Virtual Memory II

CSE 351 Winter 2021

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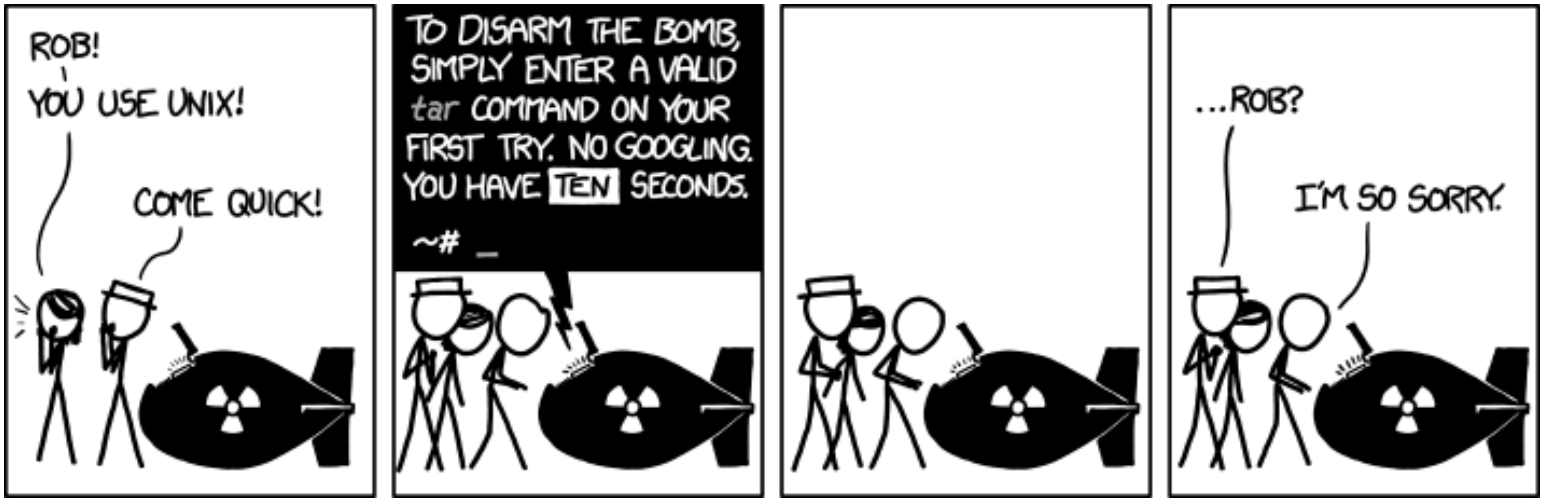


http://xkcd.com/1831/

Administrivia

- hw18 due *Tonight*, hw19 due Monday (3/1)
- hw20 due next Friday (3/5)
  - larger homework on VM II & III, start early!
- Study Guide 2 due Monday (3/1)
- Lab 4 due next Friday (3/5)

Reading Review

- Terminology:
  - Paging: page size (P), page offset width (p) virtual page number (VPN), physical page numbers (PPN)
  - Page table (PT): page table entry (PTE), access rights (read, write, execute)

- Questions from the Reading?

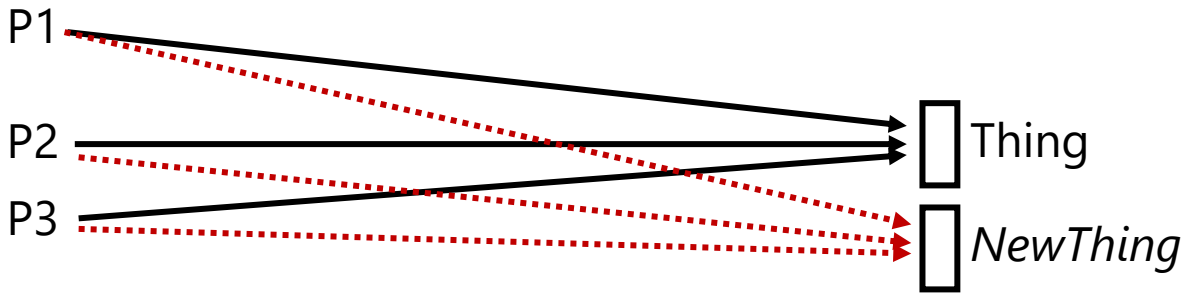
VM Motivation - Four Problems

- Problem 1: How does it all fit?
  - Virtual Memory >> Physical Memory
- Problem 2: Memory Management
  - Many processes (with large VA spaces) sharing small physical memory
  - Where does each process' code, data, etc. get placed?
- Problem 3: Protection
  - How do we prevent one process from accessing another process' memory?
- Problem 4: Sharing
  - How do we allow two processes to share code or data?

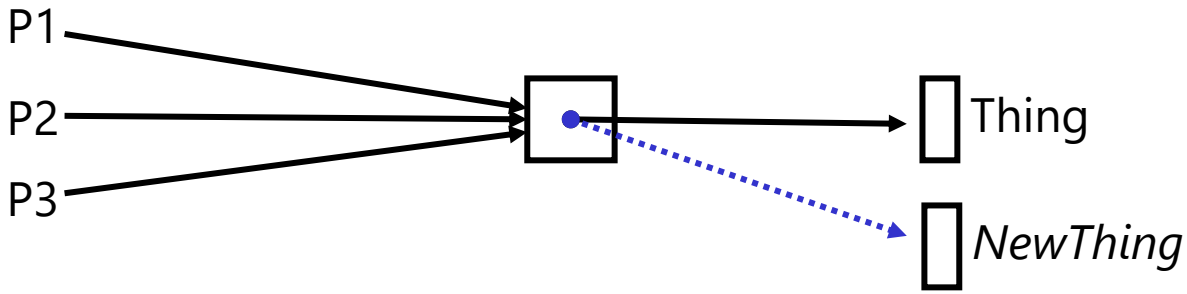
How can we solve these problems?

- "Any problem in computer science can be solved by adding another level of **indirection**." *– David Wheeler, inventor of the subroutine*

- Without Indirection



- With Indirection

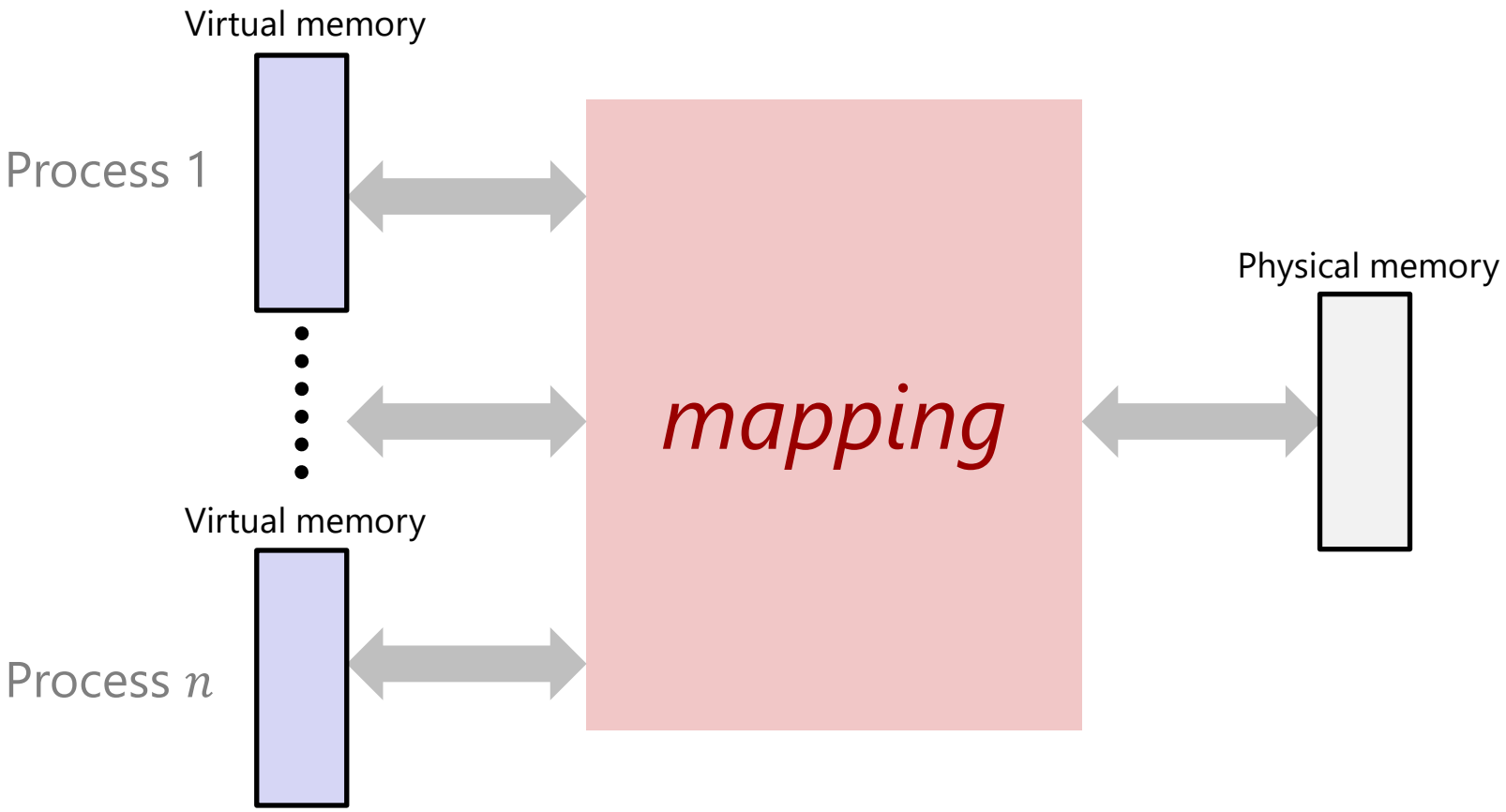


What if I want to move Thing?

Indirection

- *Indirection*: The ability to reference something using a name, reference, or container instead of the value itself. A flexible mapping between a name and a thing allows changing the thing without notifying holders of the name.
  - Adds some work (now have to look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- Examples:
  - **Phone system:** cell phone number portability
  - **Domain Name Service (DNS):** translation from name to IP address
  - **Call centers:** route calls to available operators, etc.
  - **Dynamic Host Configuration Protocol (DHCP):** local network address assignment

Indirection in Virtual Memory



- Each process gets its own private virtual address space
- Solves the previous problems!

