

Virtual Memory II

CSE 351 Spring 2021

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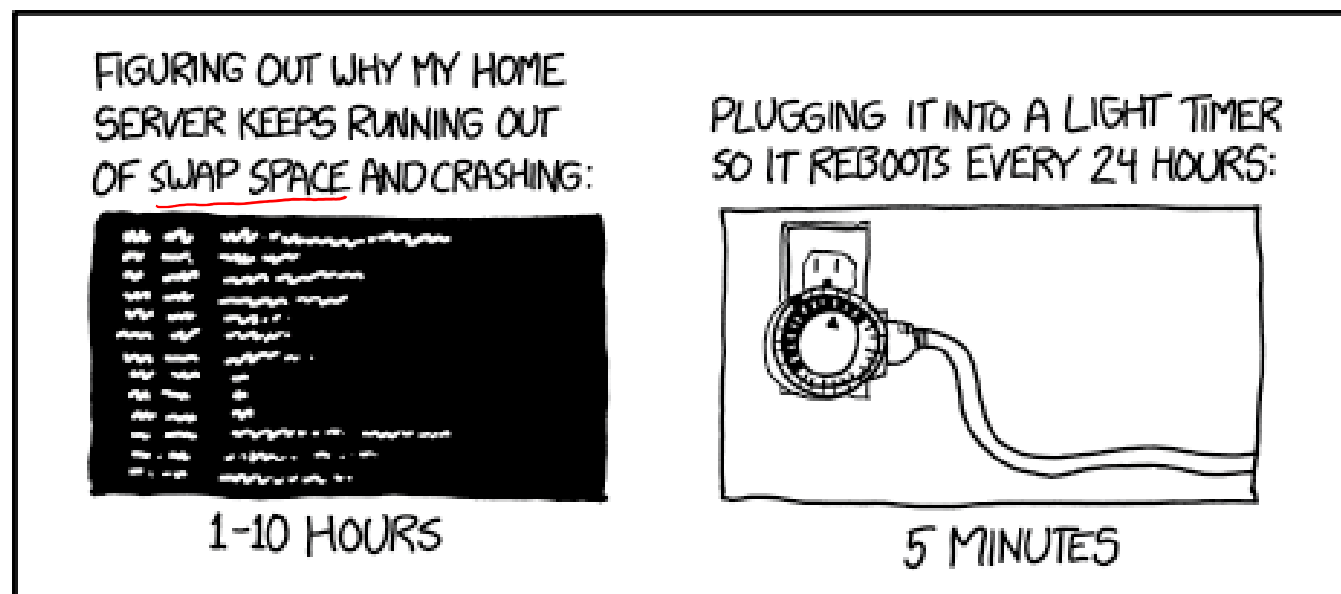
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WHY EVERYTHING I HAVE IS BROKEN

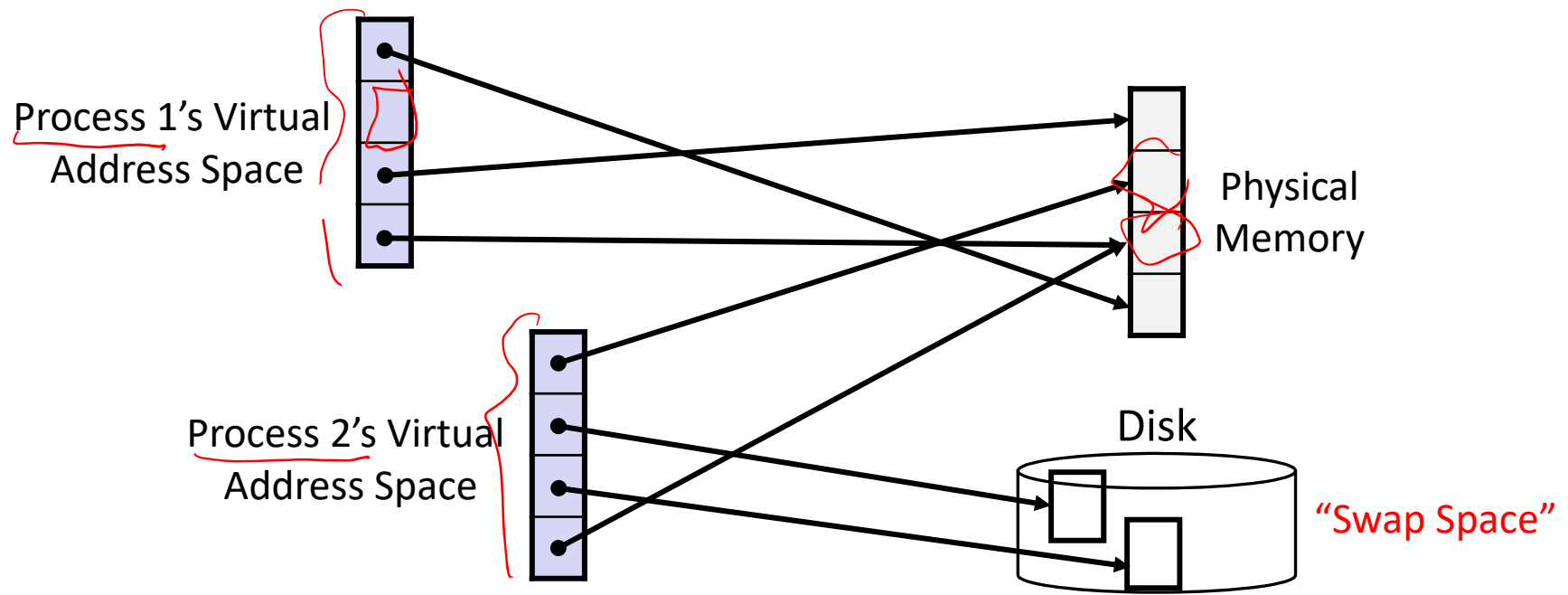
<https://xkcd.com/1495/>

Administrivia

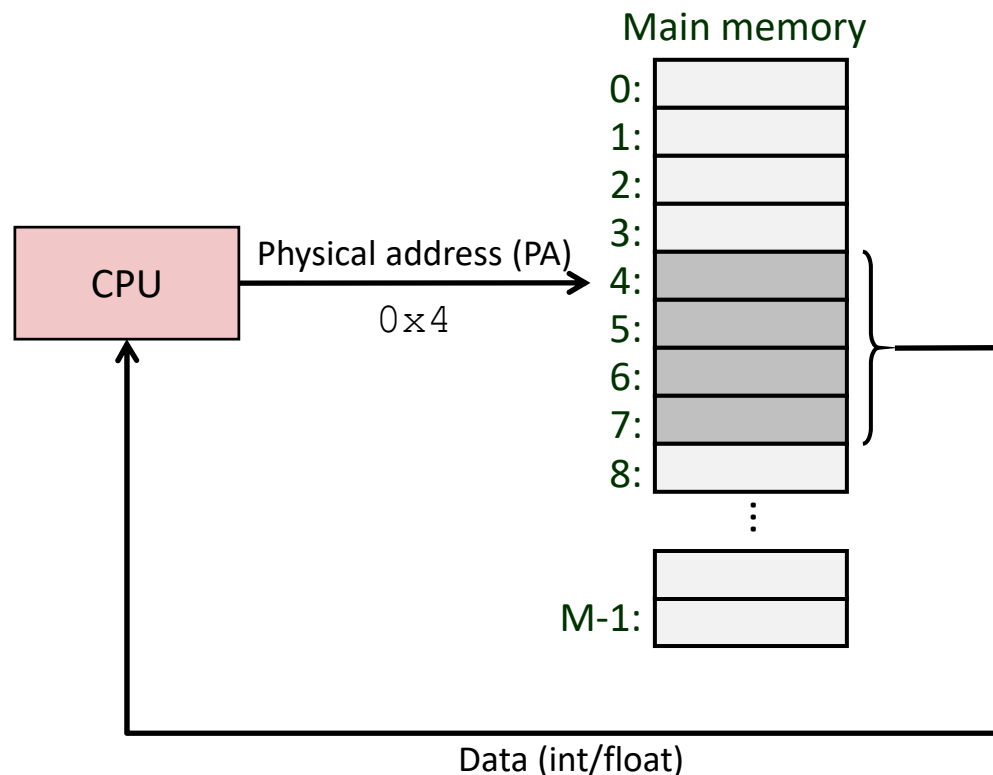
- ❖ hw19 due TONIGHT Monday (5/17)
 - Lab 4 preparation
- ❖ “Section 7.5”
 - Extra Cache Problems Posted
- ❖ Lab 4 due Friday (5/21)
 - Cache parameter puzzles and code optimizations
- ❖ **Questions Docs:** Use @uw google account to access!!
 - <https://tinyurl.com/CSE351-21sp-Questions>

