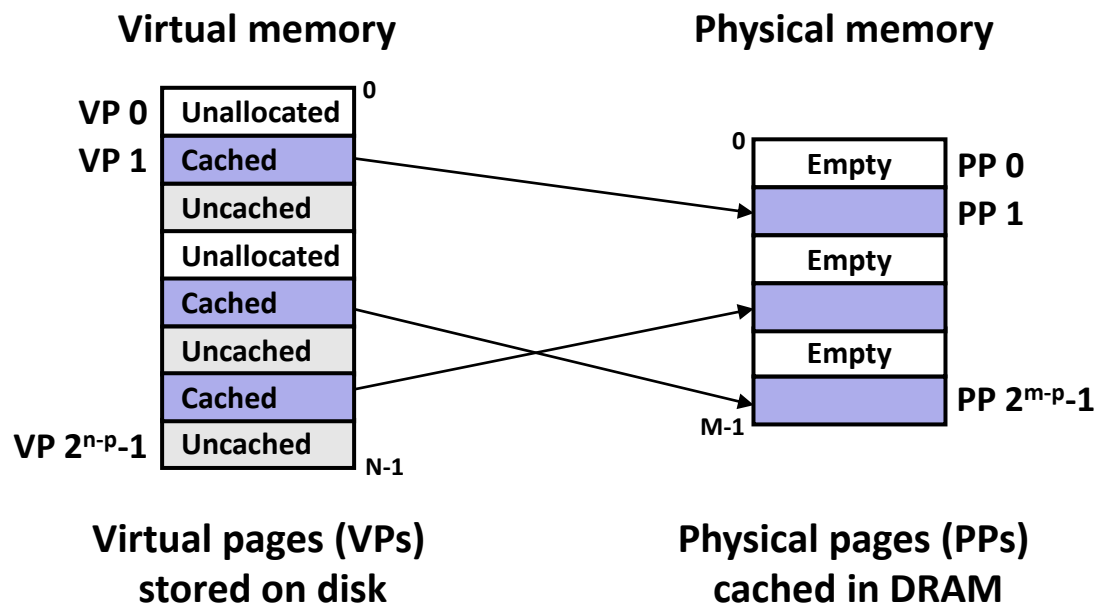
- **Uses main memory efficiently**
  - Use DRAM as a cache for parts of a virtual address space
- **Simplifies memory management**
  - Each process gets the same uniform linear address space
- **Isolates address spaces**
  - One process can't interfere with another's memory
  - User program cannot access privileged kernel information and code

# Today

- Address spaces
- **VM as a tool for caching**
- VM as a tool for memory management
- VM as a tool for memory protection
- Address translation

# VM as a Tool for Caching

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



# DRAM Cache Organization

## ■ DRAM cache organization driven by the enormous miss penalty

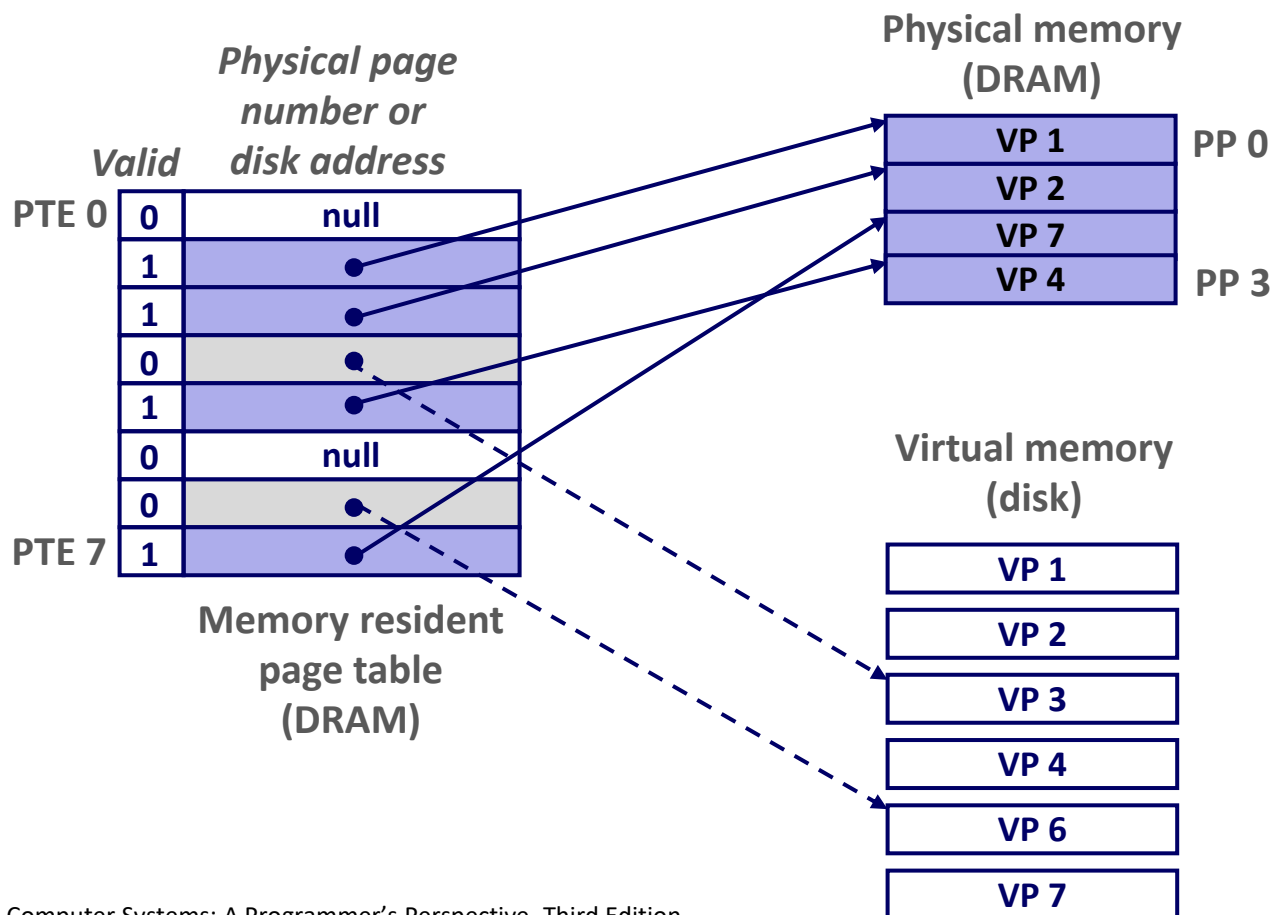
- DRAM is about **10x** slower than SRAM
- Disk is about **10,000x** slower than DRAM
- Time to load block from disk > 1ms (> 1 million clock cycles)
  - CPU can do a lot of computation during that time

## ■ Consequences

- Large page (block) size: typically 4 KB
  - Linux “huge pages” are 2 MB (default) to 1 GB
- Fully associative. *Why?*
  - Any VP can be placed in any PP
  - Requires a “large” mapping function – different from cache memories
- Highly sophisticated, expensive replacement algorithms. *Why?*
  - Too complicated and open-ended to be implemented in hardware
- Write-back rather than write-through. *Why?*

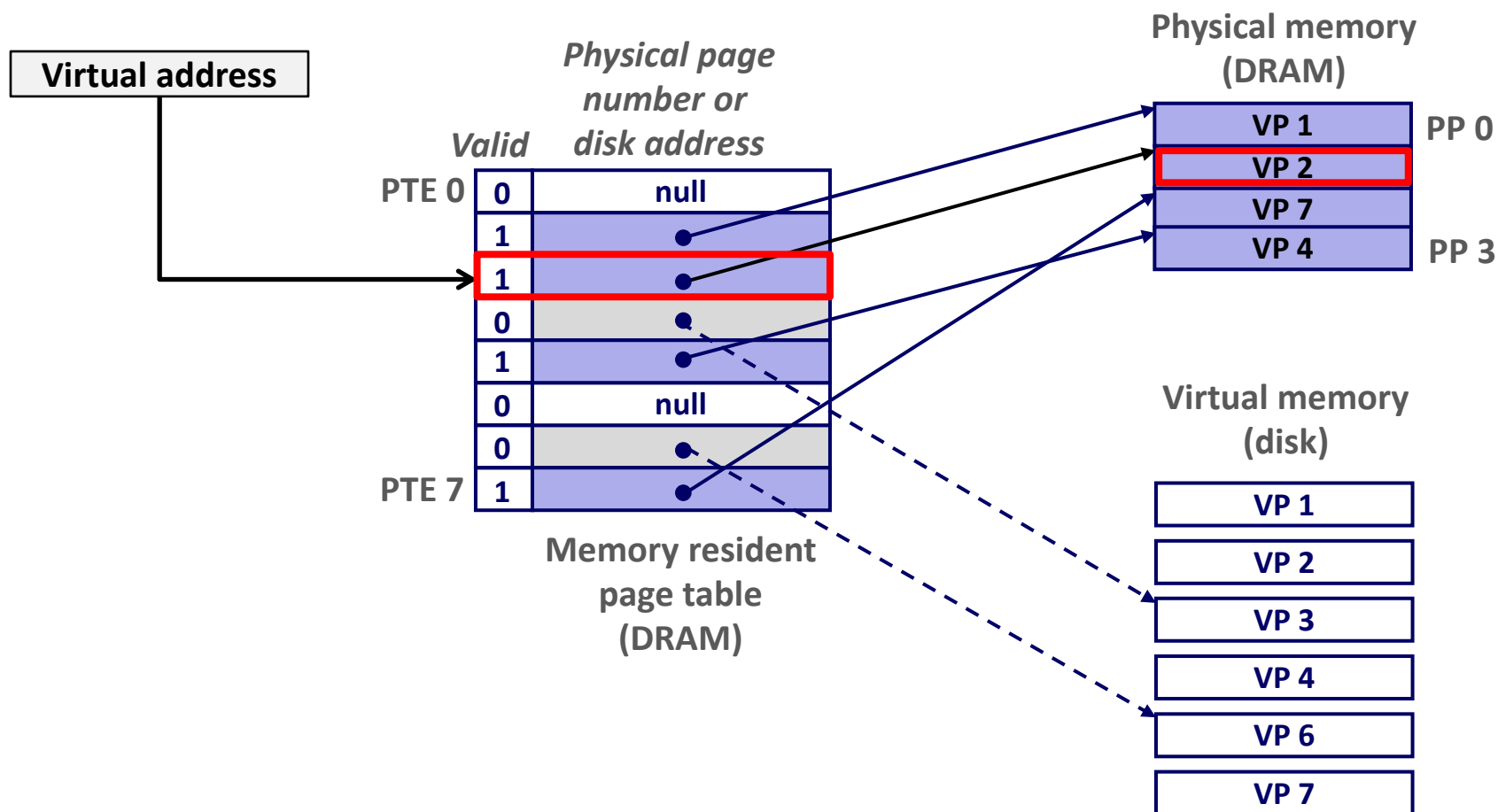
# Enabling Data Structure: Page Table

- A *page table* is an array of page table entries (PTEs) that maps virtual pages to physical pages.
  - Per-process kernel data structure in DRAM