Address Spaces

- Virtual address space: Set of $N = 2^n$ virtual addr
  - {0, 1, 2, 3, …, N-1}
- Physical address space: Set of $M = 2^m$ physical addr
  - {0, 1, 2, 3, …, M-1}

- Every byte in main memory has:
  - one physical address (PA)
  - zero, one, *or more* virtual addresses (VAs)

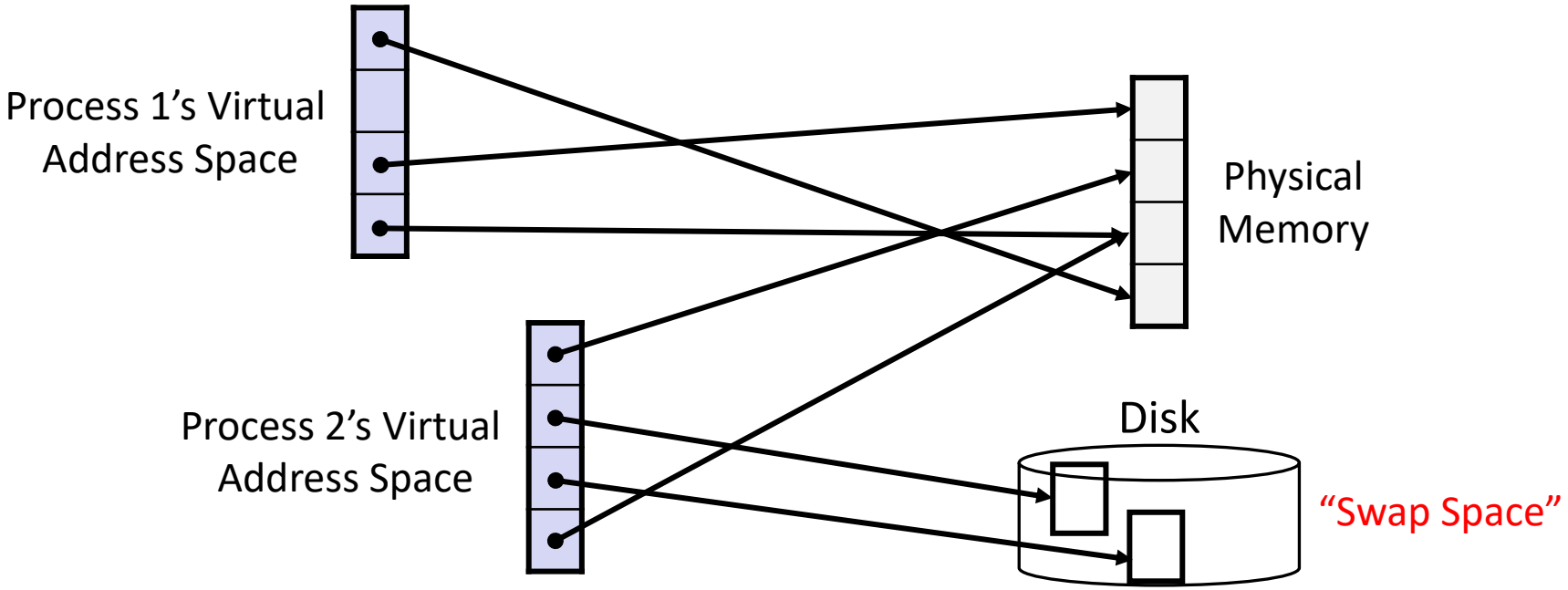
Polling Questions

- On a 64-bit machine currently running 8 processes, how much virtual memory is there?

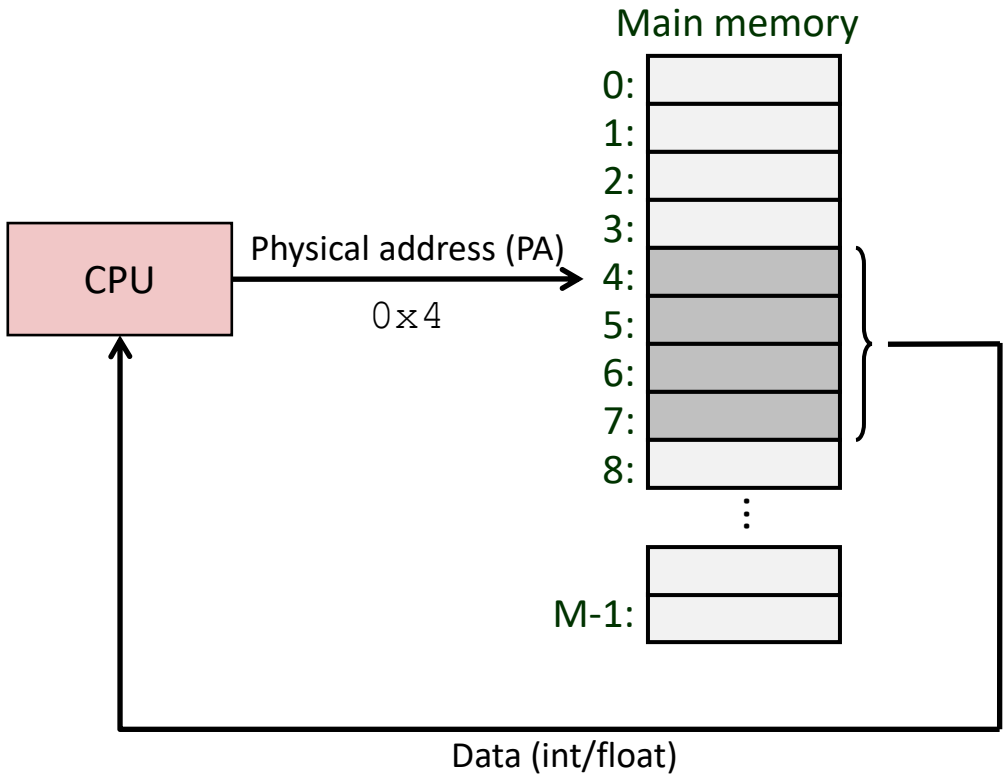
- True or False: A 32-bit machine with 8 GiB of RAM installed would never use all of it (in theory).

Mapping

- A virtual address (VA) can be mapped to either physical memory or disk
  - Unused VAs may not have a mapping
  - VAs from *different* processes may map to same location in memory/disk

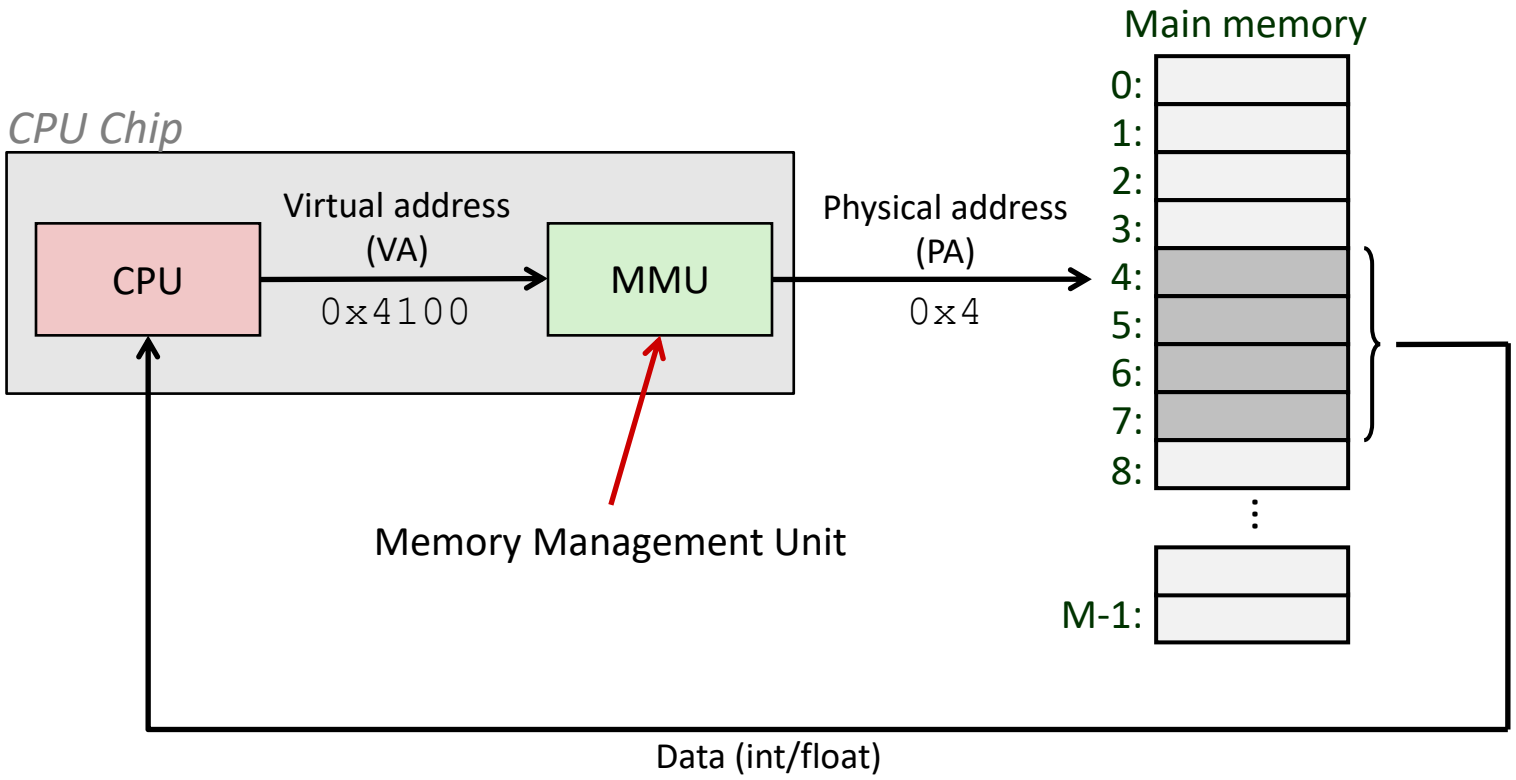


A System Using Physical Addressing



- Used in "simple" systems with (usually) just one process:
  - Embedded microcontrollers in devices like cars, elevators, and digital picture frames

A System Using Virtual Addressing



- Physical addresses are *completely invisible to programs*
  - Used in all modern desktops, laptops, servers, smartphones…
  - One of the great ideas in computer science

Why Virtual Memory (VM)?