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

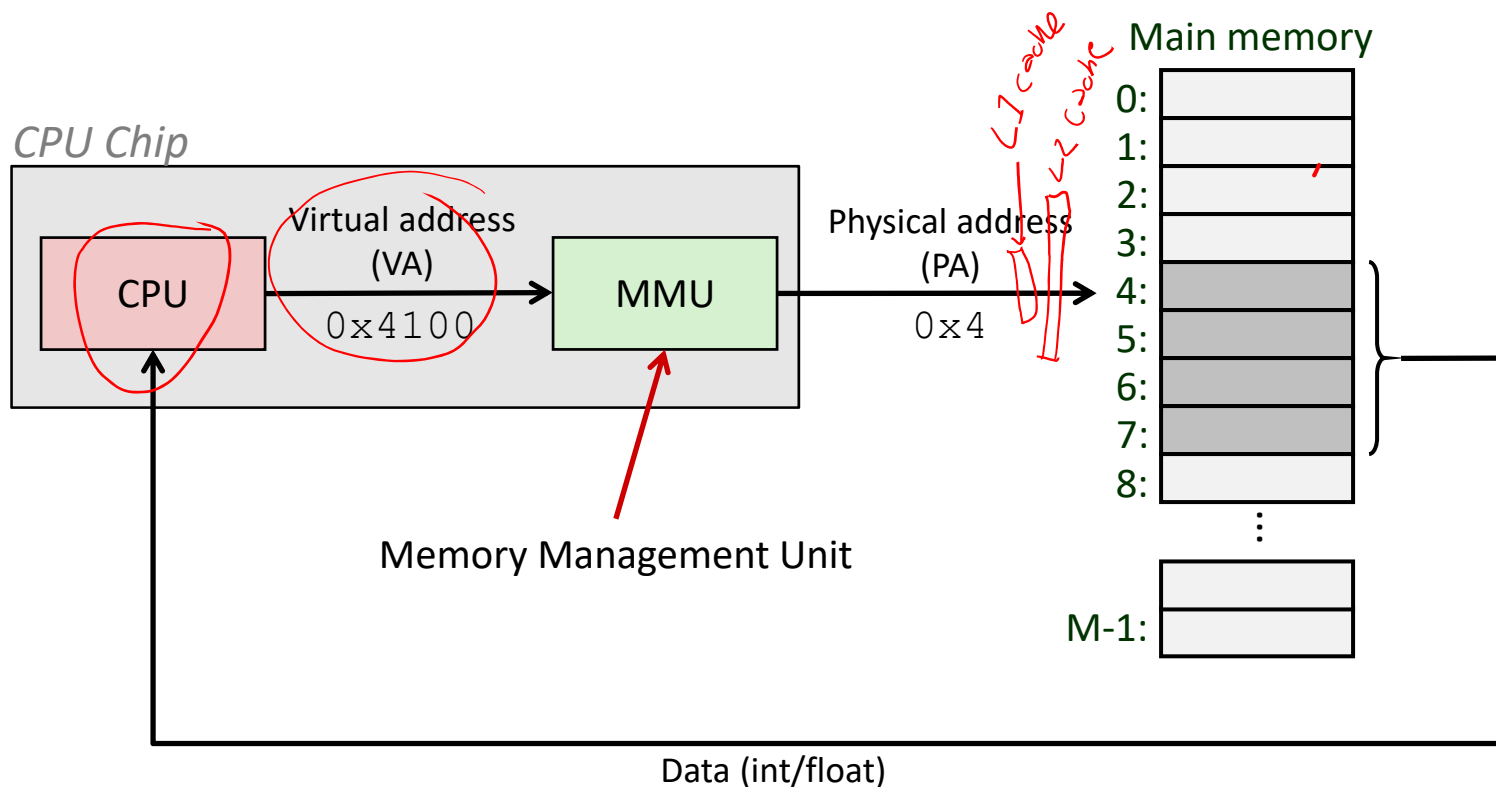


A System Using Physical Addressing



- ❖ 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

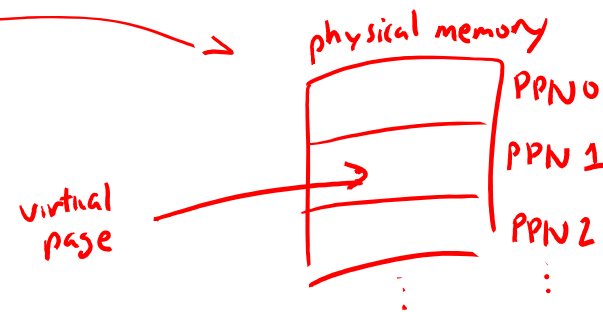
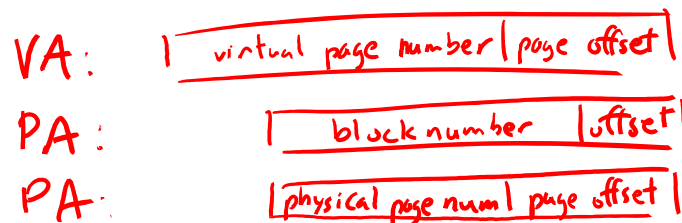
Reading Review

- ❖ 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)