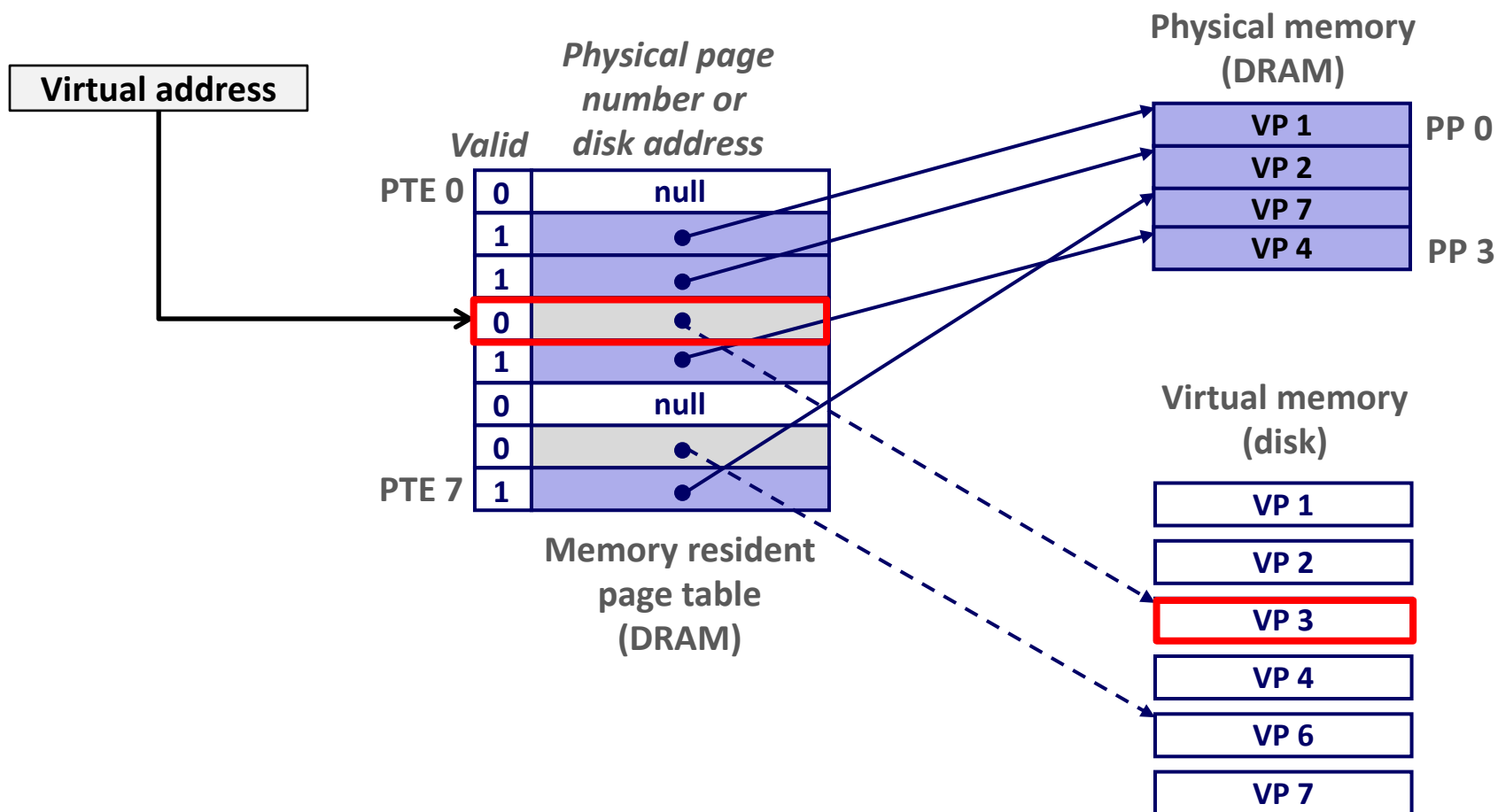
# Page Hit

- **Page hit:** reference to VM word that is in physical memory (DRAM cache hit)



# Page Fault

- **Page fault:** reference to VM word that is not in physical memory (DRAM cache miss)



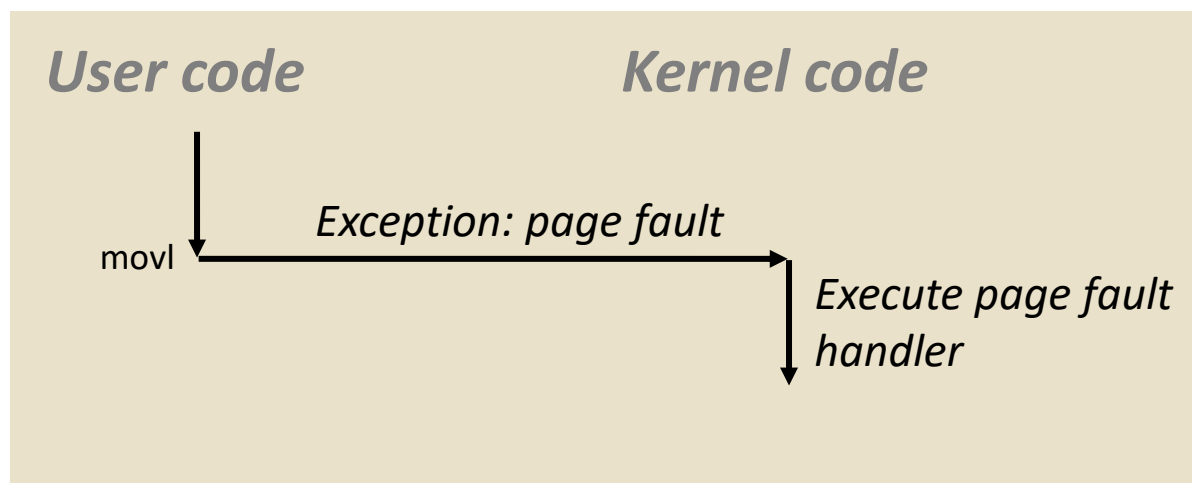
# Triggering a Page Fault

- User writes to memory location

```
80483b7:      c7 05 10 9d 04 08 0d  movl   $0xd,0x8049d10
```

- That portion (page) of user's memory is currently on disk
- MMU triggers page fault exception
  - (More details in later lecture)
  - Raise privilege level to supervisor mode
  - Causes procedure call to software page fault handler

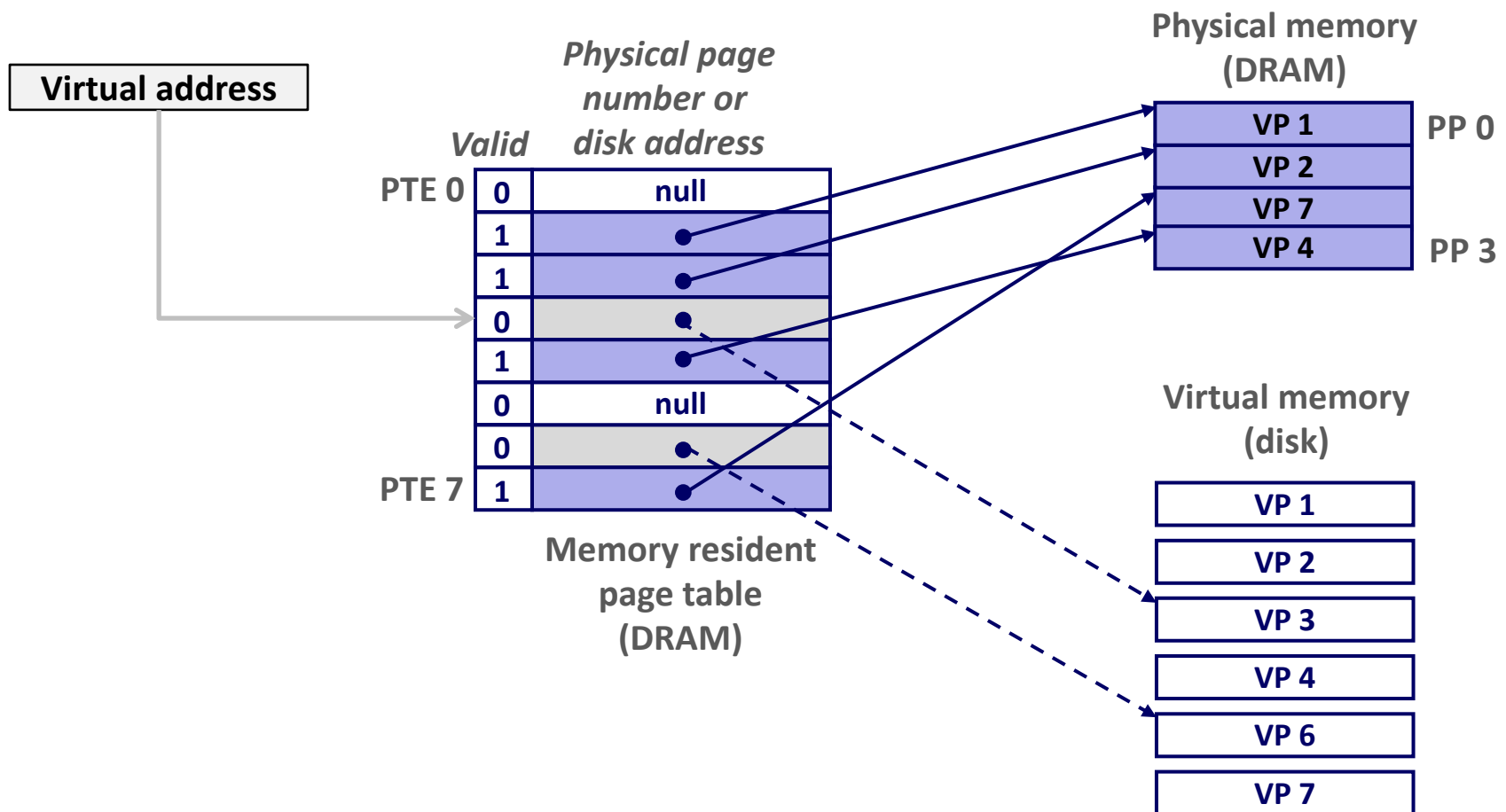
```
int a[1000];
main ()
{
    a[500] = 13;
}
```





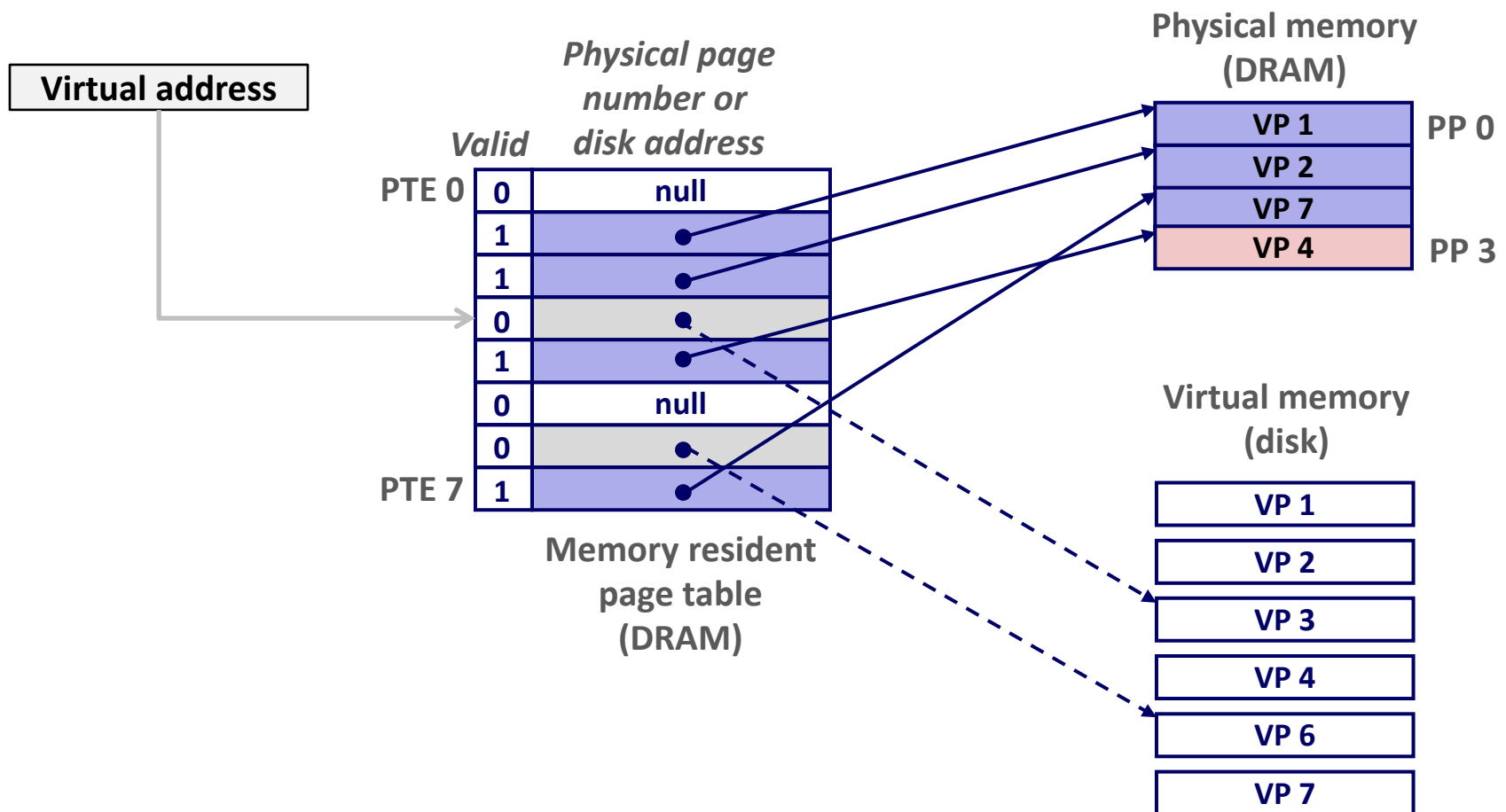
# Handling Page Fault

- Page miss causes page fault (an exception)