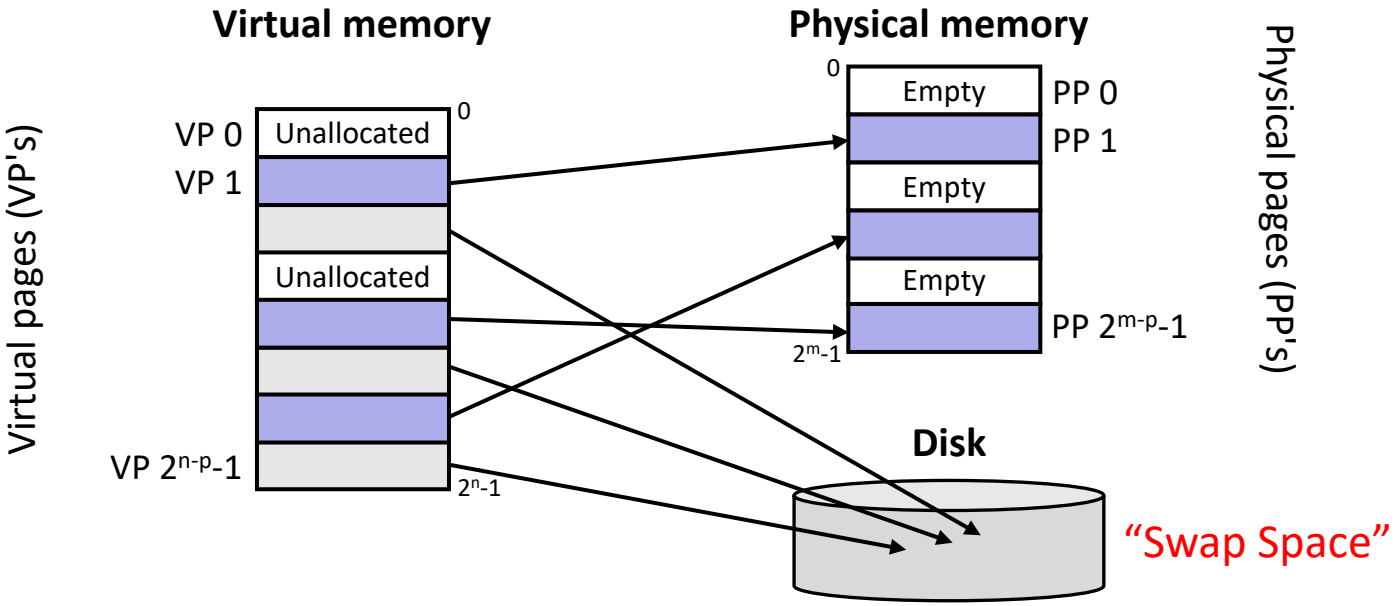
- Efficient use of limited main memory (RAM)
  - Use RAM as a cache for the parts of a virtual address space
    - Some non-cached parts stored on disk
    - Some (unallocated) non-cached parts stored nowhere
  - Keep only active areas of virtual address space in memory
    - Transfer data back and forth as needed
- Simplifies memory management for programmers
  - Each process "gets" the same full, private linear address space
- Isolates address spaces (protection)
  - One process can't interfere with another's memory
    - They operate in *different address spaces*
  - User process cannot access privileged information
    - Different sections of address spaces have different permissions

Review Questions

- Which terms from caching are most similar/analogous to the new virtual memory terms?
  - page size
  - page offset width
  - virtual page number
  - physical page number
  - page table entry
  - access rights

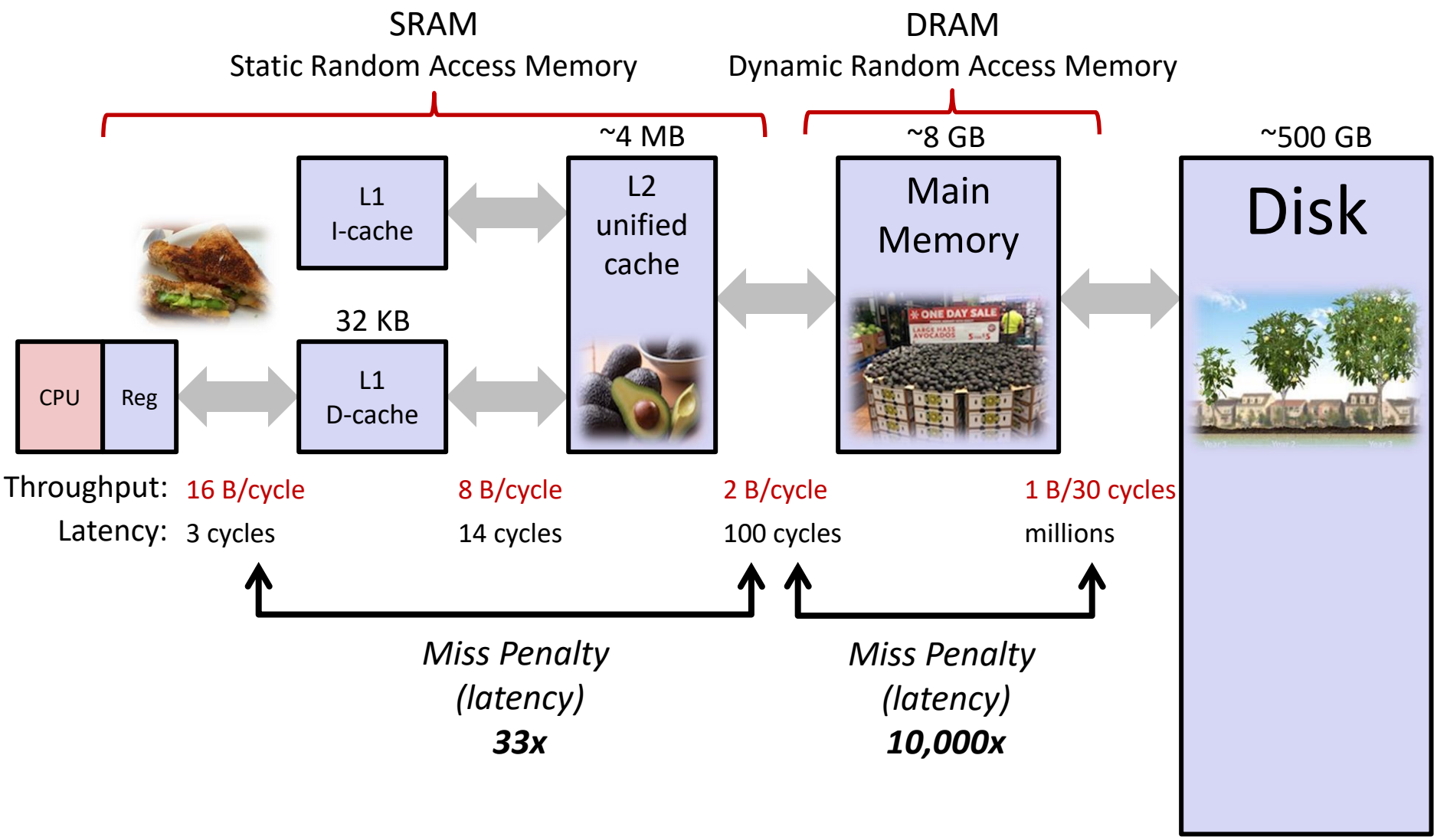
VM and the Memory Hierarchy

- Think of memory (virtual or physical) as an array of bytes, now split into *pages*
  - Pages are another unit of aligned memory (size is $\mathrm{P} = 2^p$ bytes)
  - Each virtual page can be stored in *any* physical page (no fragmentation!)
- Pages of virtual memory are usually stored in physical memory, but sometimes spill to disk



Memory Hierarchy: Core 2 Duo

Not drawn to scale



Virtual Memory Design Consequences

- Large page size: typically 4-8 KiB or 2-4 MiB
  - *Can* be up to 1 GiB (for "Big Data" apps on big computers)
  - Compared with 64-byte cache blocks
- Fully associative
  - Any virtual page can be placed in any physical page
  - Requires a "large" mapping function – different from CPU caches
- Highly sophisticated, expensive replacement algorithms in OS
  - Too complicated and open-ended to be implemented in hardware
- *Write-back* rather than *write-through*
  - *Really* don't want to write to disk every time we modify memory
  - Some things may never end up on disk (*e.g.*, stack for short-lived process)

Why does VM work on RAM/disk?

- Avoids disk accesses because of *locality*
  - Same reason that L1 / L2 / L3 caches work