Review Questions

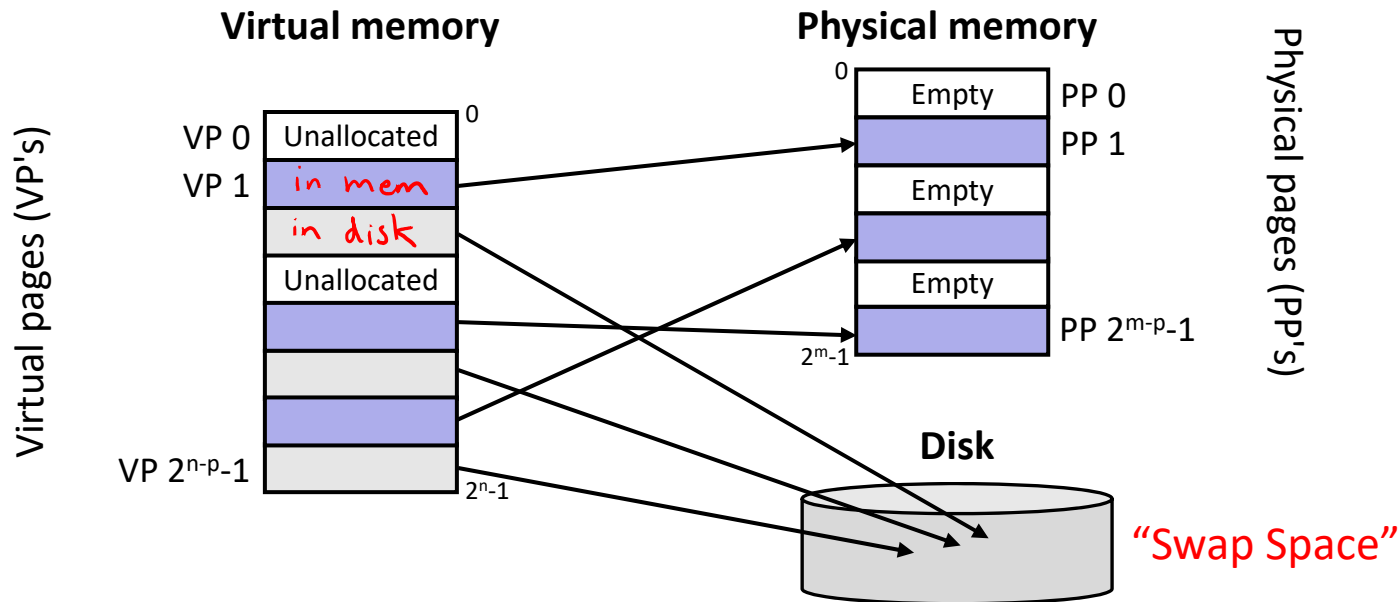
❖ Which terms from caching are most similar/analogous to the new virtual memory terms?

- page size
block size
- page offset width
(block) offset width
- virtual page number
block number
- physical page number
block number or cache set
- page table entry
cache line: data of interest + management bits
- access rights
management bits



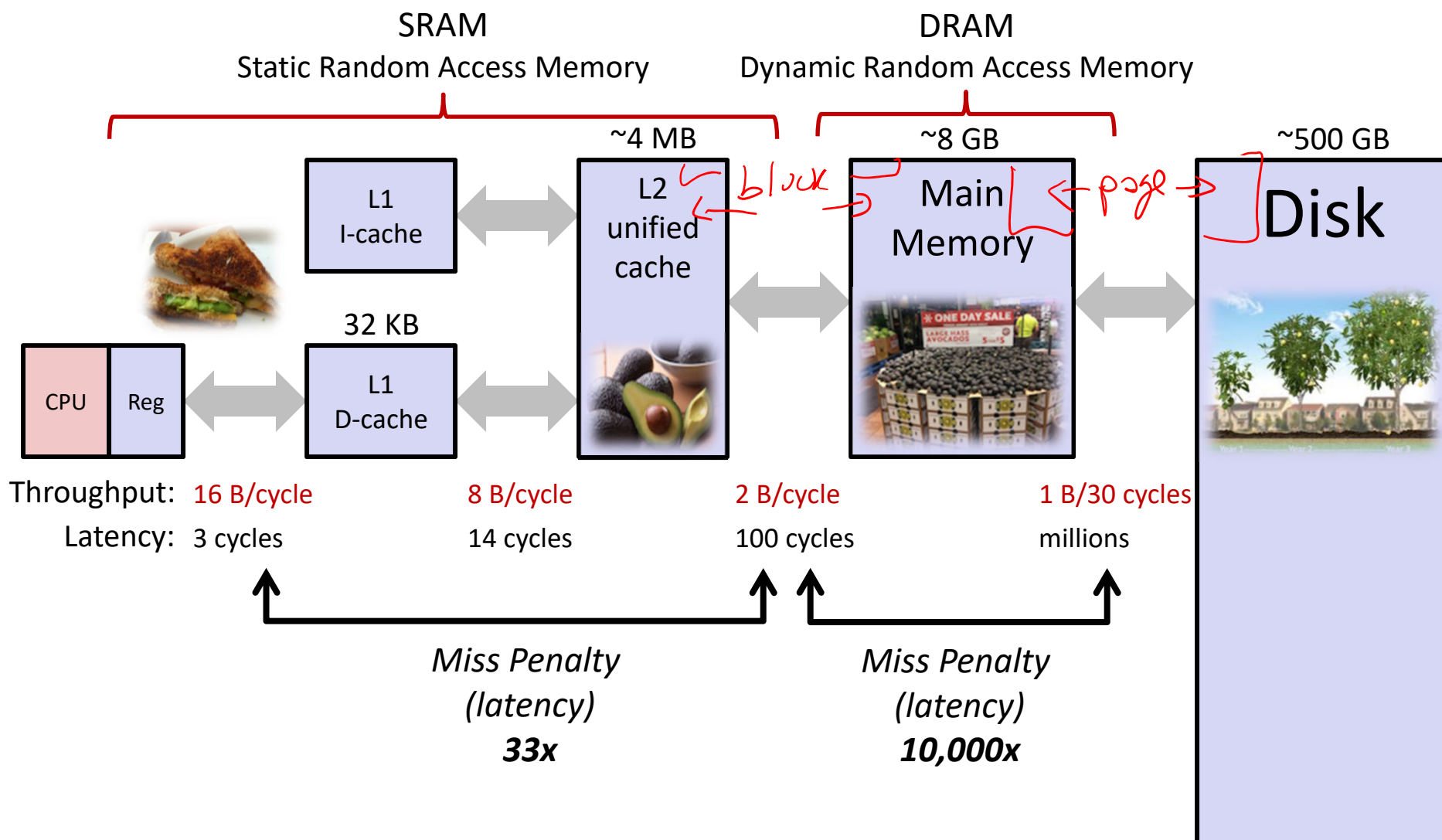
VM and the Memory Hierarchy

- ❖ Think of memory (virtual or physical) as an array of bytes, now split into *pages*
 - Pages are another unit of aligned memory (size is $P = 2^p$ bytes)
 - Each virtual page can be stored in *any* physical page (no fragmentation!)
 - p = ⌈log₂ P⌉*
 - no wasted space/gaps*
- ❖ 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 *(physical memory is single set)*
 - 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* *(track dirty pages)*
 - Really don't want to write to disk every time we modify something in memory
 - Some things may never end up on disk (e.g. stack for short-lived process)

Why does VM work on RAM/disk?