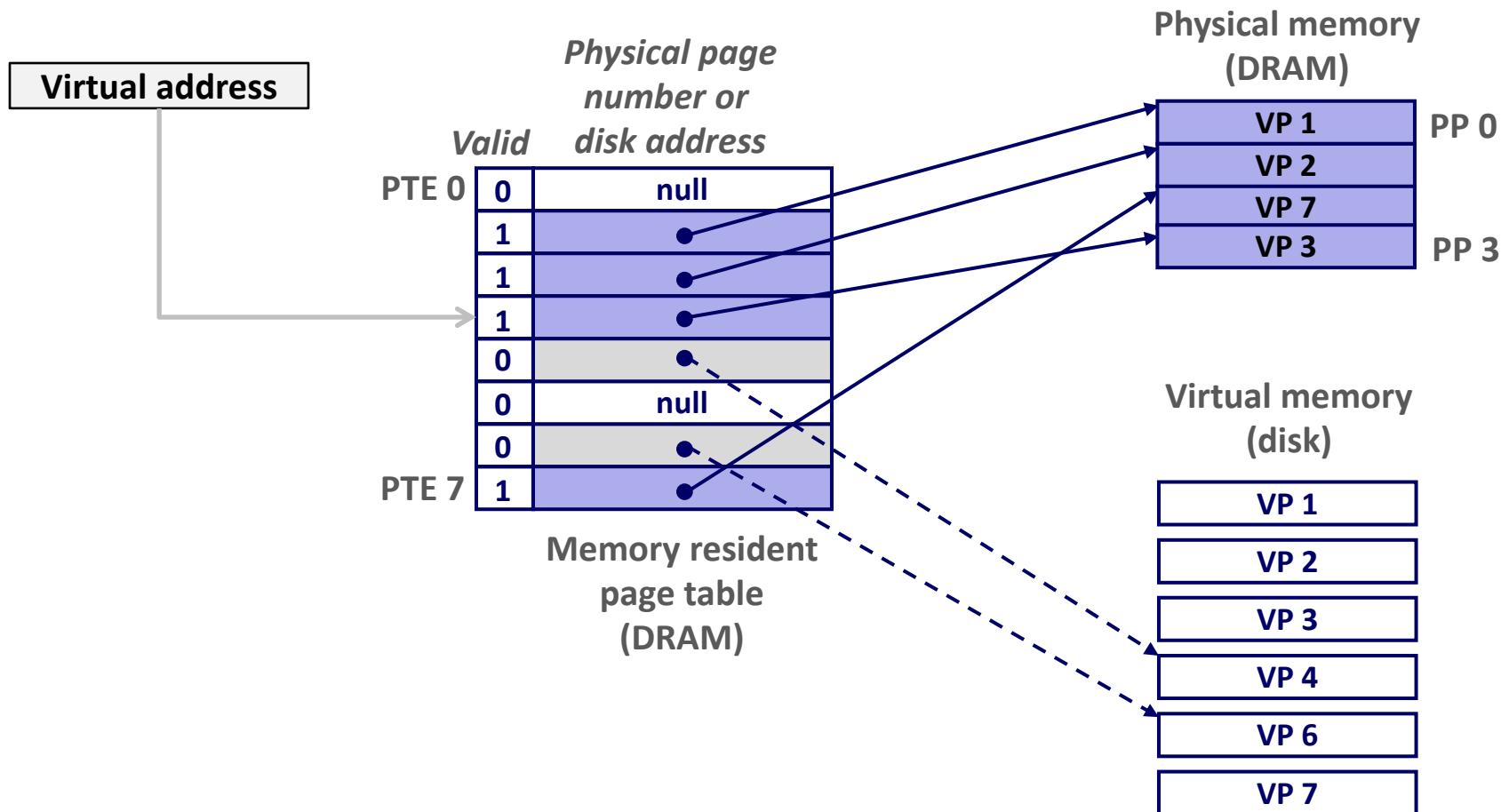
# Handling Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)



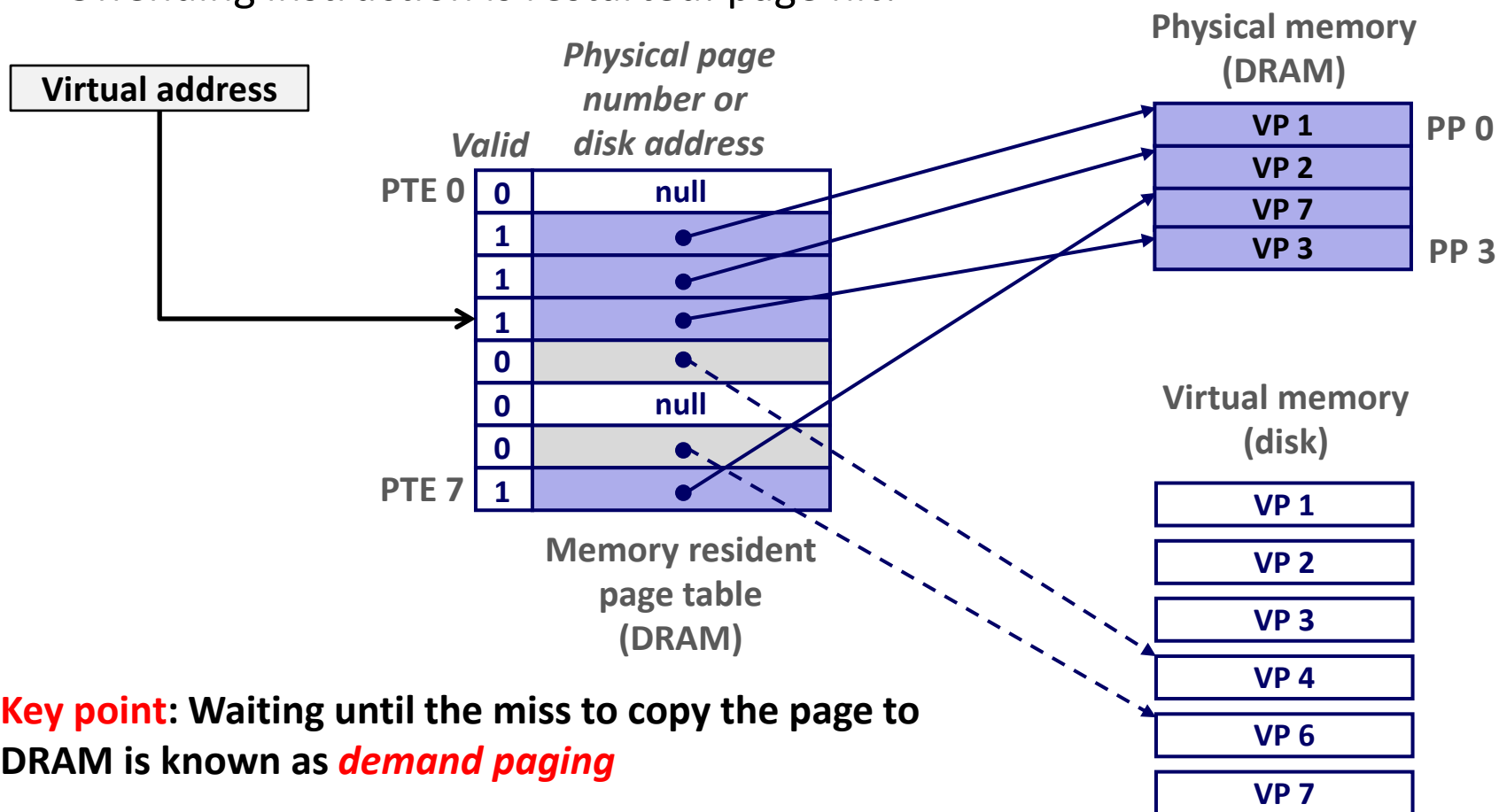
# Handling Page Fault

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# Handling Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)
- Offending instruction is restarted: page hit!

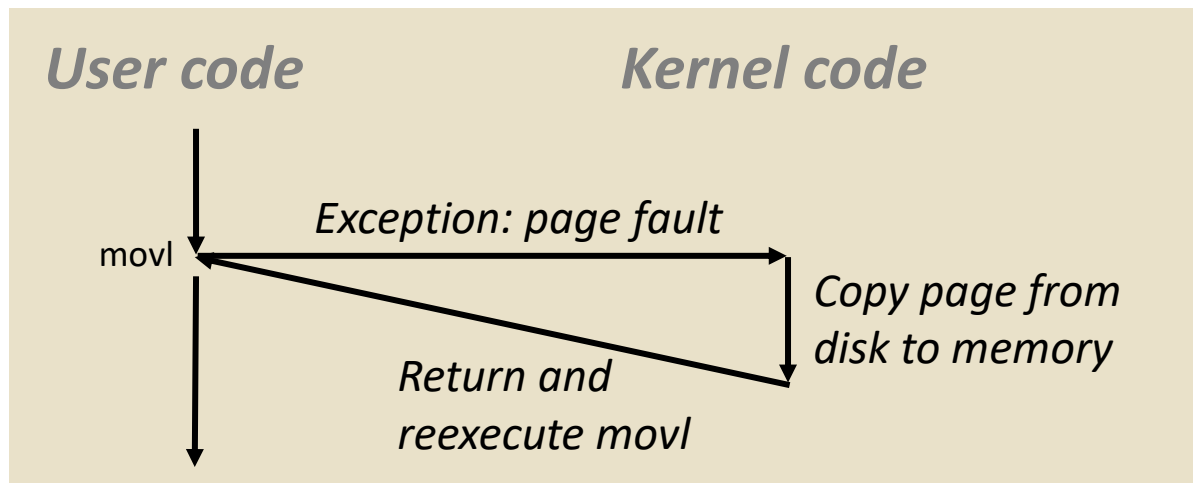


# Completing page fault

- Page fault handler executes return from interrupt (**iret**) instruction
  - Like **ret** instruction, but also restores privilege level
  - Return to instruction that caused fault
  - But, this time there is no page fault