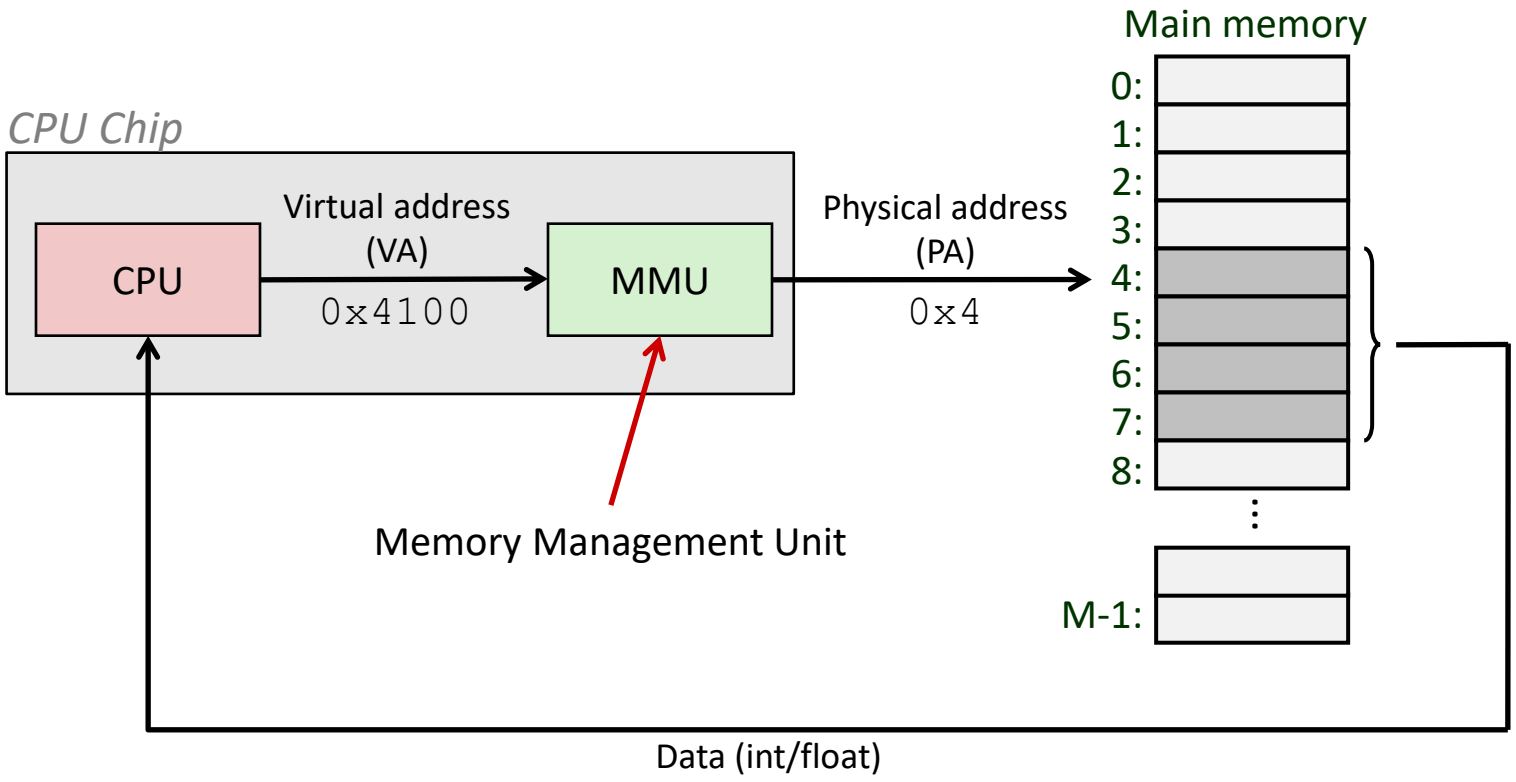
- The set of virtual pages that a program is "actively" accessing at any point in time is called its *working set*
  - If (*working set of one process* ≤ *physical memory*):
    - Good performance for one process (after compulsory misses)
  - If (*working sets of all processes* > *physical memory*):
    - ***Thrashing:*** Performance meltdown where pages are swapped between memory and disk continuously (CPU always waiting or paging)
    - This is why your computer can feel faster when you add RAM

Virtual Memory (VM)

- Overview and motivation
- VM as a tool for caching
- **Address translation**
- VM as a tool for memory management
- VM as a tool for memory protection

Address Translation

How do we perform the virtual → physical address translation?



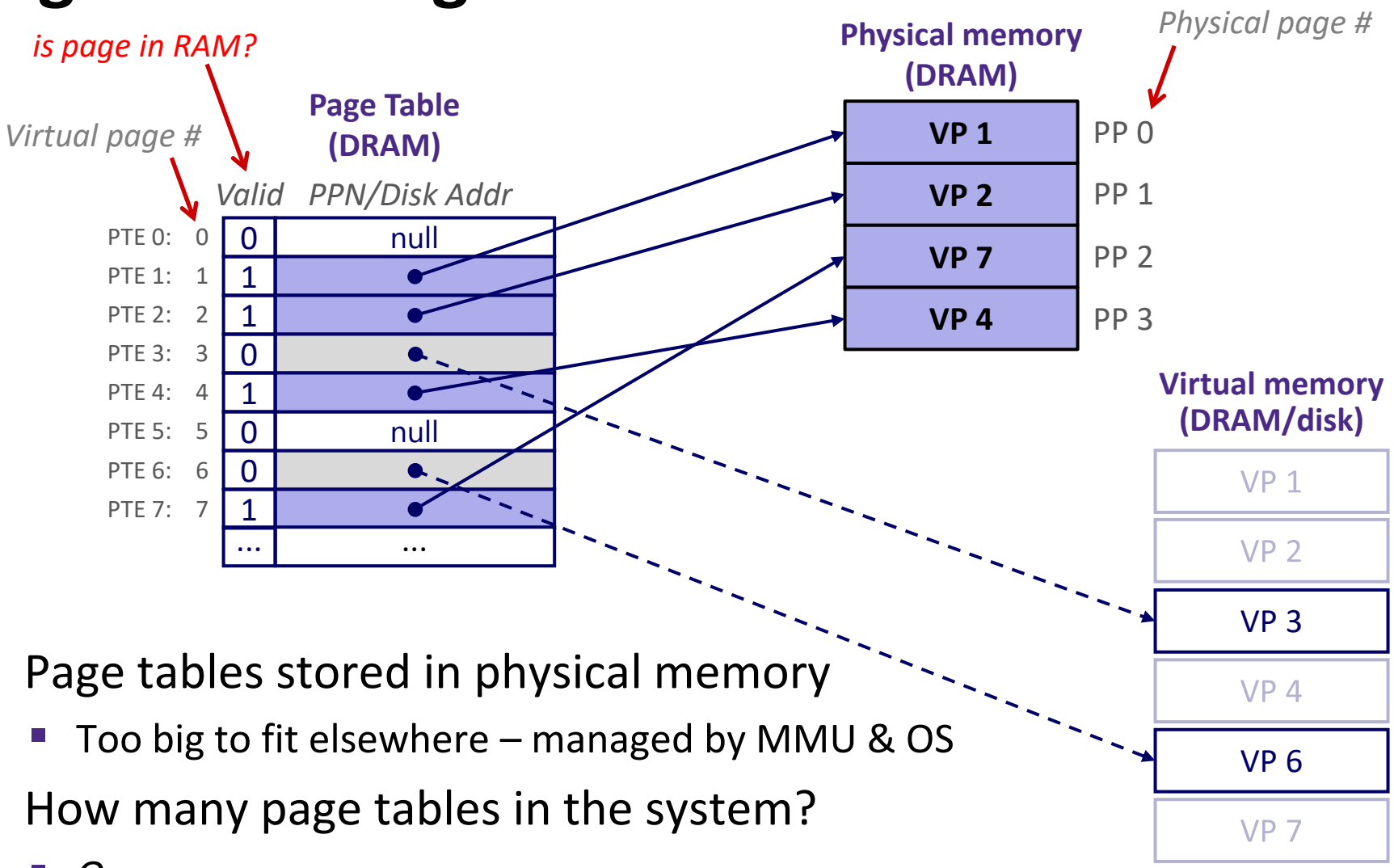
Address Translation: Page Tables

- CPU-generated address can be split into:

  - Request is Virtual Address (VA), want Physical Address (PA)
  - Note that Physical Offset = Virtual Offset (page-aligned)

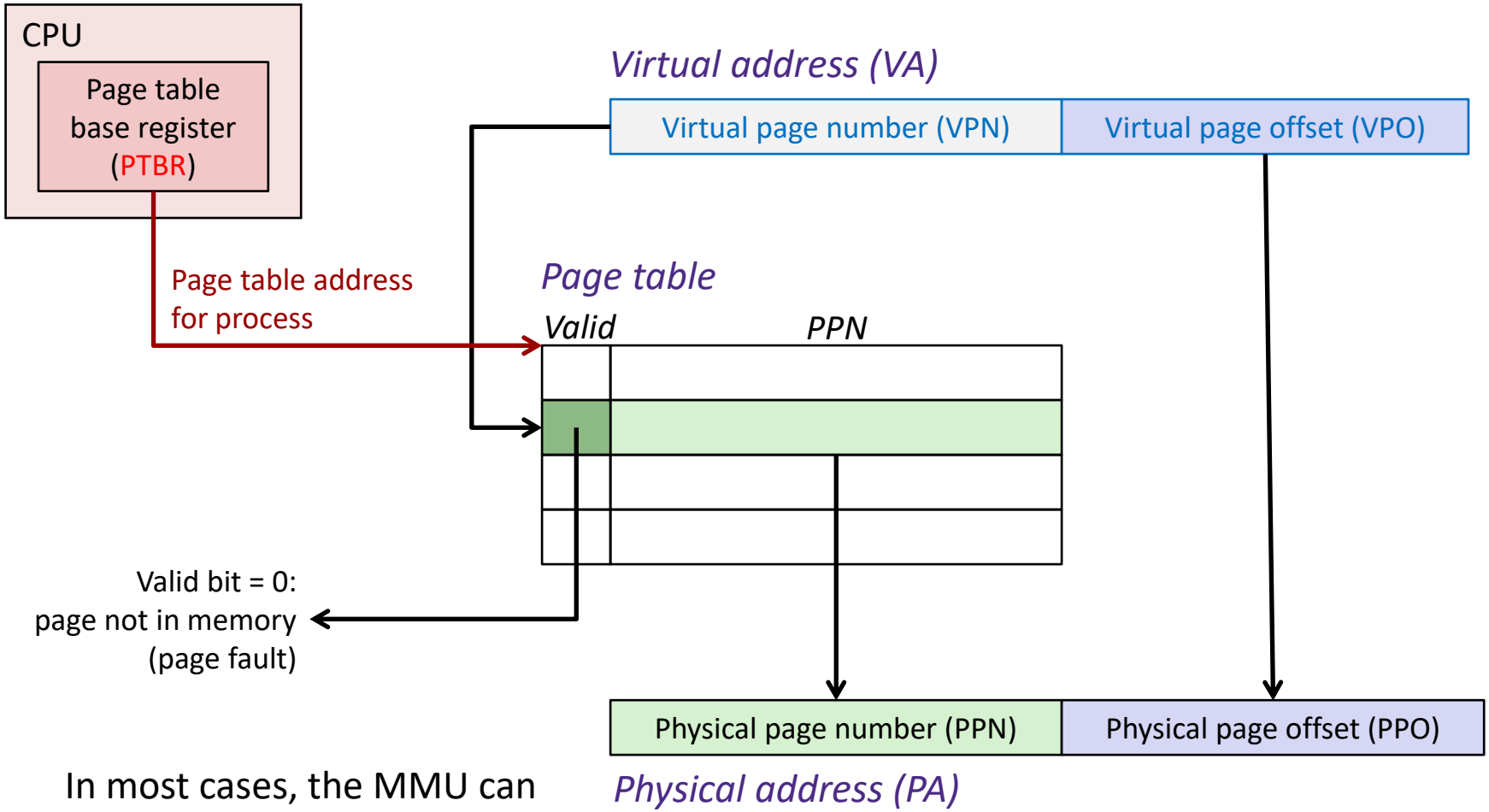
- Use lookup table that we call the *page table* (PT)
  - Replace Virtual Page Number (VPN) for Physical Page Number (PPN) to generate Physical Address
  - Index PT using VPN: page table entry (PTE) stores the PPN plus management bits (*e.g.*, Valid, Dirty, access rights)
  - Has an entry for *every* virtual page