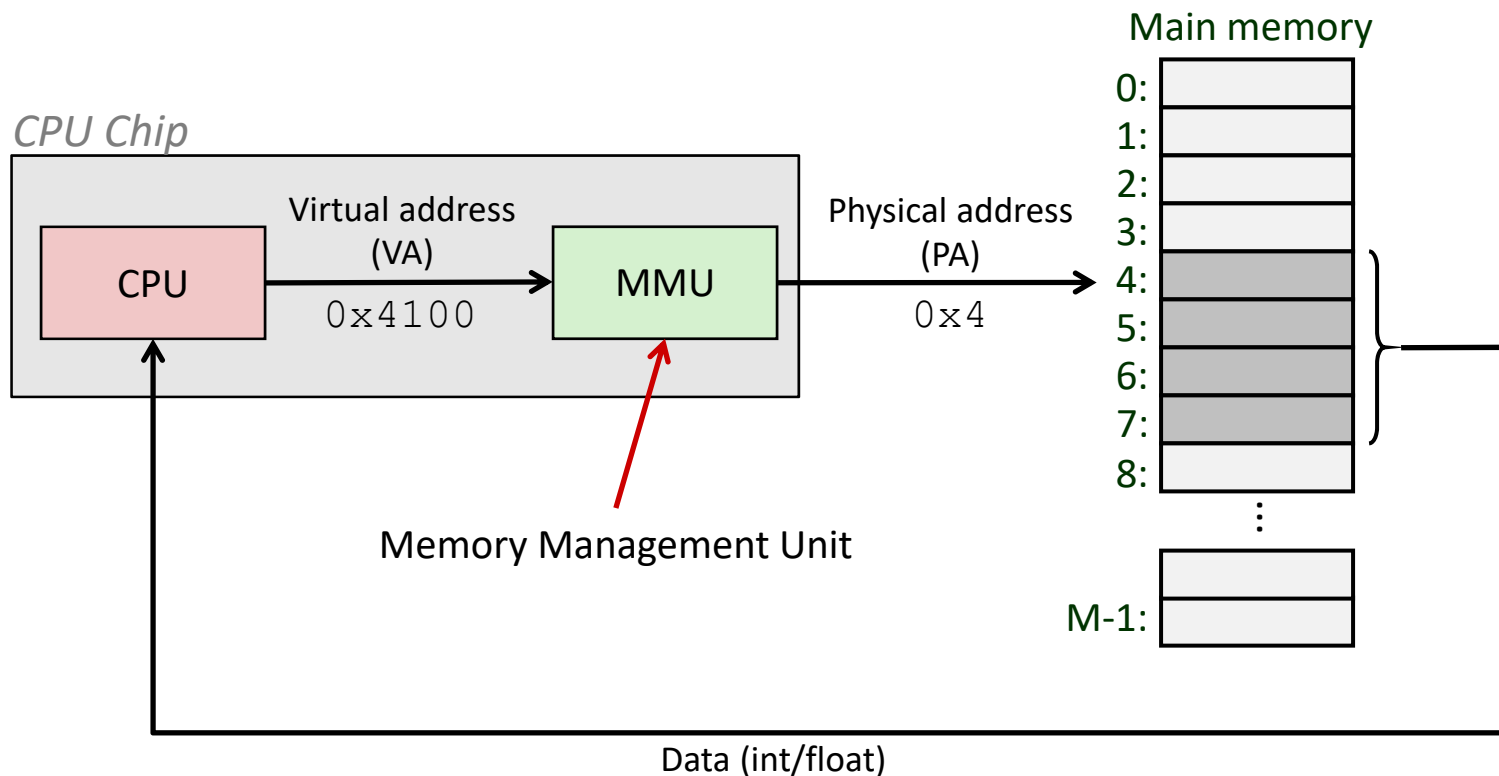
- ❖ Avoids disk accesses because of *locality*
 - Same reason that L1 / L2 / L3 caches work
- ❖ The set of virtual pages that a program is “actively” accessing at any point in time is called its working set
 - If (*working set of one process* \leq *physical memory*):
 - Good performance for one process (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?

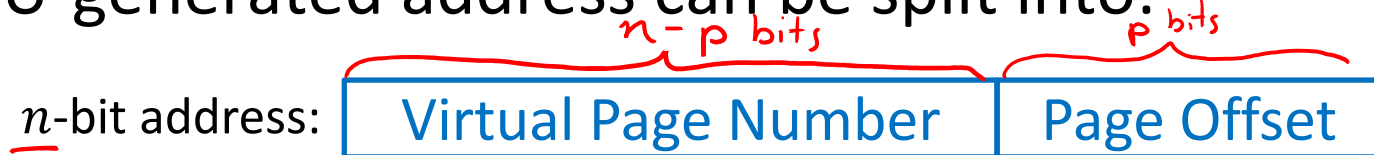


Address Translation: Page Tables

VPN width $n-p \Leftrightarrow$ we have 2^{n-p} pages in VA space

page size P bytes
 $\Leftrightarrow p = \lceil \log_2 P \rceil$ bits

❖ CPU-generated address can be split into:



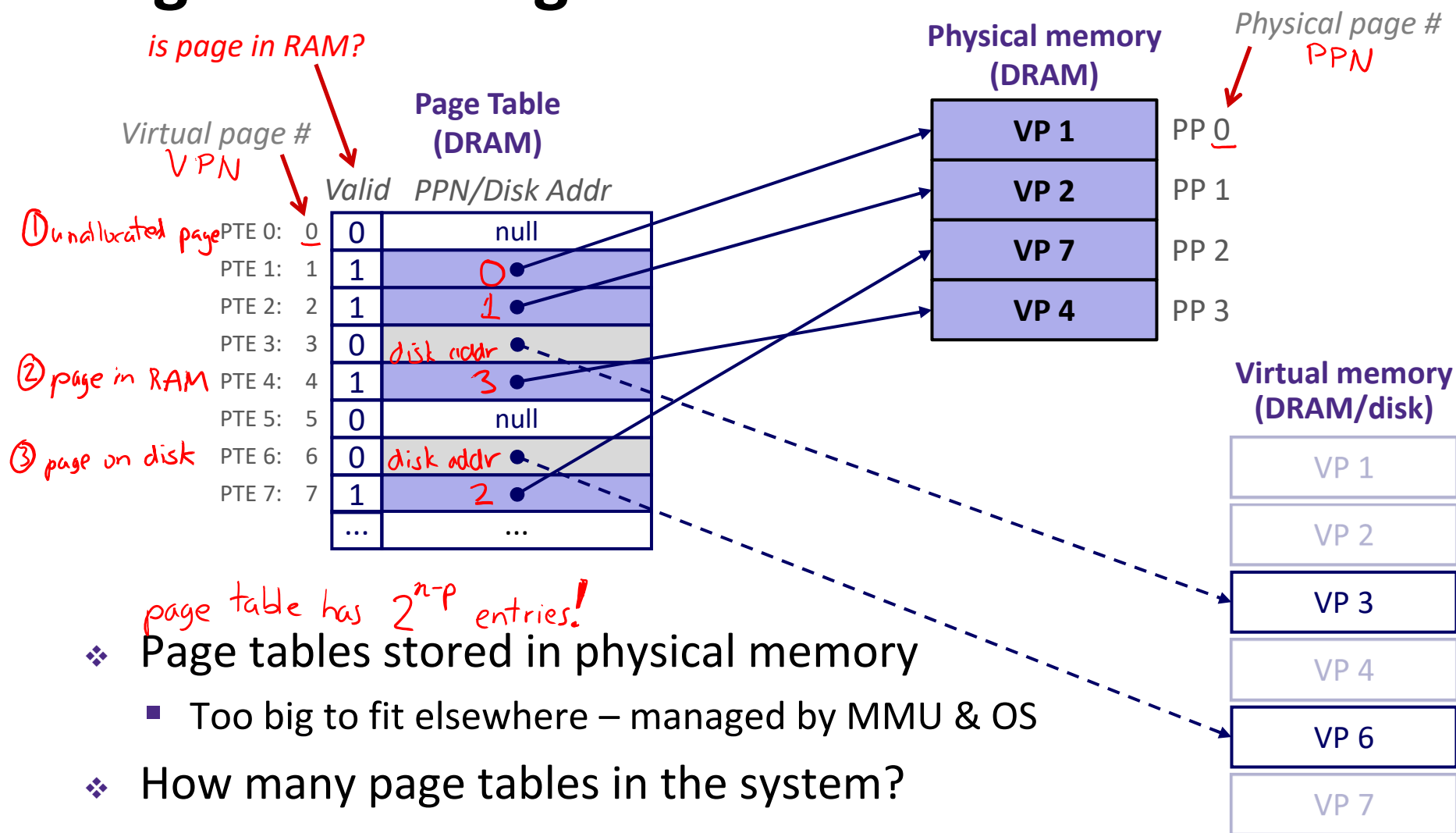
- Request is Virtual Address (**VA**), want Physical Address (**PA**)
 - Note that Physical Offset = Virtual Offset (page-aligned)
- (Handwritten annotation: "analogous to:" with a box around "block number" and "block offset" for caches)*