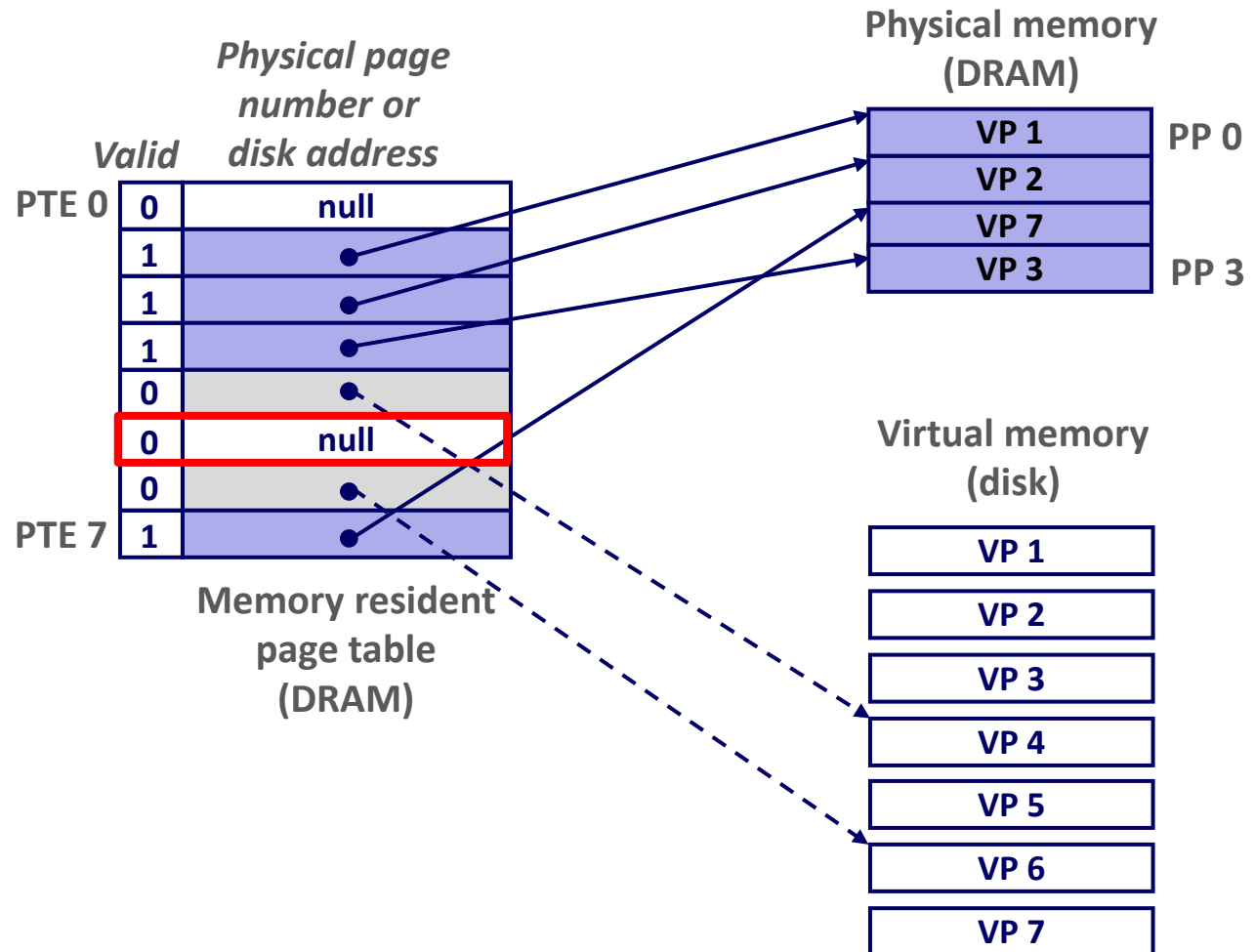
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80483b7:      c7 05 10 9d 04 08 0d  movl   $0xd,0x8049d10
```



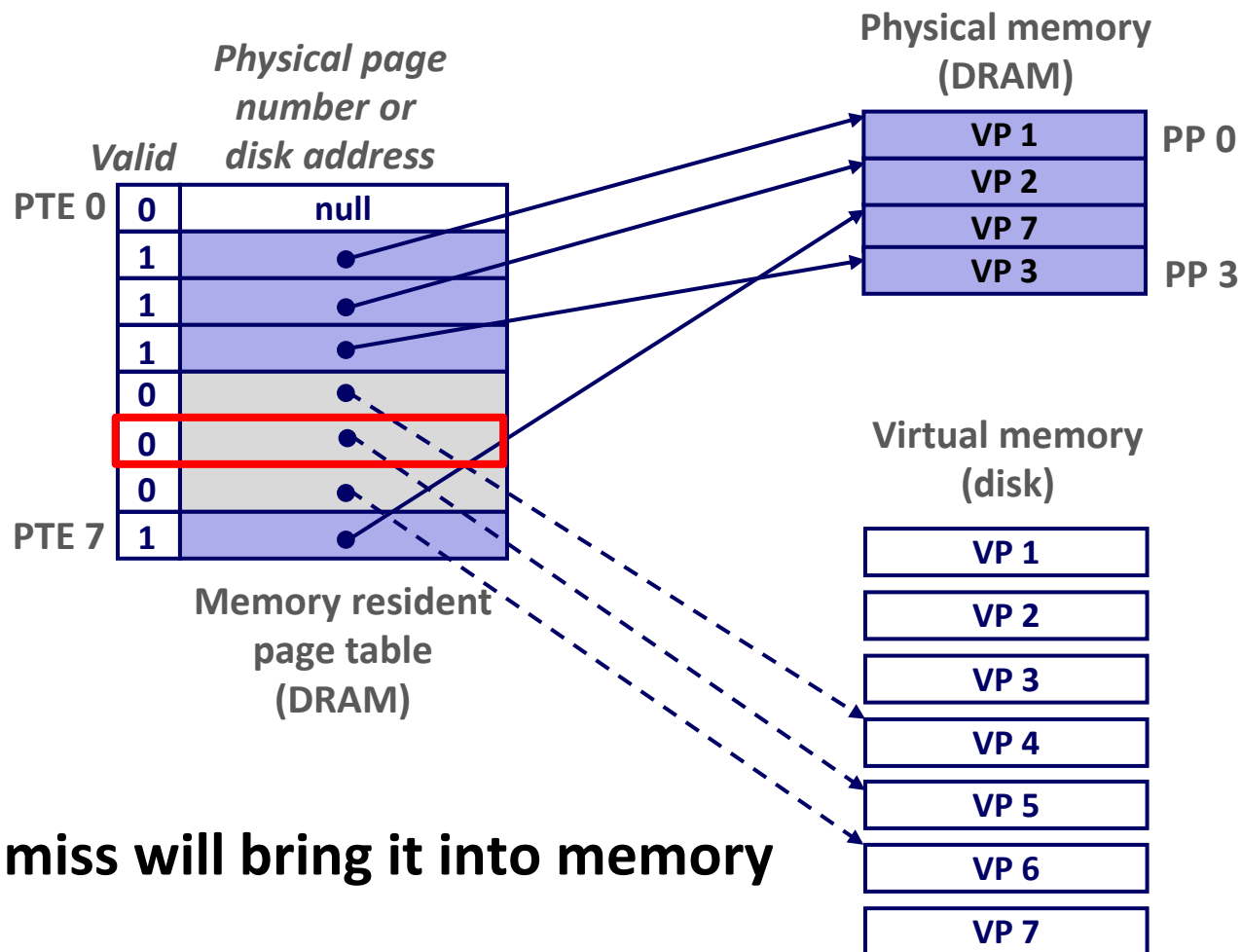
# Allocating Pages

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



# Allocating Pages

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



- Subsequent miss will bring it into memory

# Locality to the Rescue 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 cold misses)
- If (working set size > main memory size )
  - *Thrashing*: Performance meltdown where pages are swapped (copied) in and out continuously
  - If multiple processes run at the same time, thrashing occurs if their total working set size > main memory size

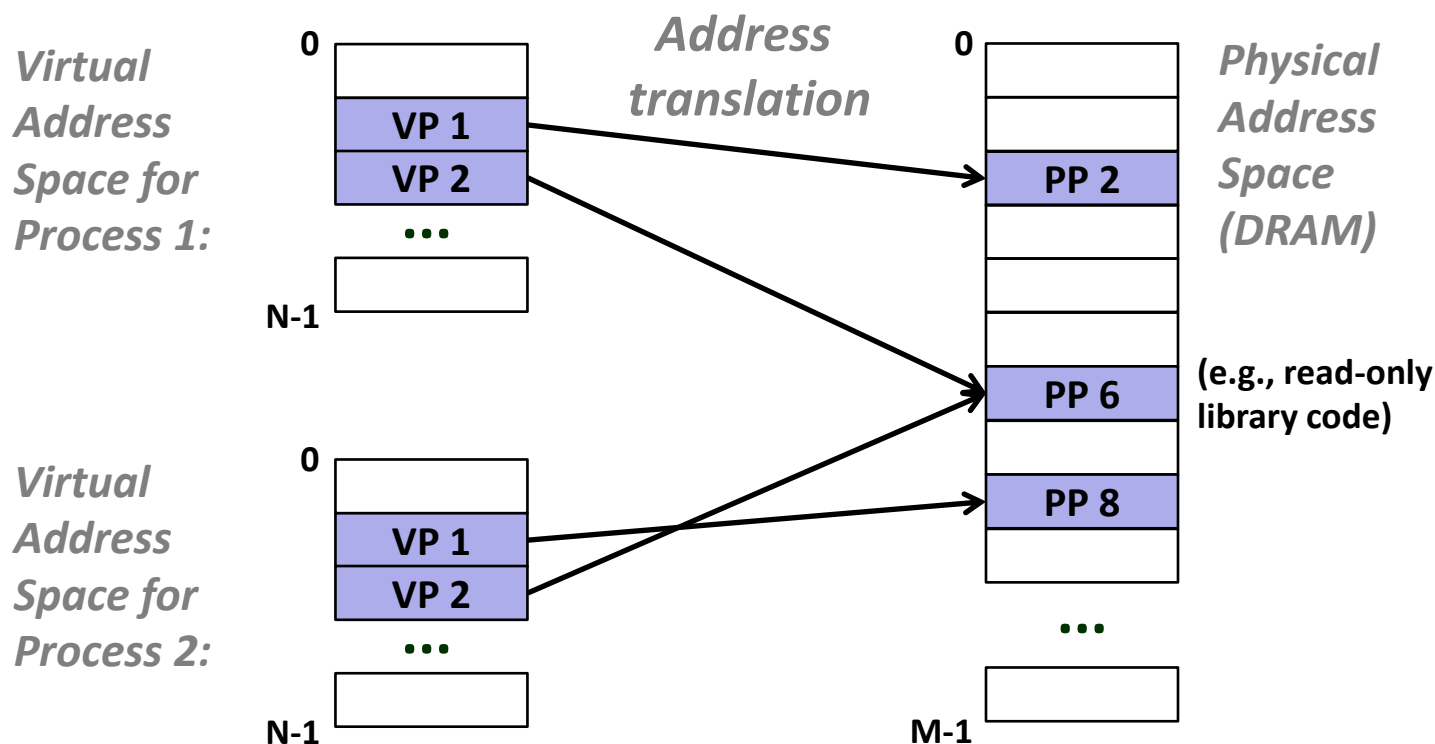


# Today

- Address spaces
- VM as a tool for caching
- **VM as a tool for memory management**
- VM as a tool for memory protection
- Address translation

# VM as a Tool for Memory Management

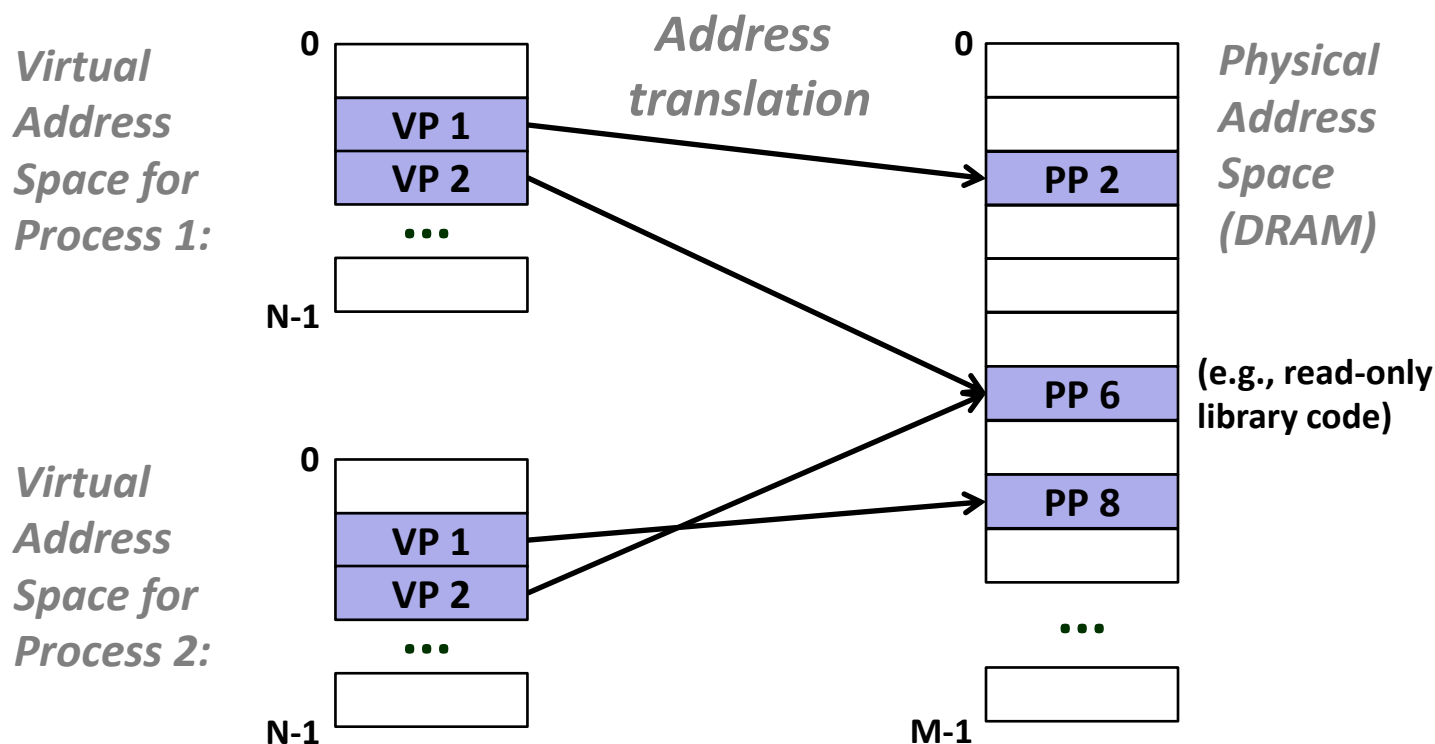
- **Key idea: each process has its own virtual address space**
  - It can view memory as a simple linear array
  - Mapping function scatters addresses through physical memory
    - Well-chosen mappings can improve locality



# VM as a Tool for Memory Management

## ■ Simplifying memory allocation

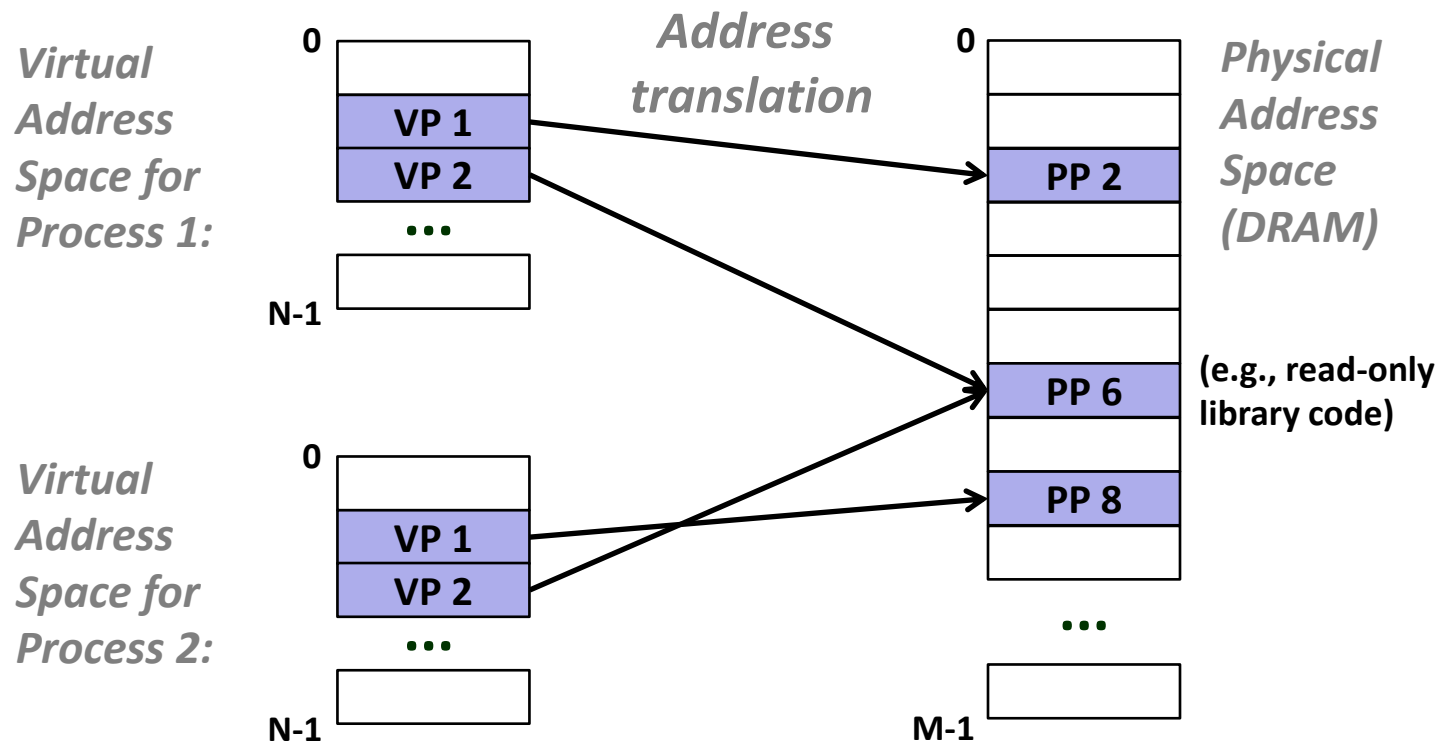