Page Table Diagram



- Page tables stored in physical memory
  - Too big to fit elsewhere – managed by MMU & OS
- How many page tables in the system?
  - *One per process*

Page Table Address Translation



In most cases, the MMU can perform this translation without software assistance

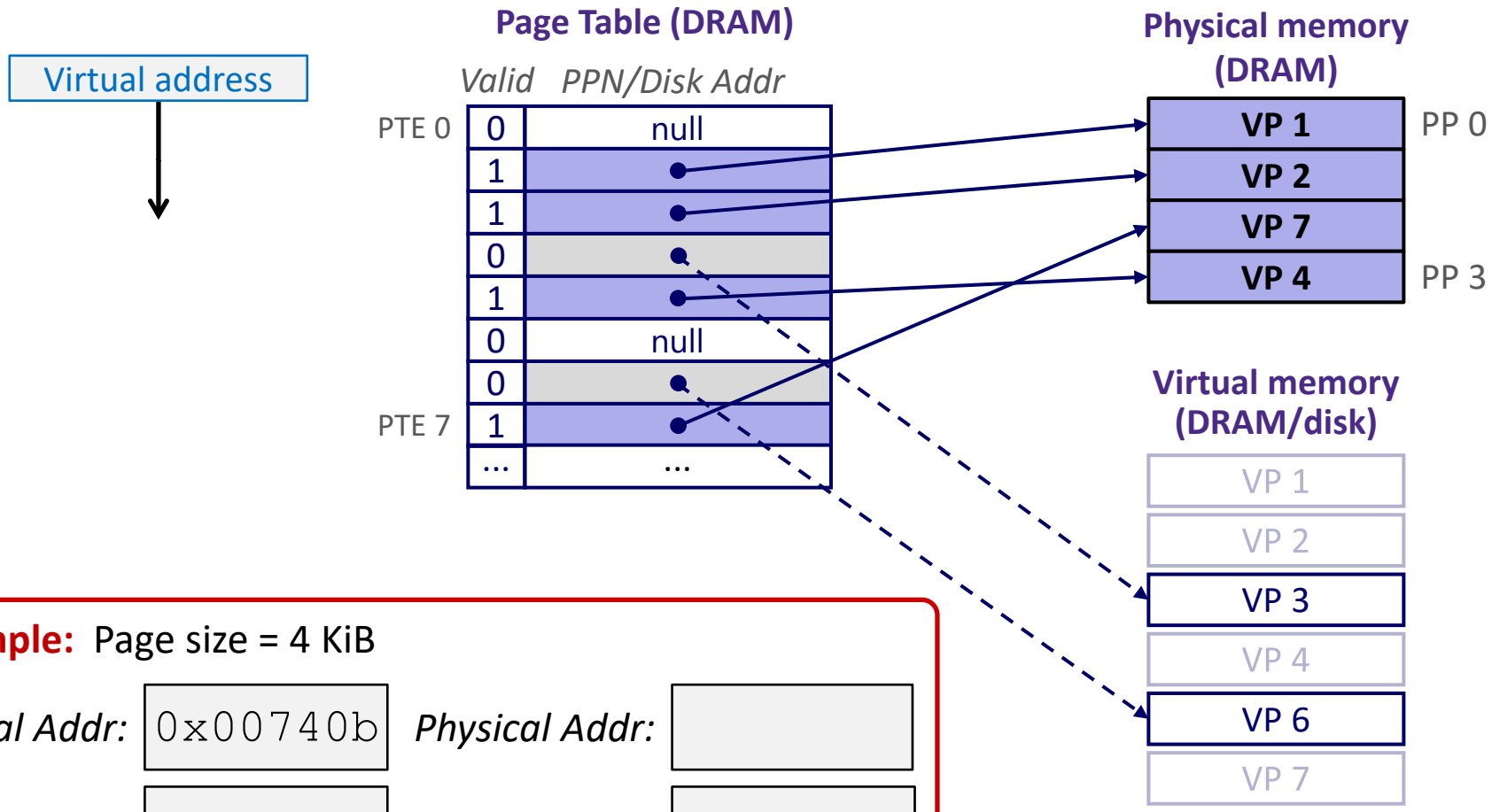
Polling Question

- How many bits wide are the following fields?
  - 16 KiB pages
  - 48-bit virtual addresses
  - 16 GiB physical memory
  - Vote in Ed Lessons

	VPN	PPN
(A)	34	24
(B)	32	18
(C)	30	20
(D)	34	20

Page Hit

- ***Page hit:*** VM reference is in physical memory



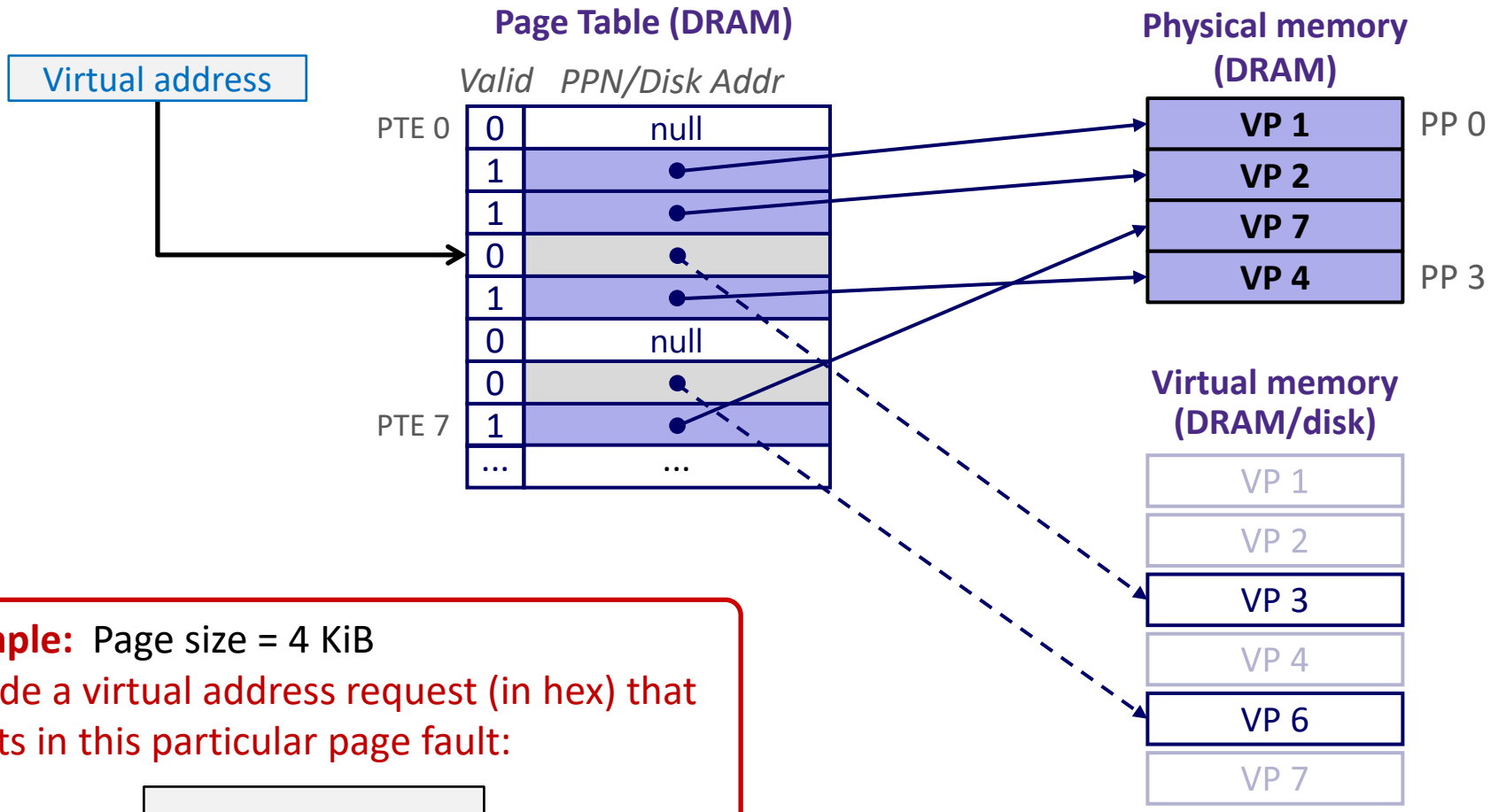
Example: Page size = 4 KiB

Virtual Addr: 0x00740b *Physical Addr:*

VPN: *PPN:*

Page Fault

- ***Page fault:*** VM reference is NOT in physical memory



Example: Page size = 4 KiB

Provide a virtual address request (in hex) that results in this particular page fault:

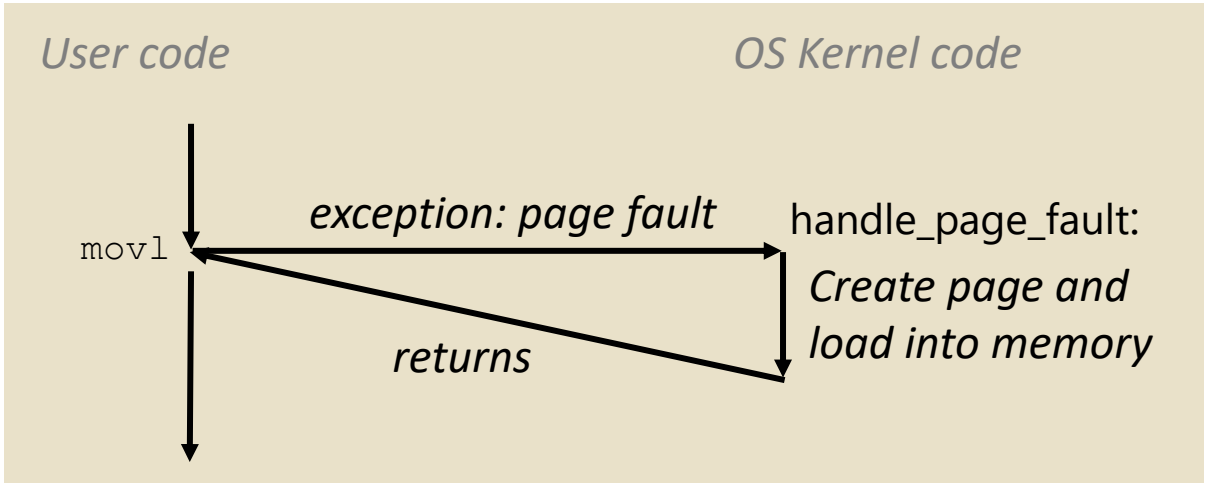
Virtual Addr:

Reminder: Page Fault Exception

- User writes to memory location
- That portion (page) of user's memory is currently on disk

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

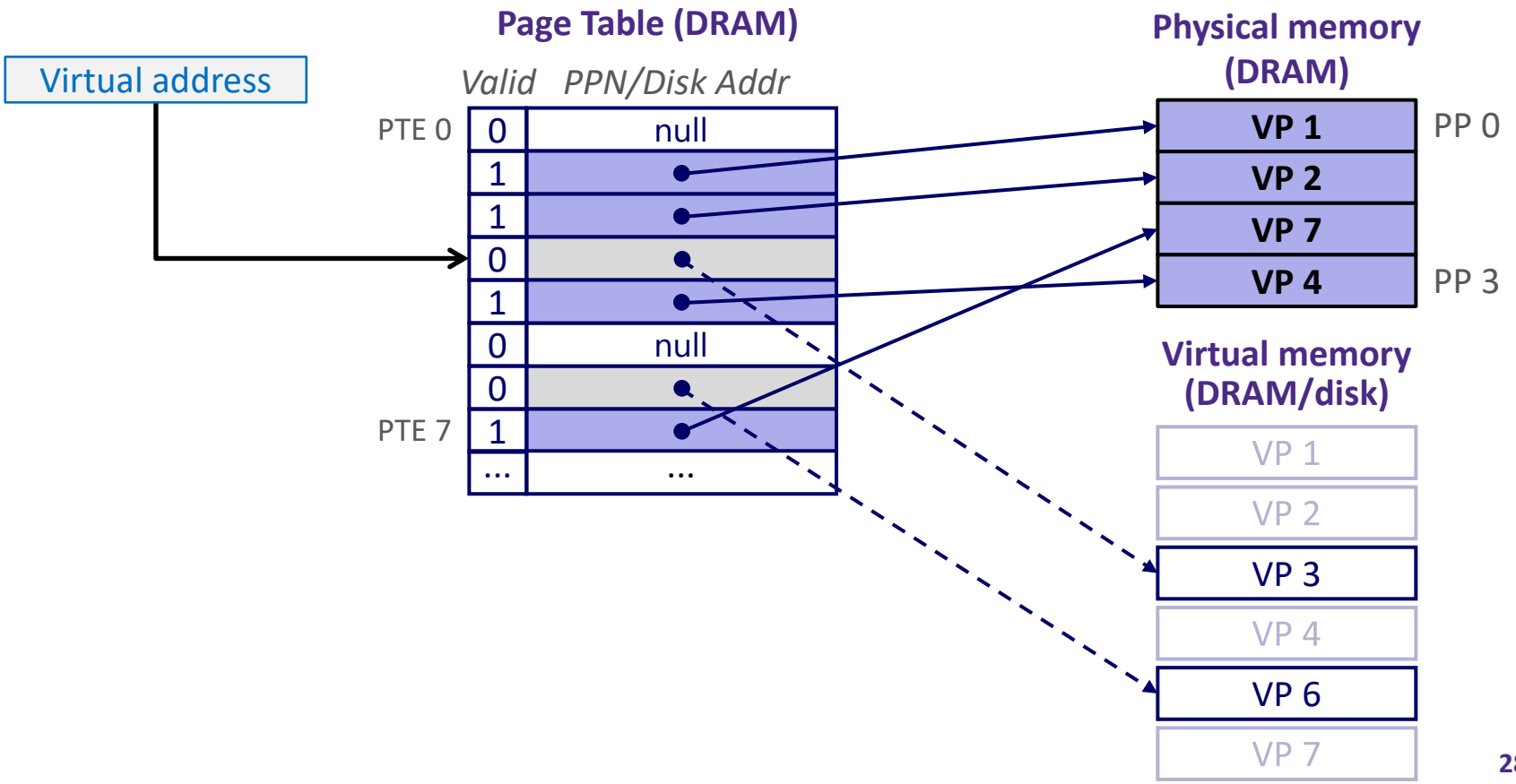
```
80483b7:    c7 05 10 9d 04 08 0d    movl   $0xd,0x8049d10
```



- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
  - Successful on second try

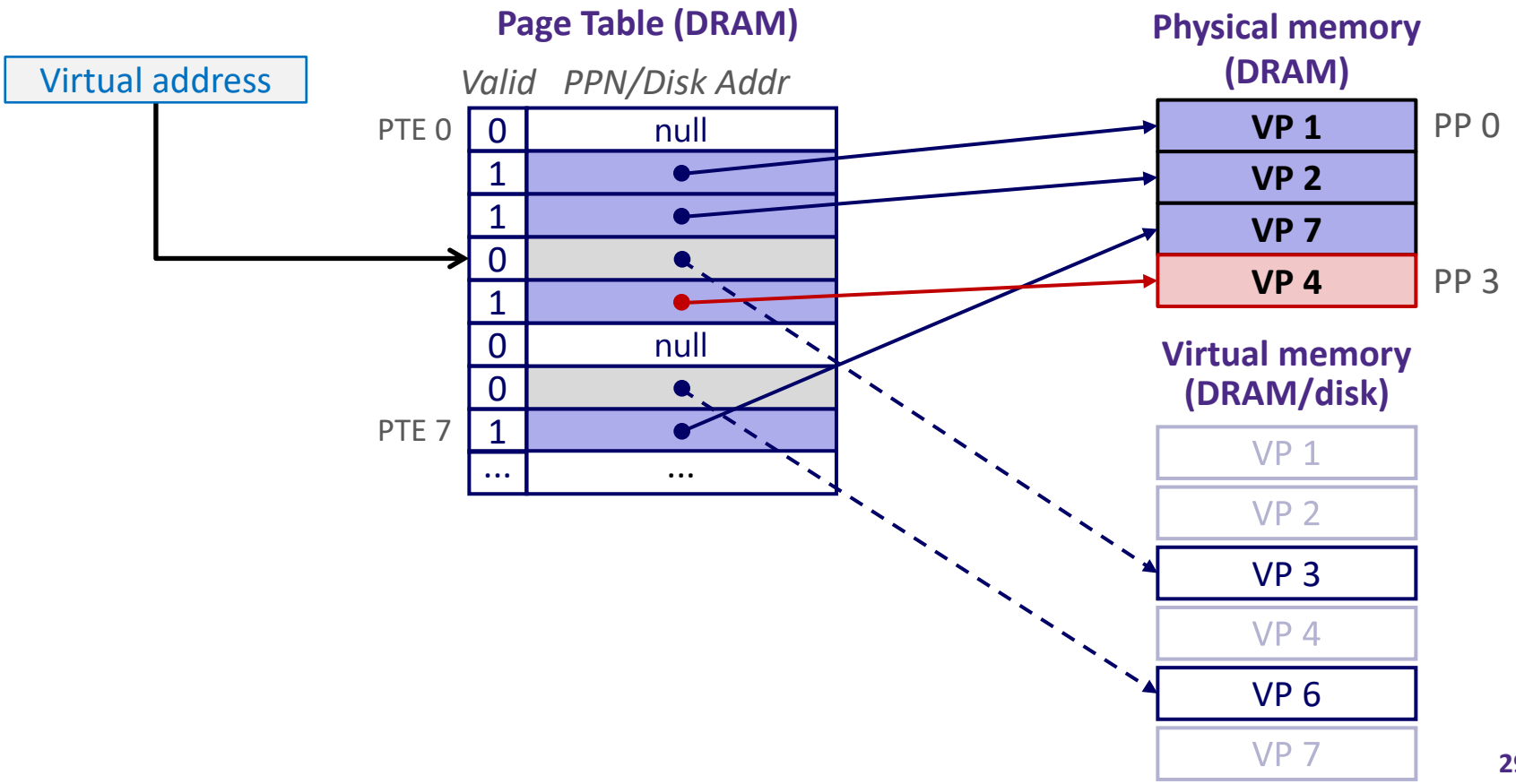
Handling a Page Fault

- Page miss causes page fault (an exception)