❖ 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)

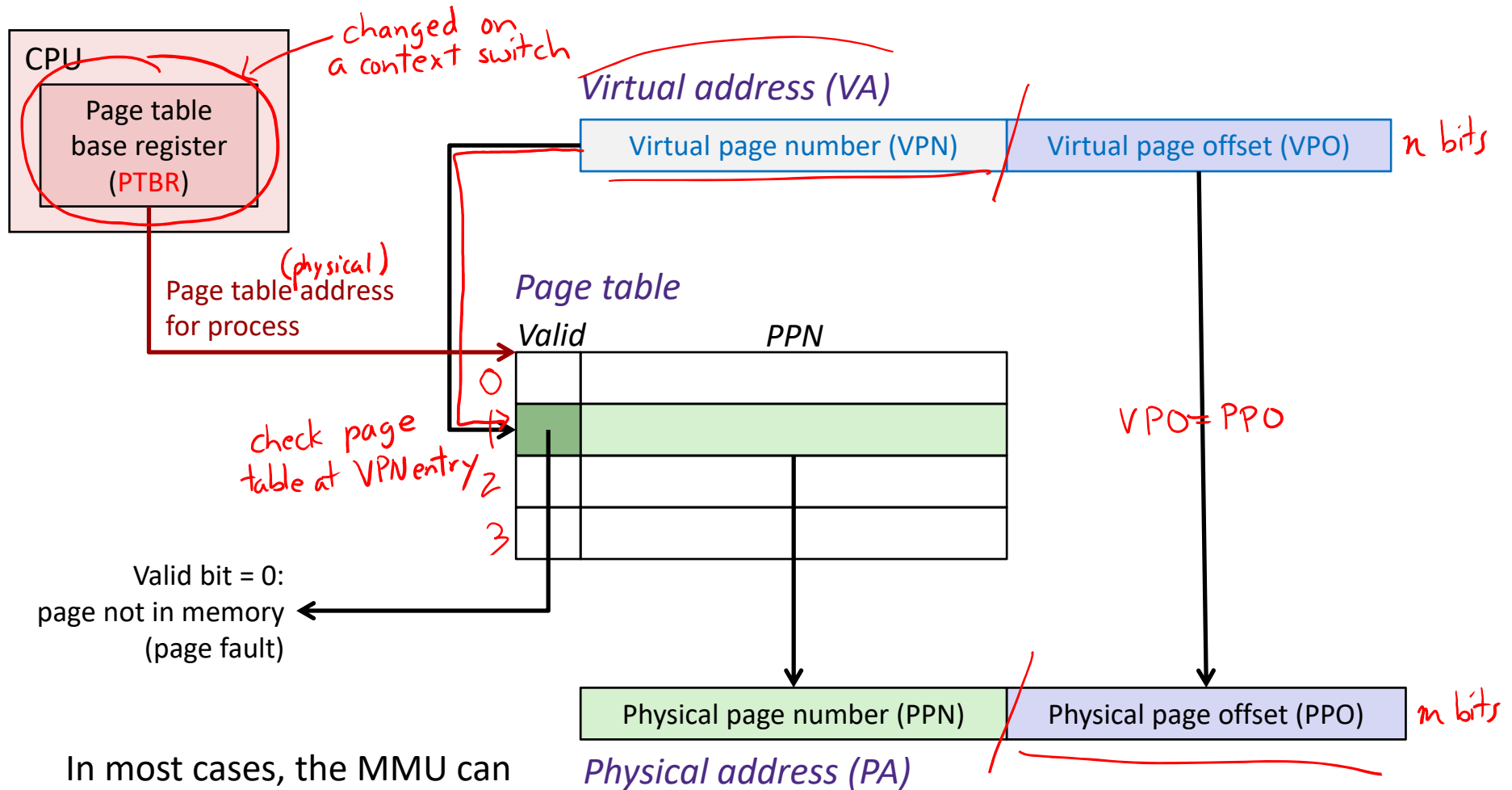
★ Has an entry for every virtual page

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 2^4 2^{10}
- 48-bit virtual addresses $p = 14$ bits $n = 48$ bits ↔ 256 TiB virtual memory
- 16 GiB physical memory $m = 34$ bits
- Vote in Ed Lessons



$VPN = n - p = 34$ bits ↔ 2^{34} pages in virtual address space

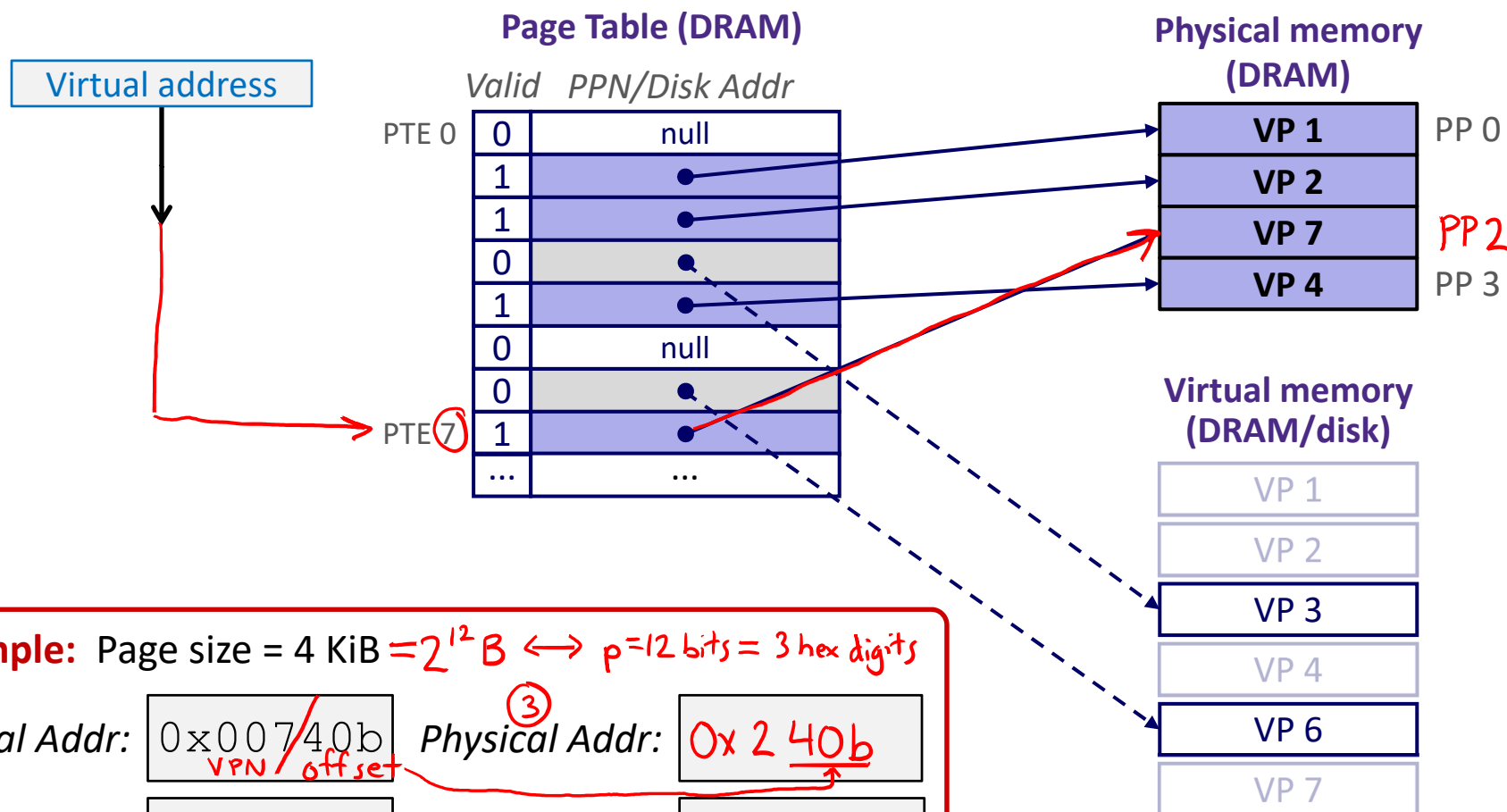


$PPN = m - p = 20$ bits ↔ 2^{20} pages in physical address space

	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 = 2^{12} B \leftrightarrow p=12 bits = 3 hex digits