- Each virtual page can be mapped to any physical page
- A virtual page can be stored in different physical pages at different times
- Can allocate the same virtual addresses on the heap for multiple processes



# VM as a Tool for Memory Management

## ■ Sharing code and data among processes

- Map virtual pages to the same physical page (here: PP 6)



# Simplifying Linking and Loading

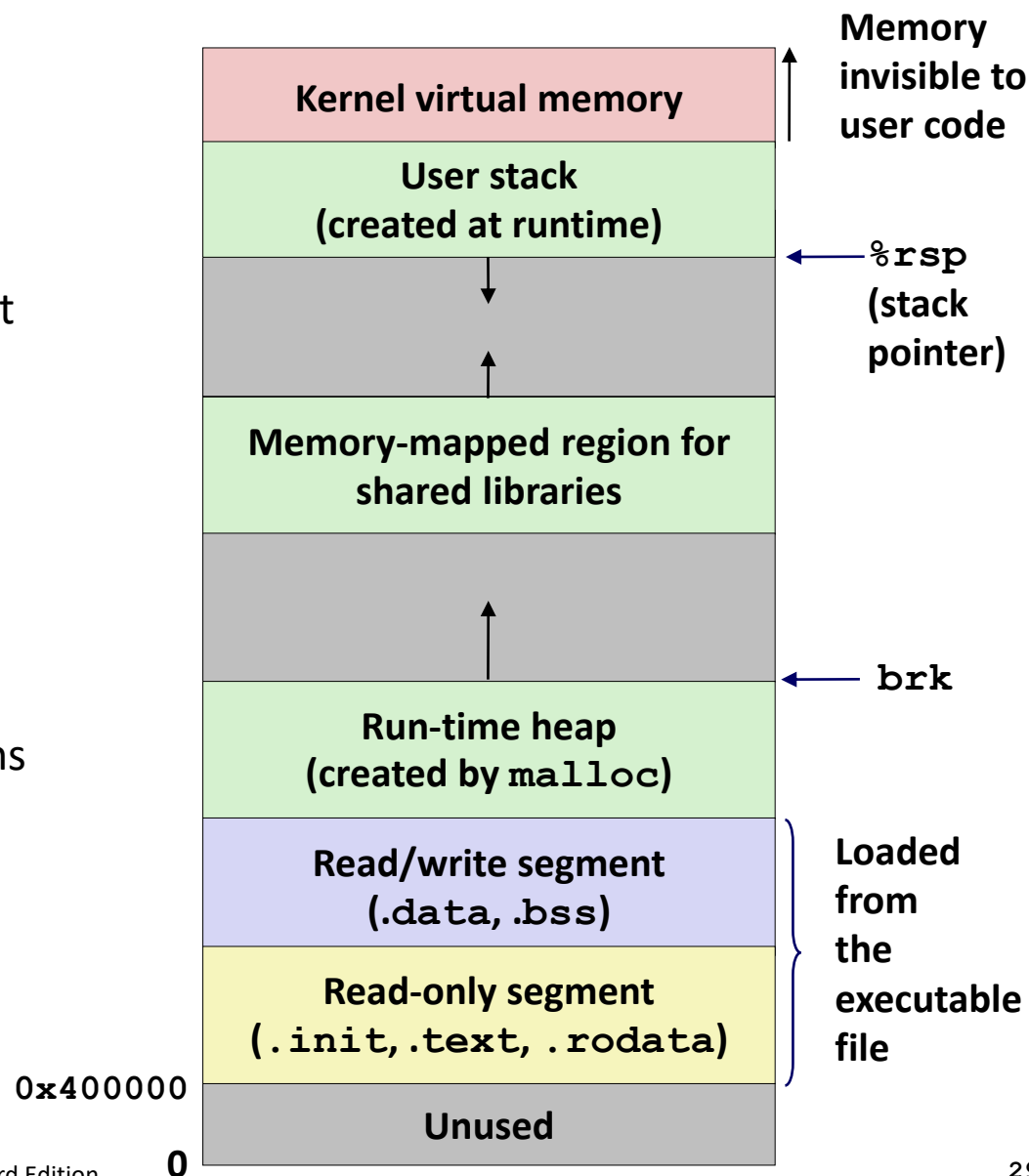
## ■ Linking

- 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 virtual memory system

## ■ Discussed later in lecture on Linking and Loading

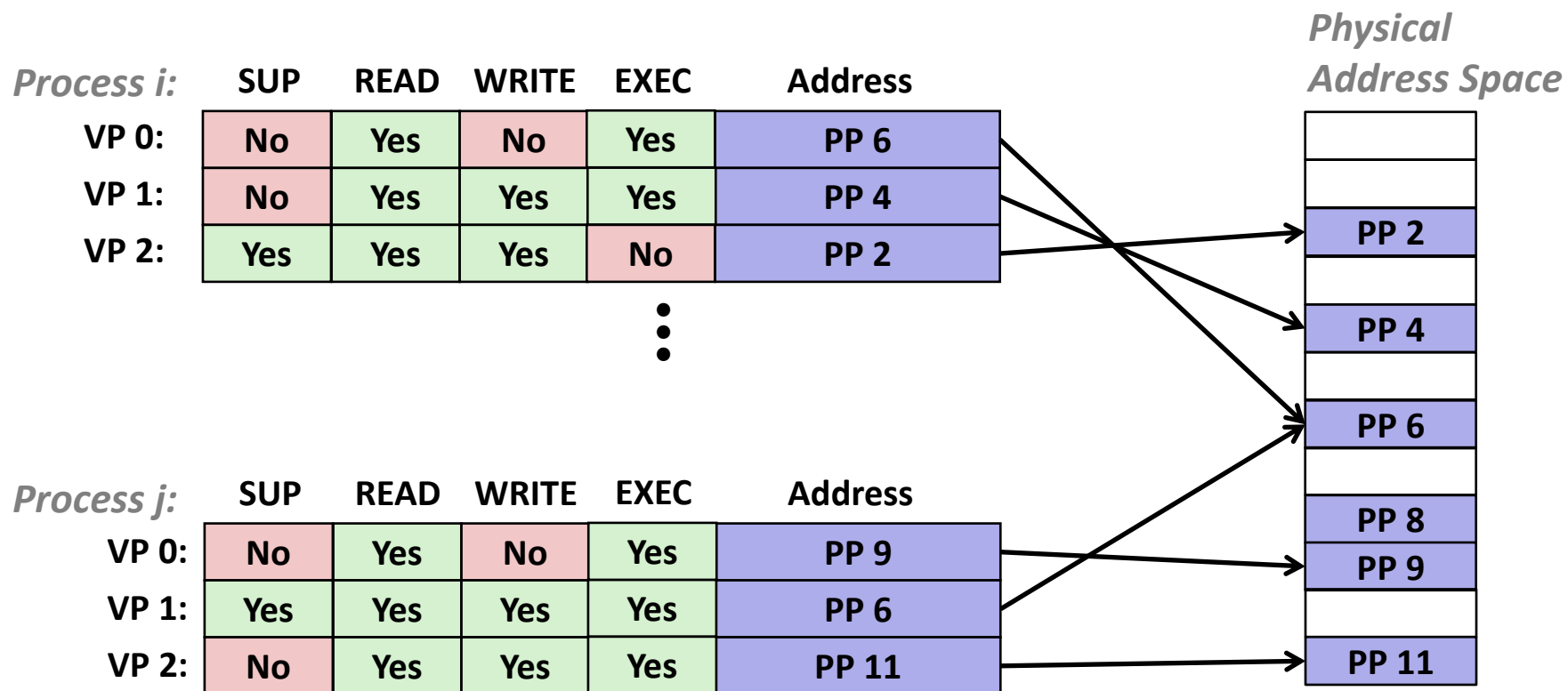


# Today

- Address spaces
- VM as a tool for caching
- VM as a tool for memory management
- **VM as a tool for memory protection**
- Address translation

# VM as a Tool for Memory Protection

- Extend page table entries (PTEs) with permission bits
- MMU checks these bits on each access



**SUP:** requires kernel mode

# Quiz Time!

Canvas Quiz: Day 12 – VM Concepts



# Today

- Address spaces
- VM as a tool for caching
- VM as a tool for memory management
- VM as a tool for memory protection
- **Address translation**

# VM Address Translation

## ■ Virtual Address Space

- $V = \{0, 1, \dots, N-1\}$

## ■ Physical Address Space

- $P = \{0, 1, \dots, M-1\}$

## ■ Address Translation

- $MAP: V \rightarrow P \cup \{\emptyset\}$