Handling a Page Fault

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



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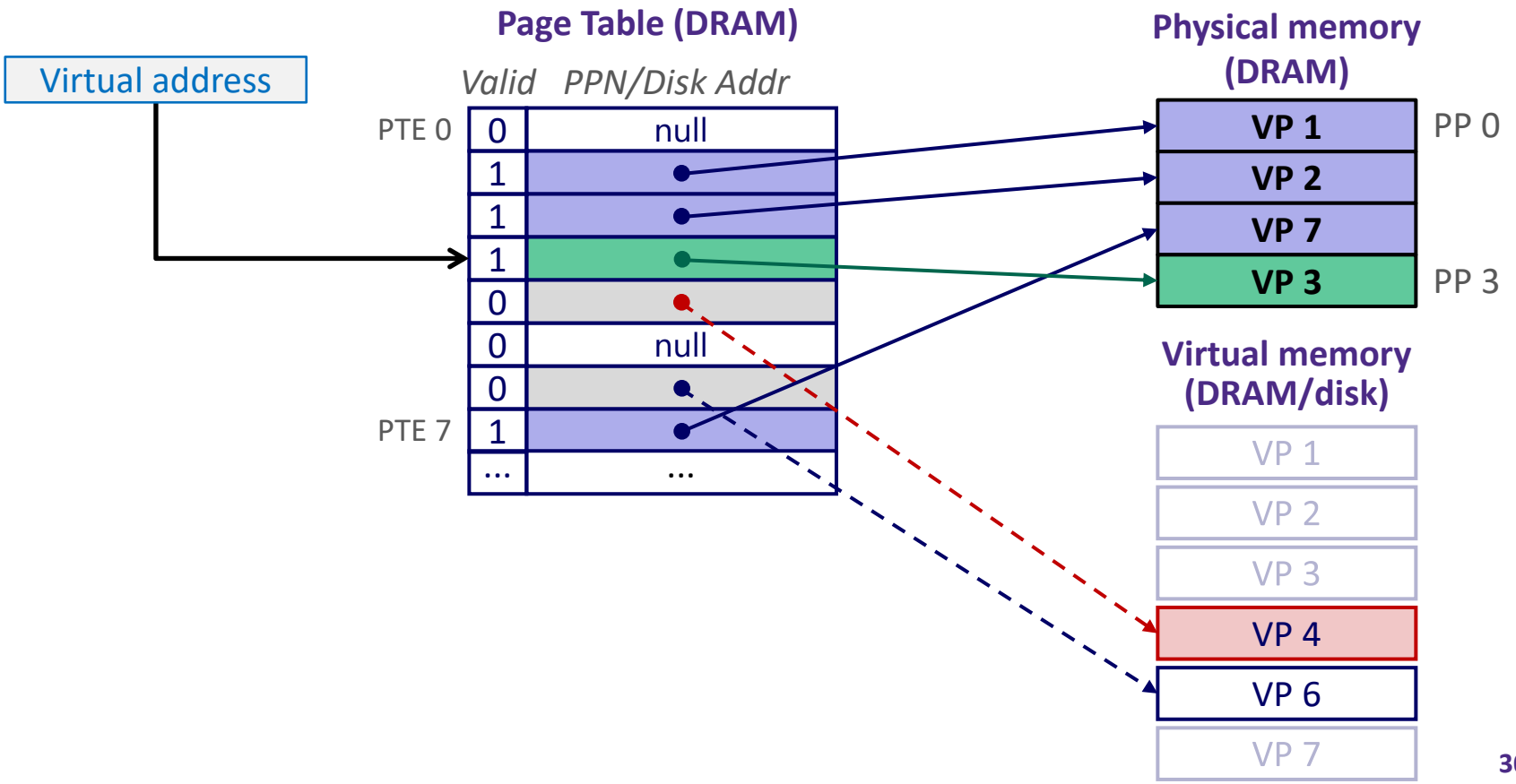
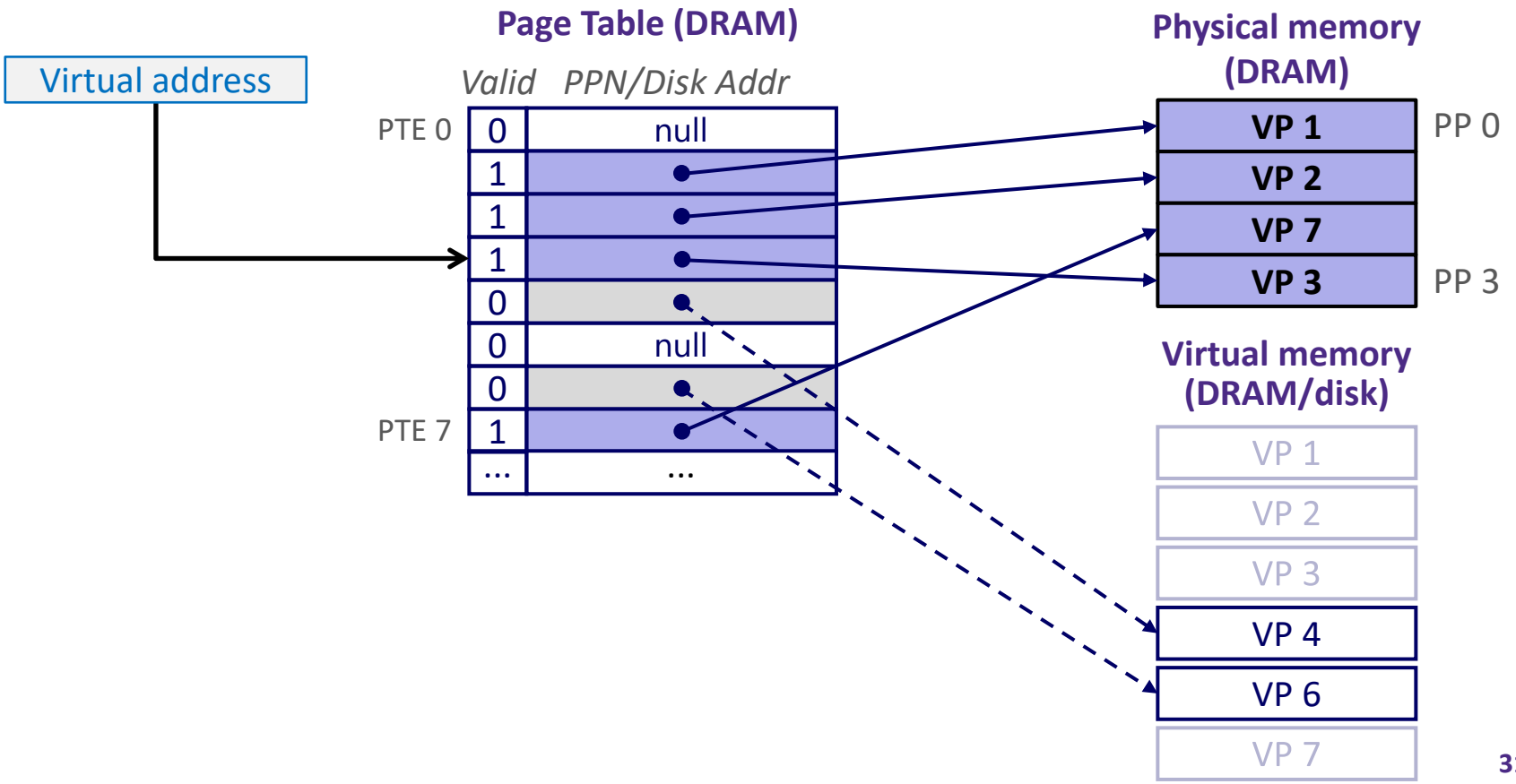


Handling a Page Fault

- 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!



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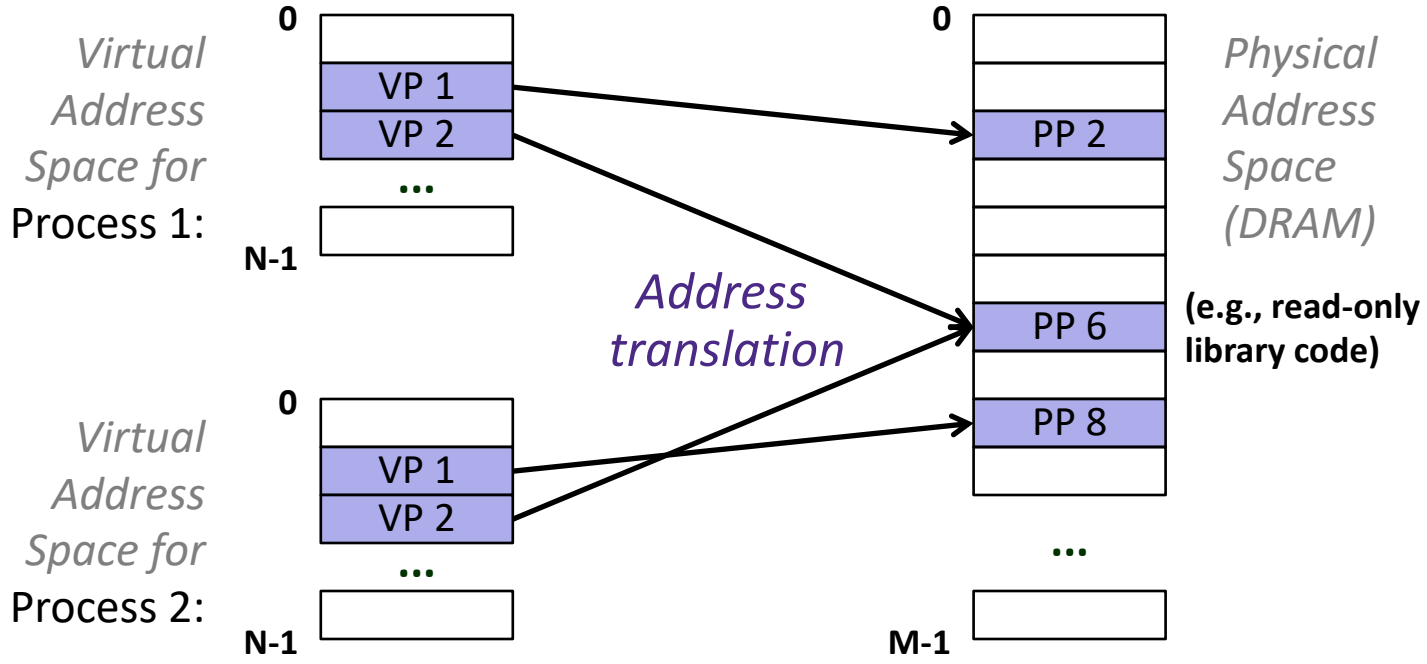
- **VM as a tool for memory protection**