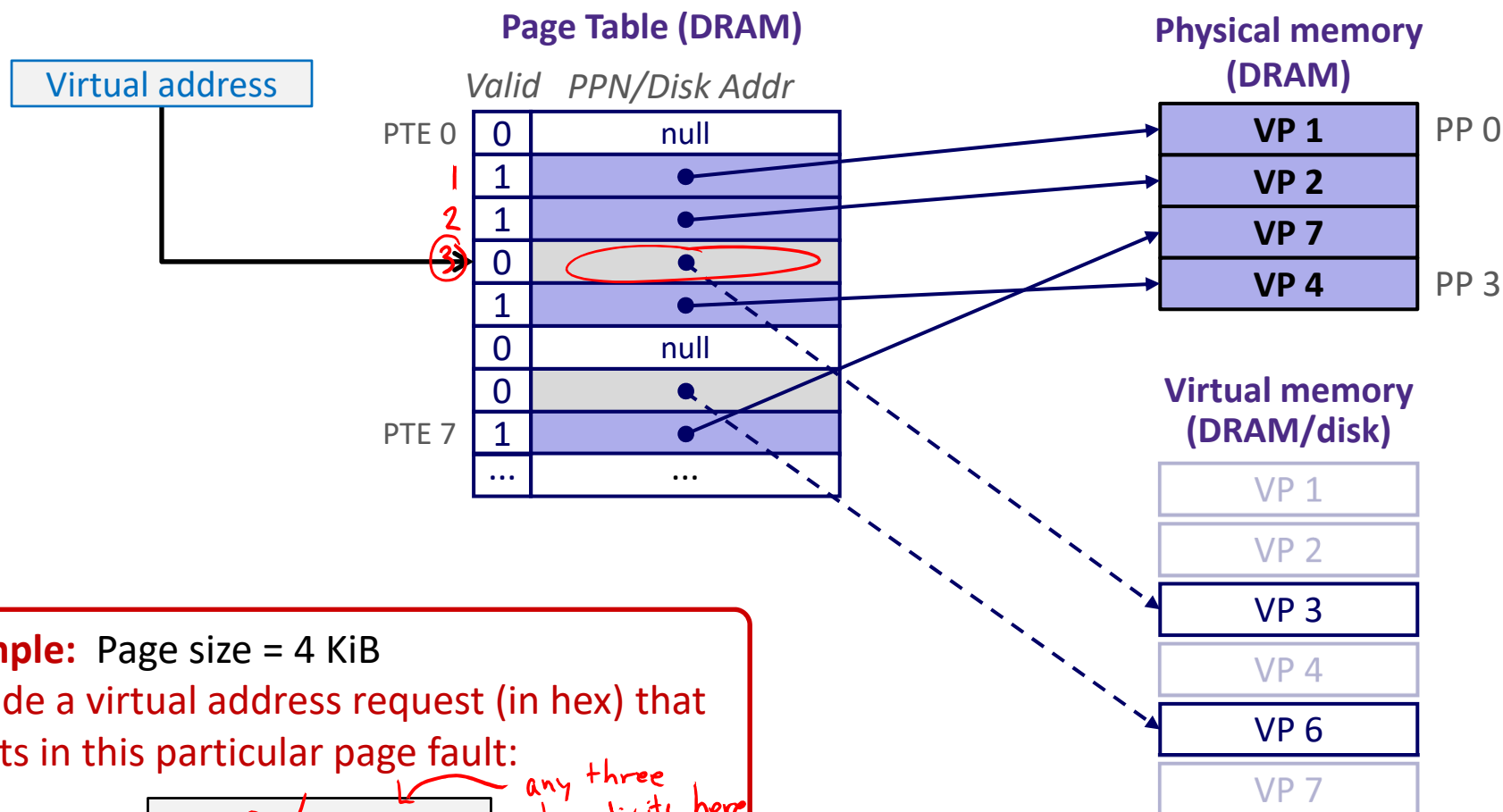
Virtual Addr: 0x007/40b
VPN / offset

Physical Addr: 0x240b
PPN / offset

① VPN: 7 ② PPN: 2

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:

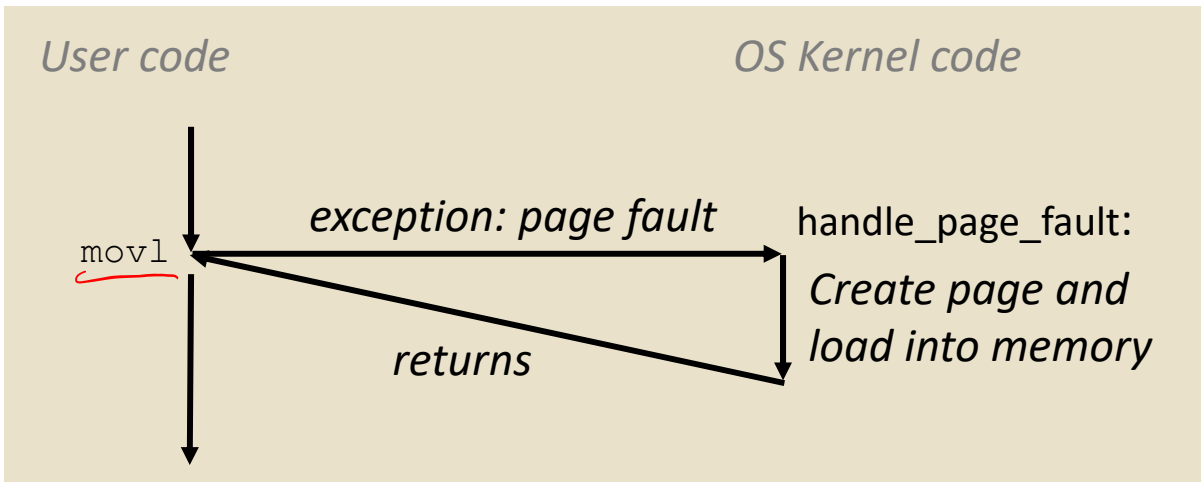
Virtual Addr: 0x003/000 *any three hex digits here*