- For virtual address  $a$ :

- $MAP(a) = a'$  if data at virtual address  $a$  is at physical address  $a'$  in  $P$
- $MAP(a) = \emptyset$  if data at virtual address  $a$  is not in physical memory
  - Either invalid or stored on disk

# Summary of Address Translation Symbols

## ■ Basic Parameters

- $N = 2^n$  : Number of addresses in virtual address space
- $M = 2^m$  : Number of addresses in physical address space
- $P = 2^p$  : Page size (bytes)

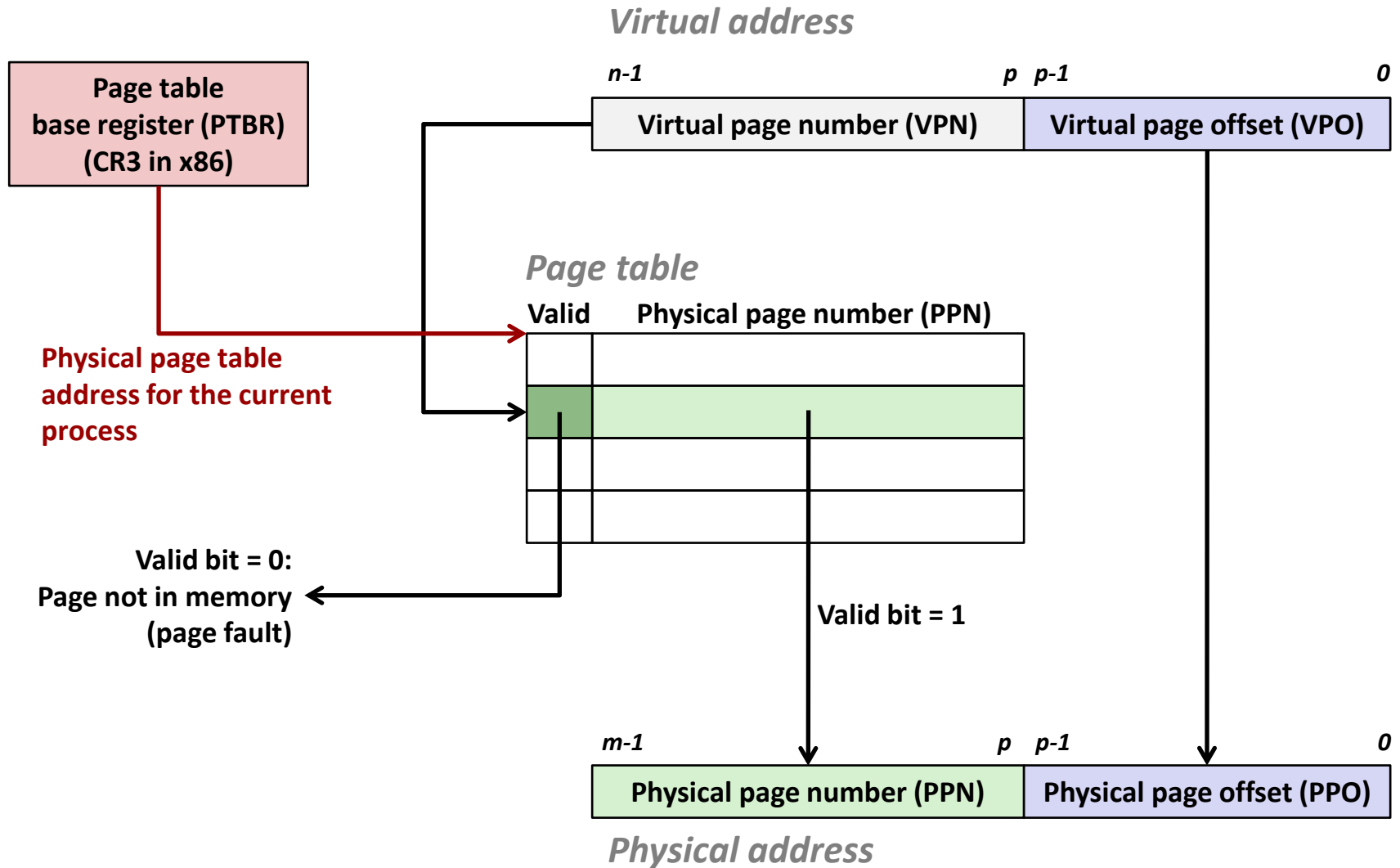
## ■ Components of the virtual address (VA)

- VPO: Virtual page offset
- VPN: Virtual page number

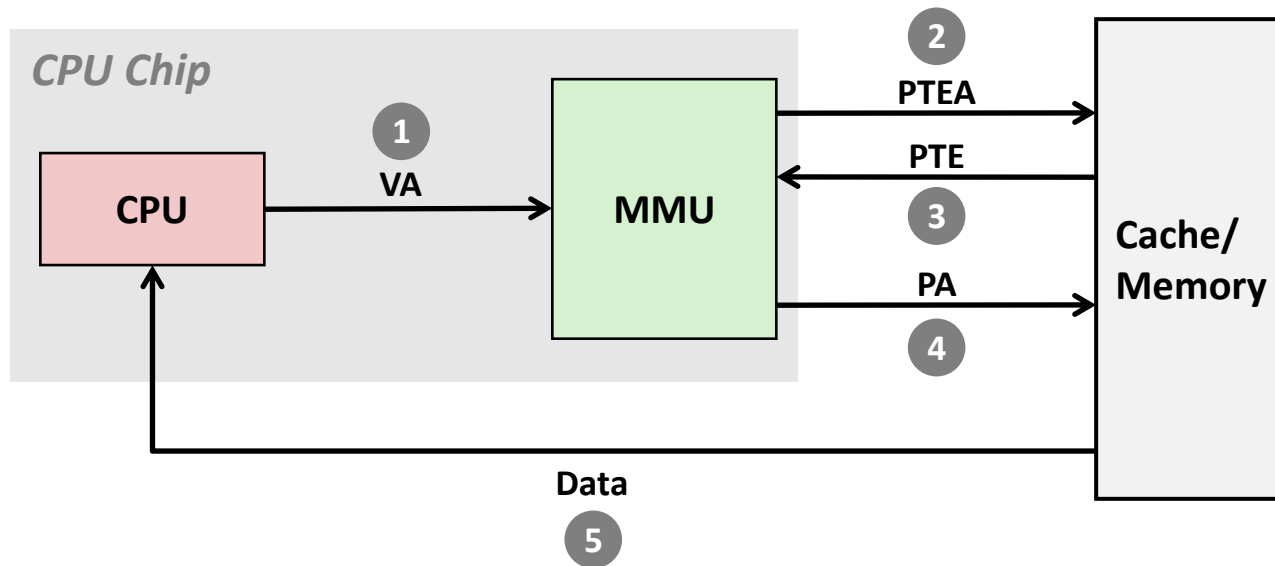
## ■ Components of the physical address (PA)

- PPO: Physical page offset (same as VPO)
- PPN: Physical page number

# Address Translation With a Page Table

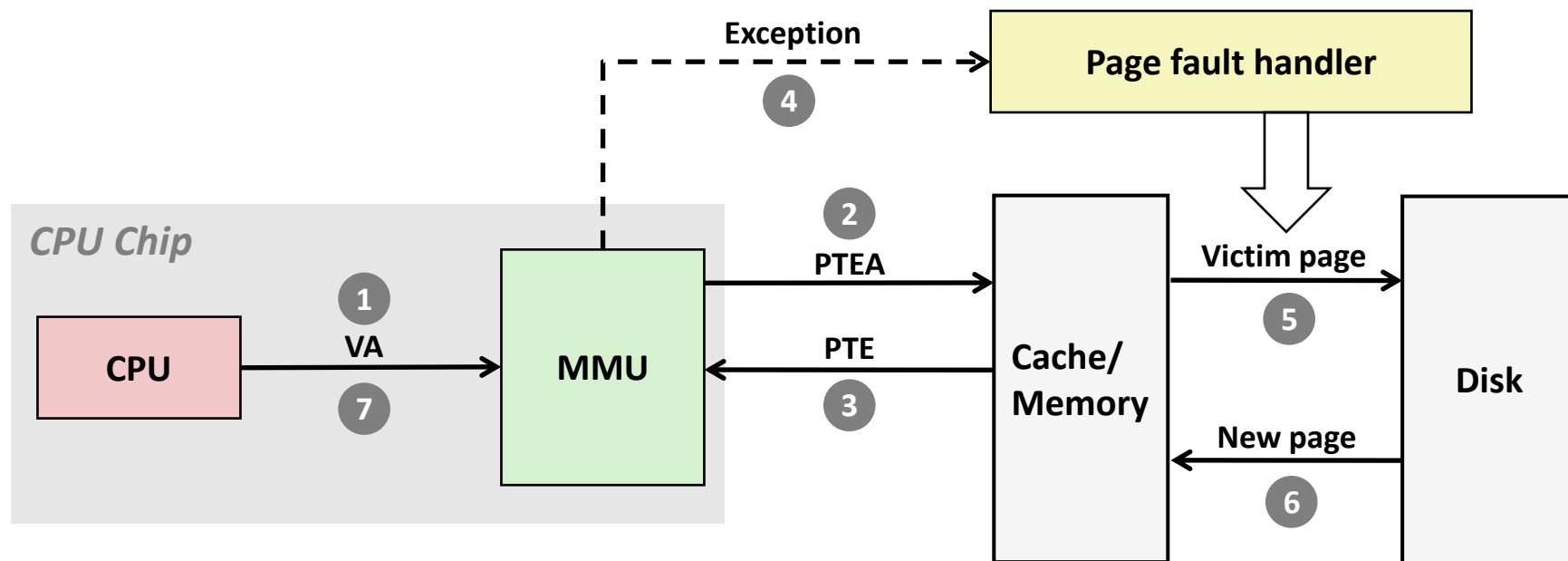


# Address Translation: Page Hit



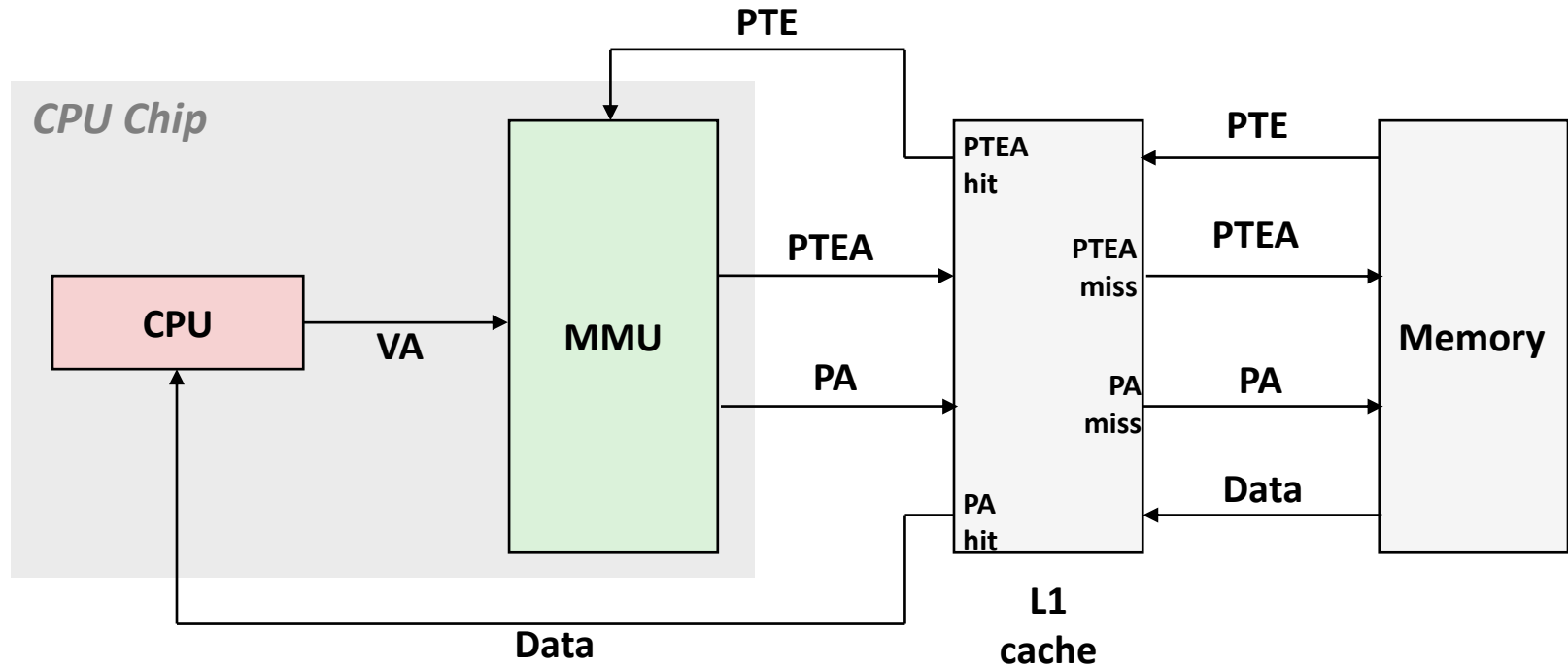
- 1) Processor sends virtual address to MMU
- 2-3) MMU fetches PTE from page table in memory
- 4) MMU sends physical address to cache/memory
- 5) Cache/memory sends data word to processor

# 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
- 5) Handler identifies victim to page out (if dirty, writes pages to disk)
- 6) Handler pages in new page and updates PTE in memory