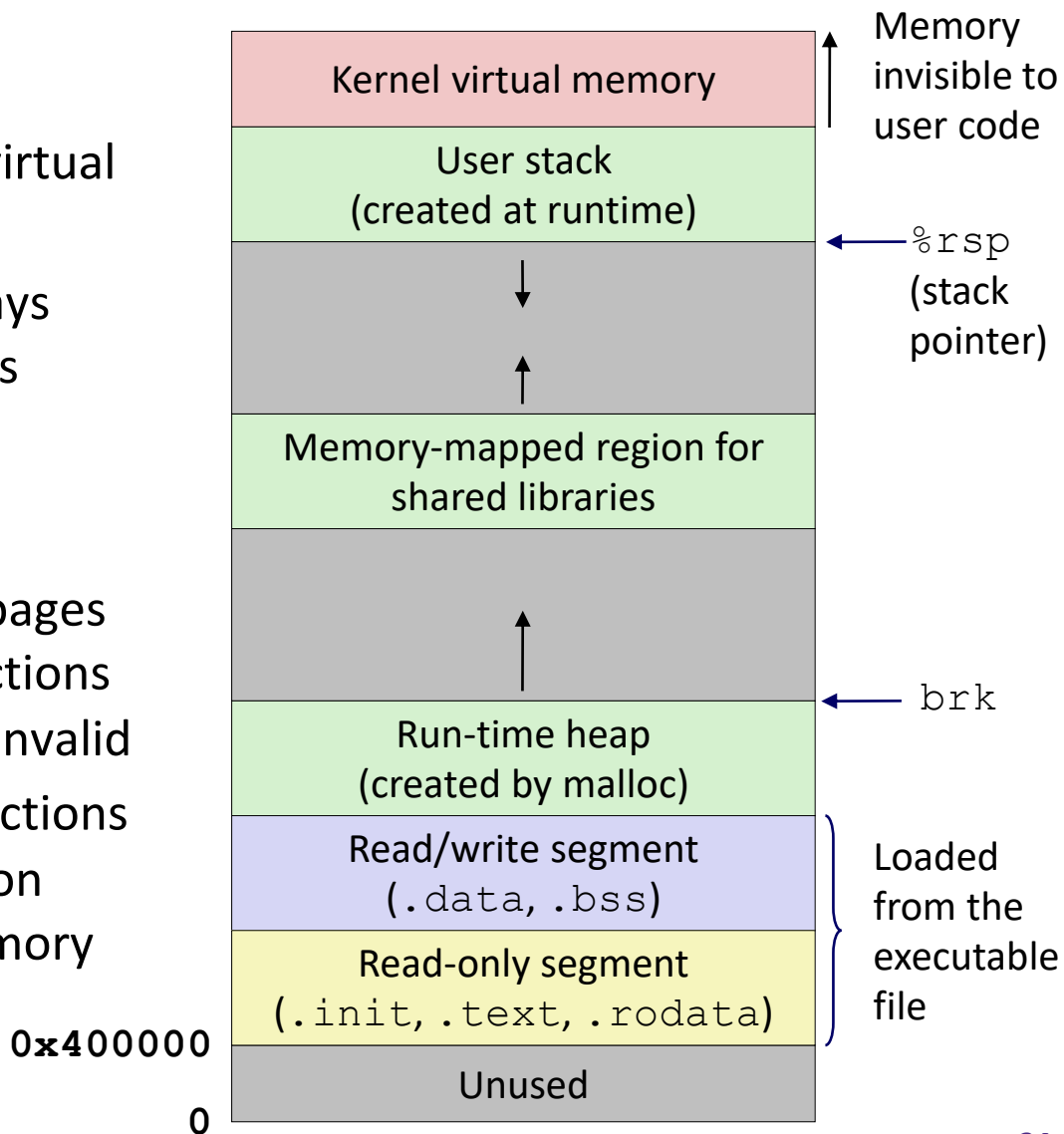
VM for Managing Multiple Processes

- Key abstraction: each process has its own virtual address space
  - It can view memory as *a simple linear array*
- With virtual memory, this simple linear virtual address space need not be contiguous in physical memory
  - Process needs to store data in another VP? Just map it to *any* PP!



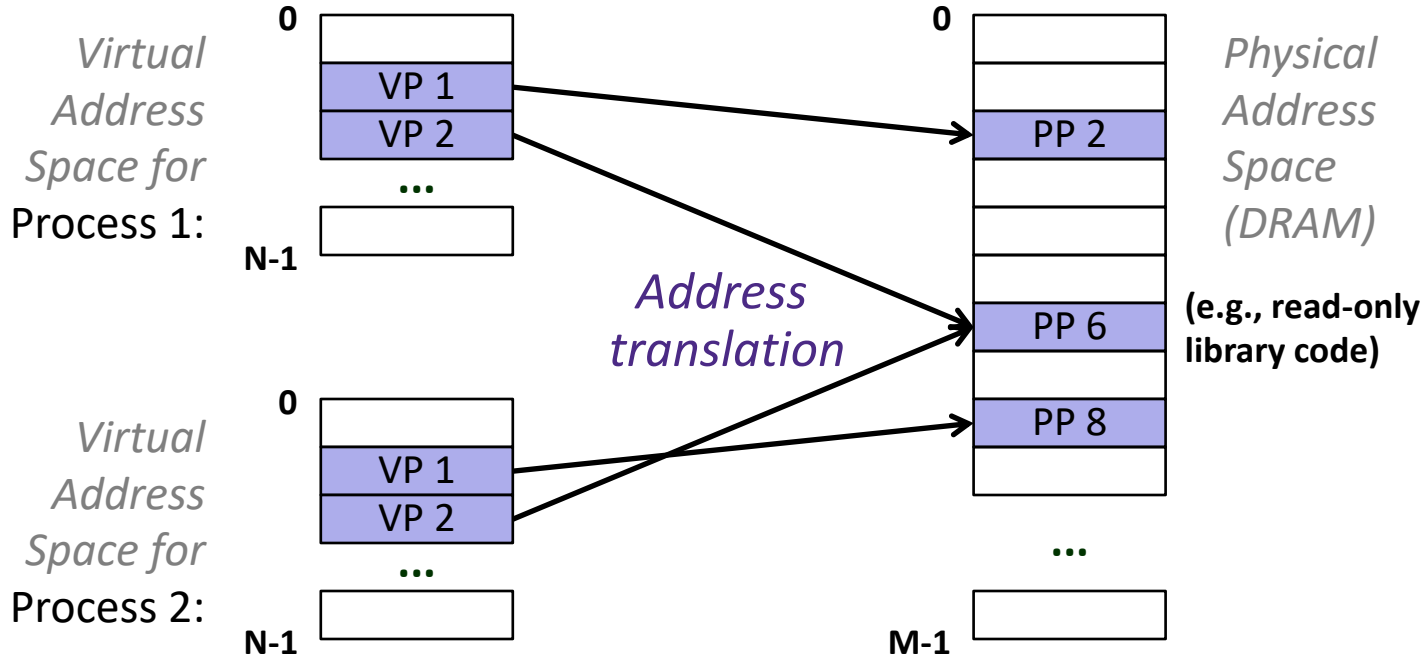
Simplifying Linking and Loading

- 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



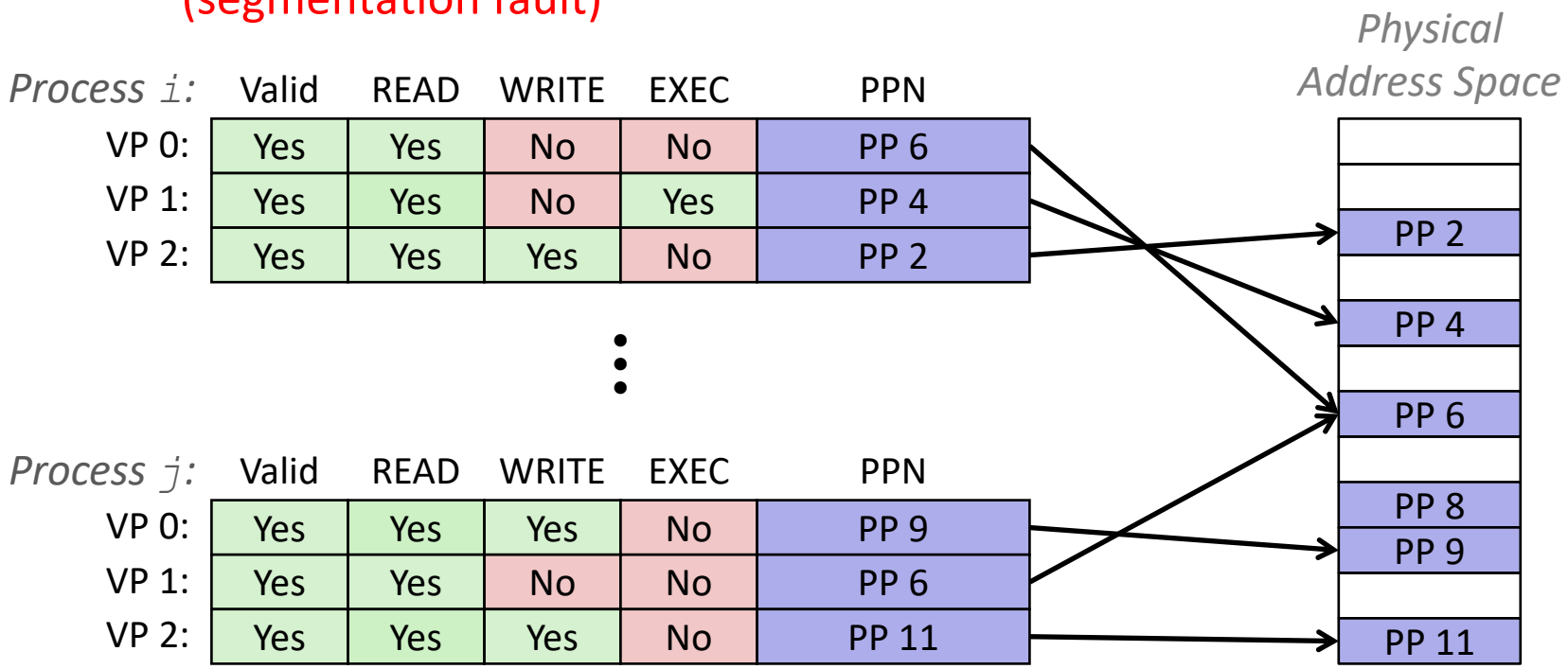
VM for Protection and Sharing

- The mapping of VPs to PPs provides a simple mechanism to *protect* memory and to *share* memory between processes
  - **Sharing:** map virtual pages in separate address spaces to the same physical page (here: PP 6)
  - **Protection:** process can't access physical pages to which none of its virtual pages are mapped (here: Process 2 can't access PP 2)



Memory Protection Within Process

- VM implements read/write/execute permissions
  - Extend page table entries with permission bits
  - MMU checks these permission bits on every memory access
    - If violated, raises exception and OS sends SIGSEGV signal to process (segmentation fault)



Memory Review Question

- What should the permission bits be for pages from the following sections of virtual memory?

Section	Read	Write	Execute
Stack			
Heap			
Static Data			
Literals			
Instructions			