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;
}
```

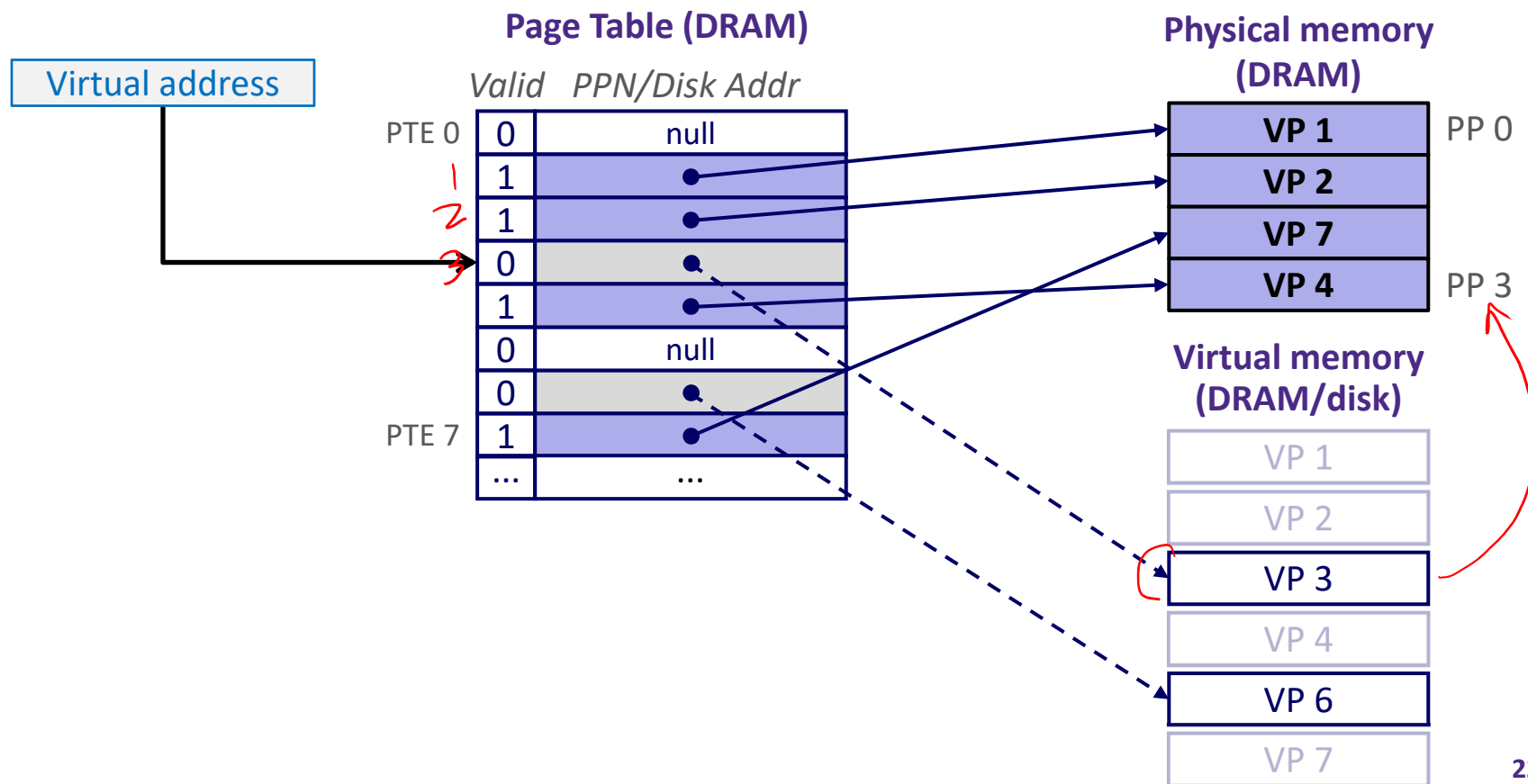
```
80483b7:      c7 05 10 9d 04 08 0d  movl    $0xd,0x8049d10
```



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

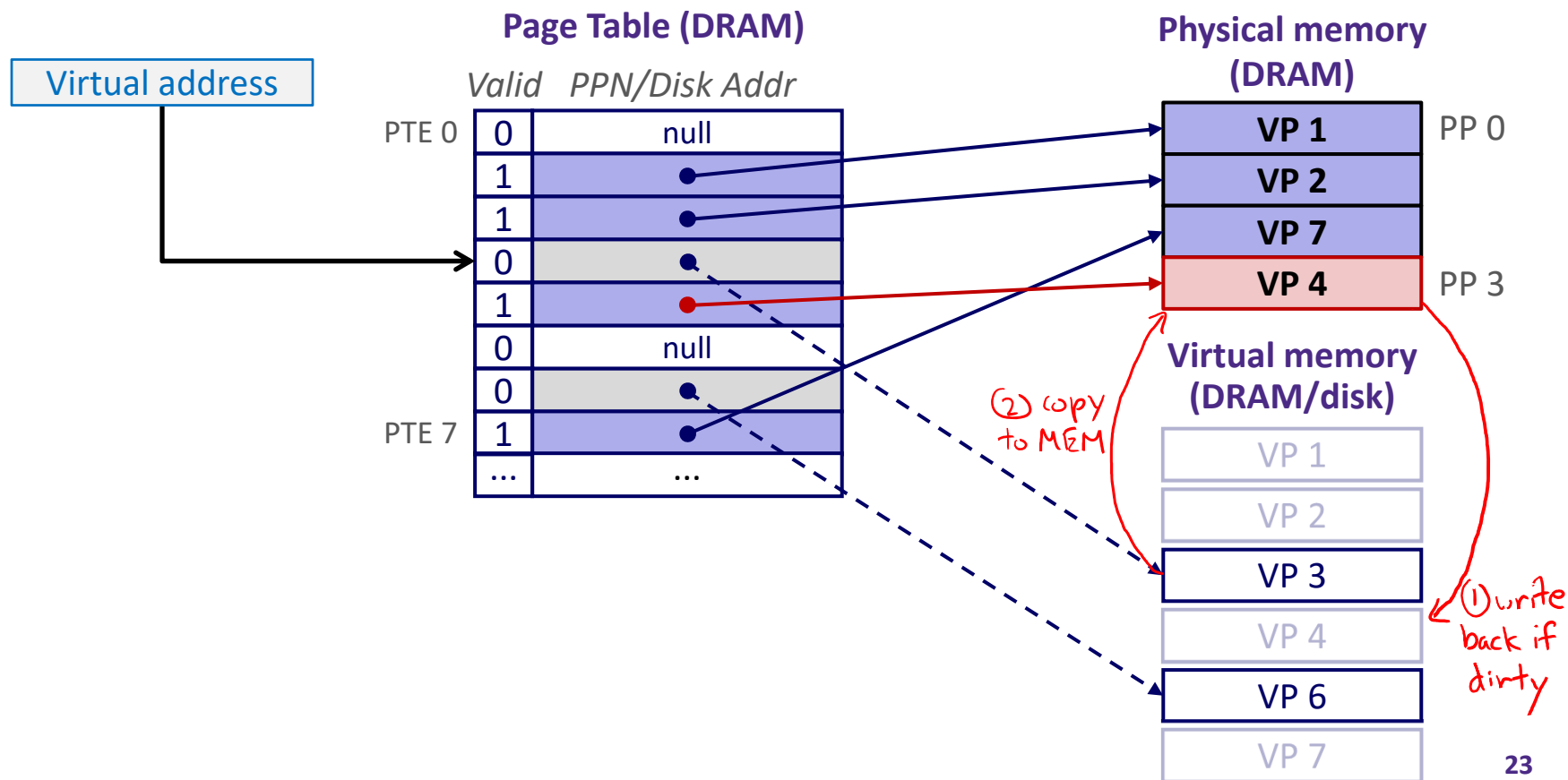
Handling a Page Fault

- ❖ Page miss causes page fault (an exception)