- 7) Handler returns to original process, restarting faulting instruction

# Integrating VM and Cache



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

# Speeding up Translation with a TLB

- **Page table entries (PTEs) are cached in L1 like any other memory word**
  - PTEs may be evicted by other data references
  - PTE hit still requires a small L1 delay
- **Solution: *Translation Lookaside Buffer* (TLB)**
  - Small set-associative hardware cache in MMU
  - Maps virtual page numbers to physical page numbers
  - Contains complete page table entries for small number of pages



# Summary of Address Translation Symbols

## ■ Basic Parameters

- $N = 2^n$  : Number of addresses in virtual address space
- $M = 2^m$  : Number of addresses in physical address space
- $P = 2^p$  : Page size (bytes)

## ■ Components of the virtual address (VA)

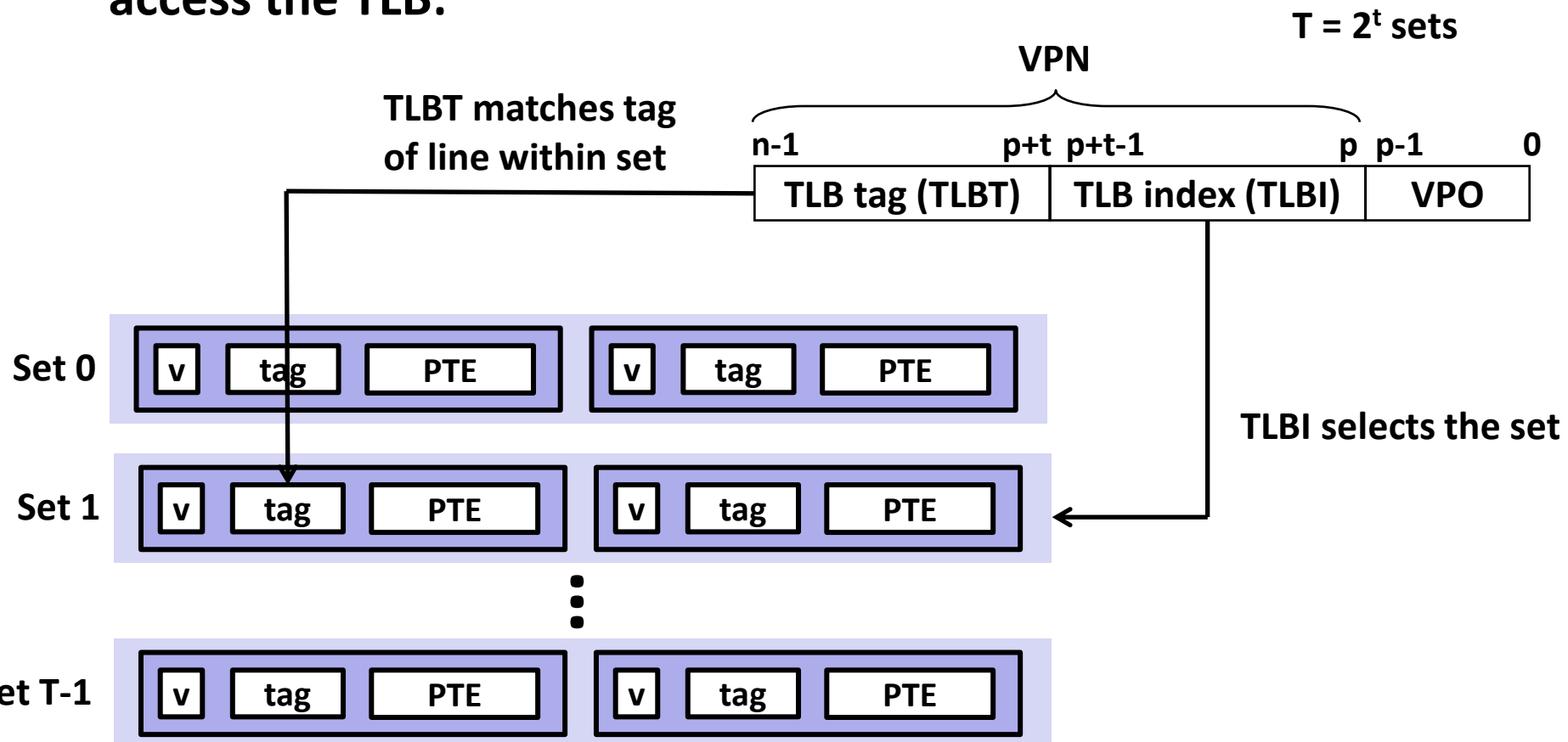
- *TLBI: TLB index*
- *TLBT: TLB tag*
- **VPO**: Virtual page offset
- **VPN**: Virtual page number

## ■ Components of the physical address (PA)

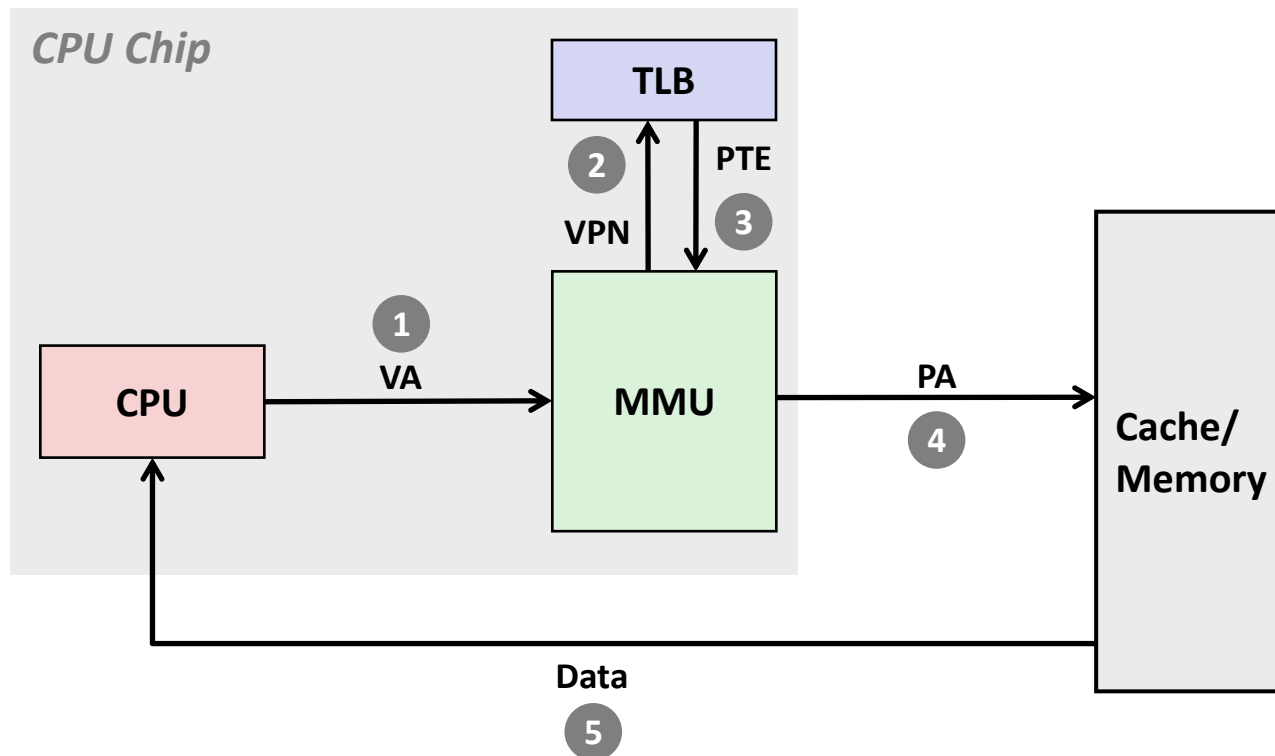
- **PPO**: Physical page offset (same as VPO)
- **PPN**: Physical page number

# Accessing the TLB

- MMU uses the VPN portion of the virtual address to access the TLB:

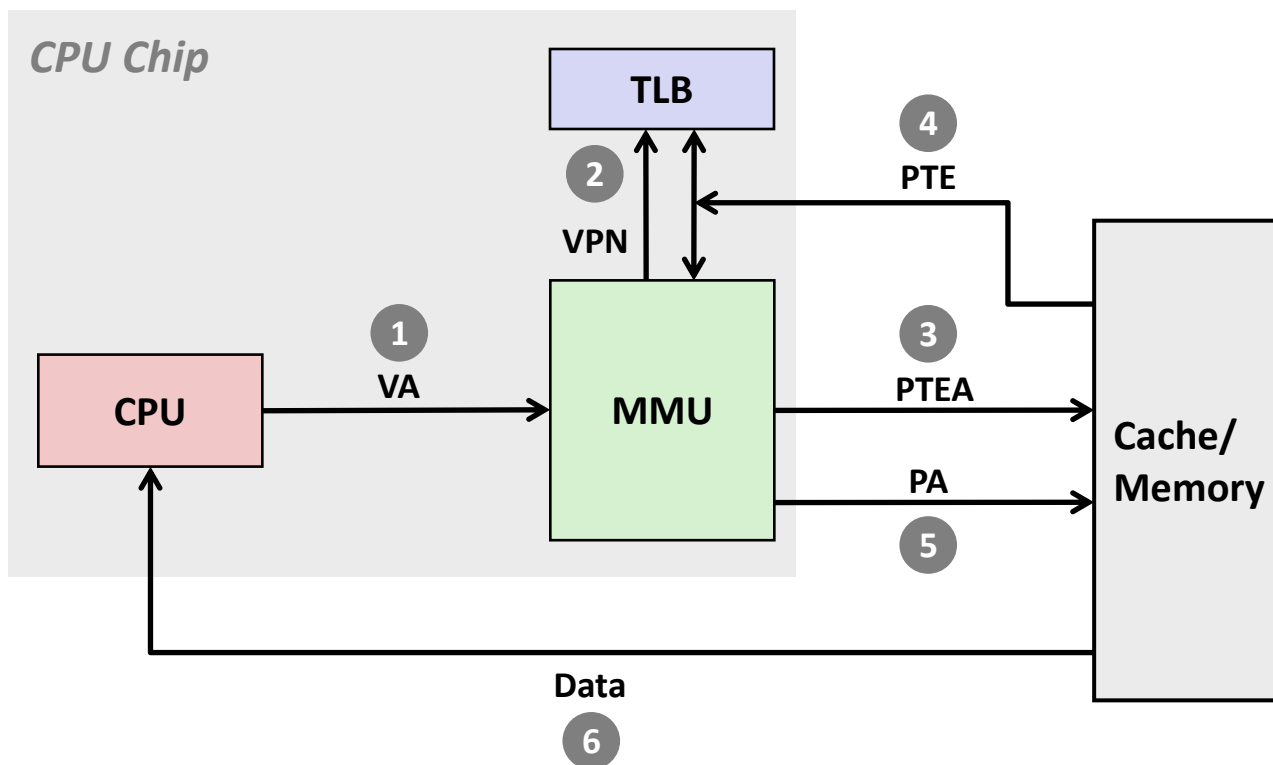


# TLB Hit



**A TLB hit eliminates a cache/memory access**

# TLB Miss



**A TLB miss incurs an additional cache/memory access (the PTE)**

Fortunately, TLB misses are rare. *Why?*

# Multi-Level Page Tables

## ■ Suppose:

- 4KB ( $2^{12}$ ) page size, 48-bit address space, 8-byte PTE

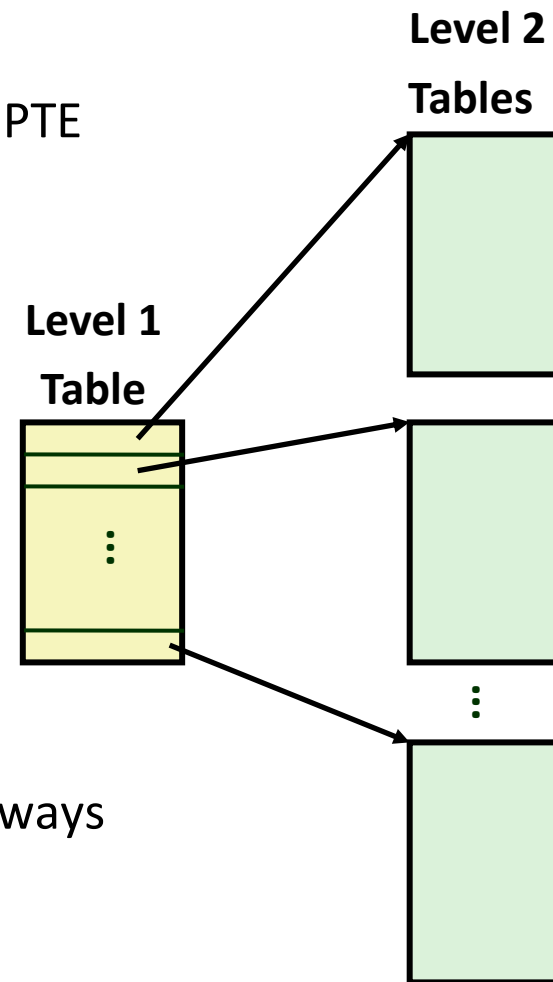
## ■ Problem:

- Would need a 512 GB page table!
  - $2^{48} * 2^{-12} * 2^3 = 2^{39}$  bytes

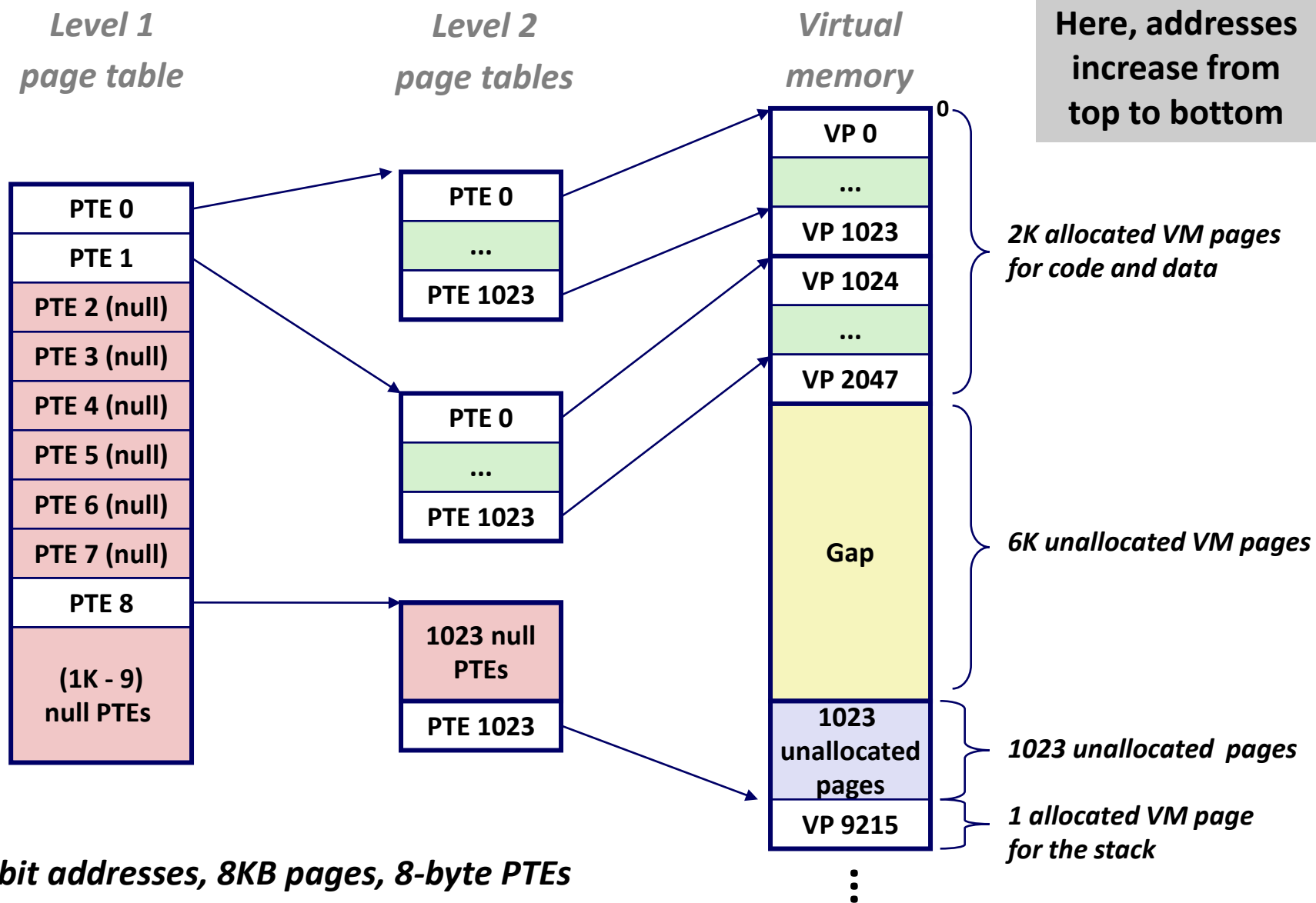
## ■ Common solution: Multi-level page table

## ■ Example: 2-level page table

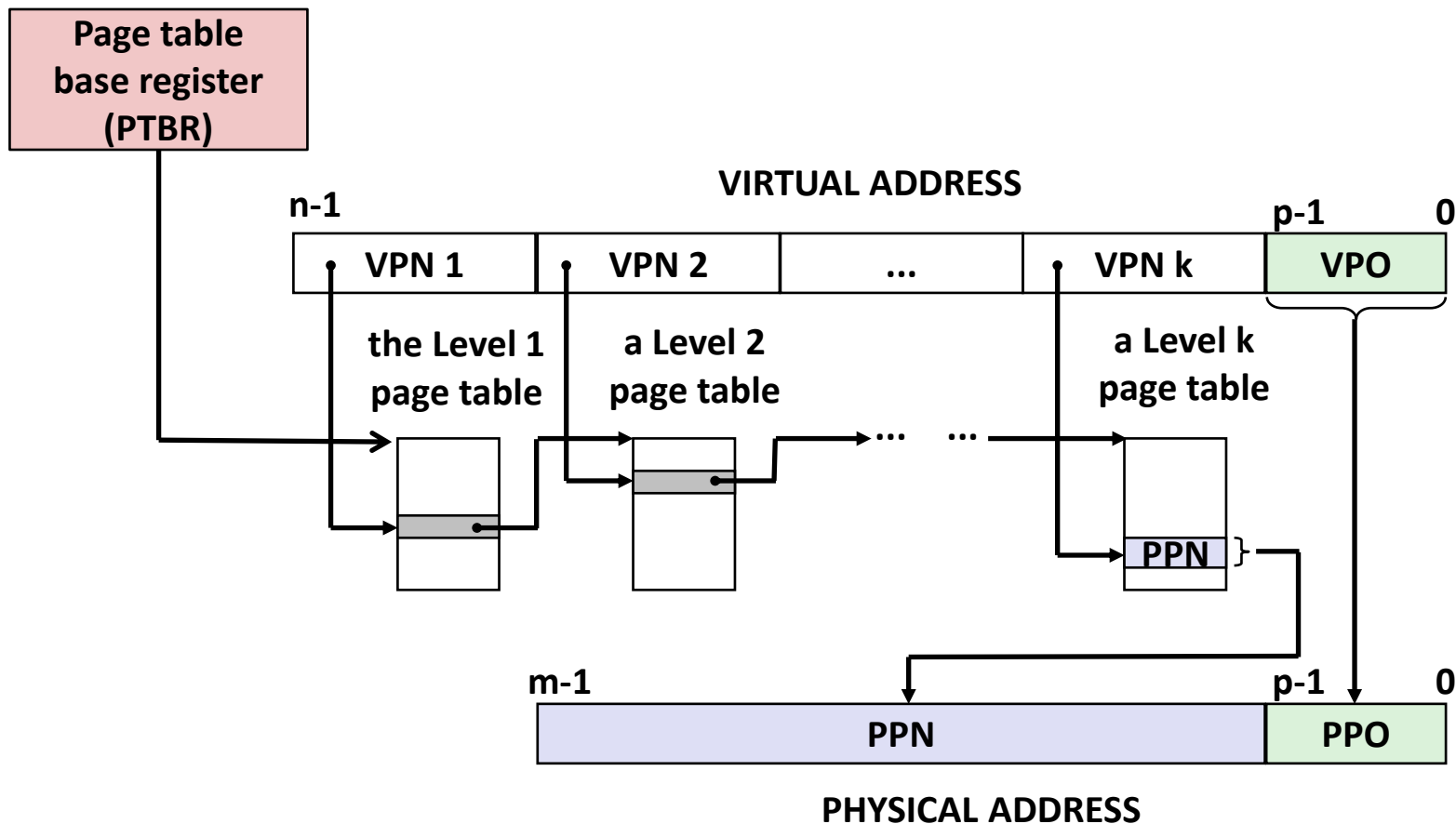
- Level 1 table: each PTE points to a page table (always memory resident)
- Level 2 table: each PTE points to a page (paged in and out like any other data)



# A Two-Level Page Table Hierarchy



# Translating with a k-level Page Table



# Summary

## ■ Programmer's view of virtual memory

- Each process has its own private linear address space
- Cannot be corrupted by other processes

## ■ System view of virtual memory

- Uses memory efficiently by caching virtual memory pages
  - Efficient only because of locality
- Simplifies memory management and programming
- Simplifies protection by providing a convenient interpositioning point to check permissions

## ■ Implemented via combination of hardware & software

- MMU, TLB, exception handling mechanisms part of hardware
- Page fault handlers, TLB management performed in software