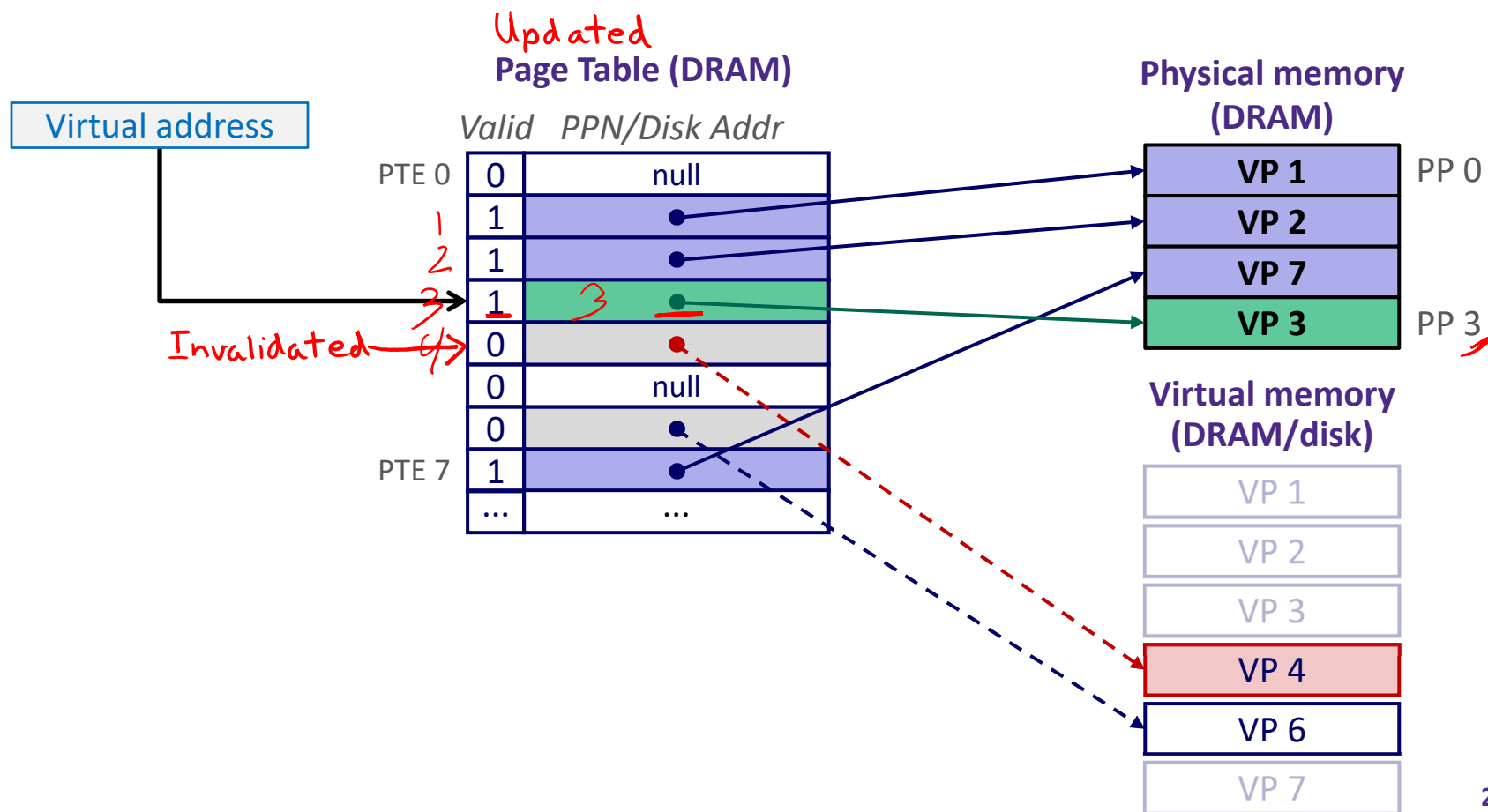
Handling a Page Fault

- ❖ Page miss causes page fault (an exception)
- ❖ Page fault handler selects a *victim* to be evicted (here VP 4) PP 3



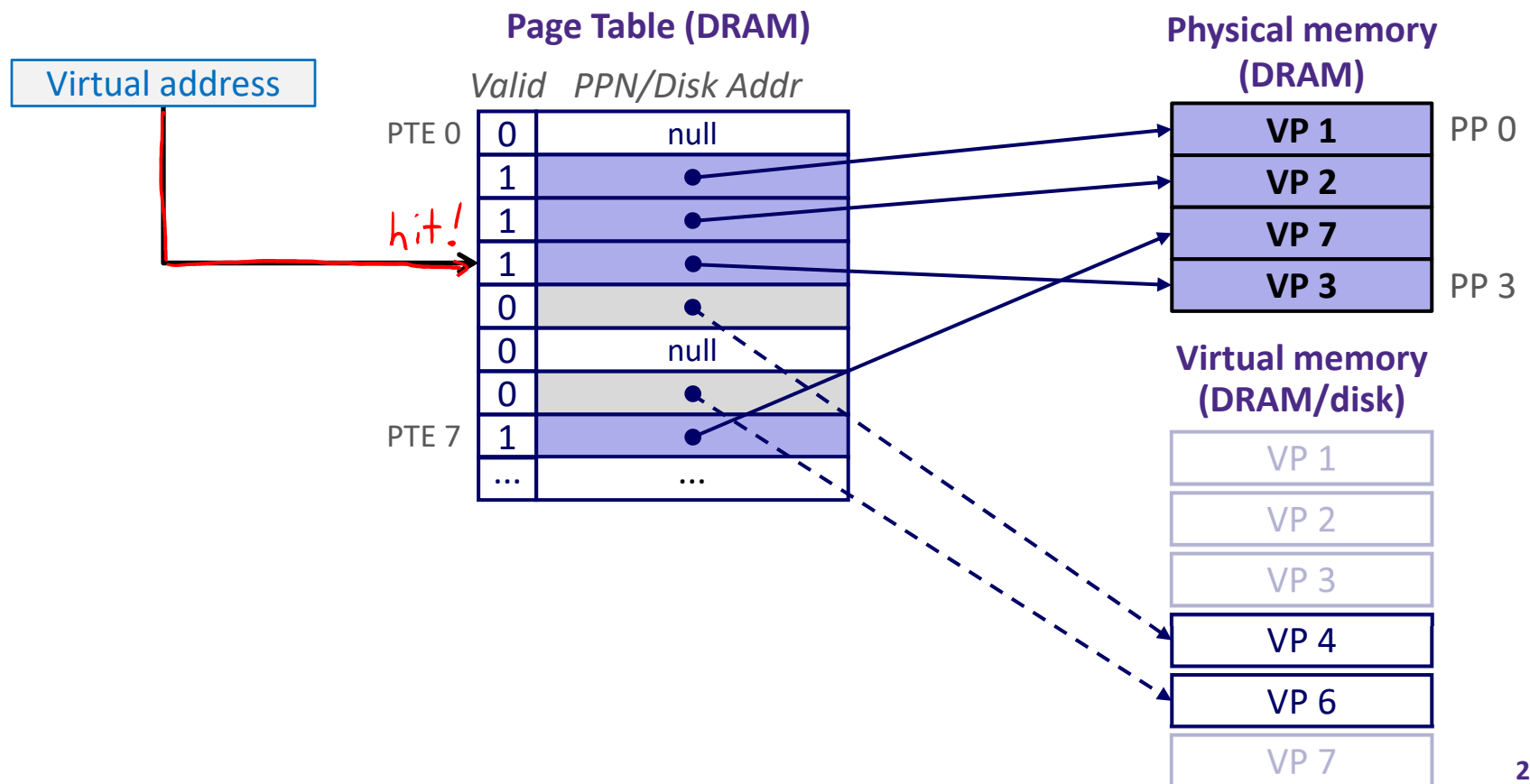
Handling a Page Fault

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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!**

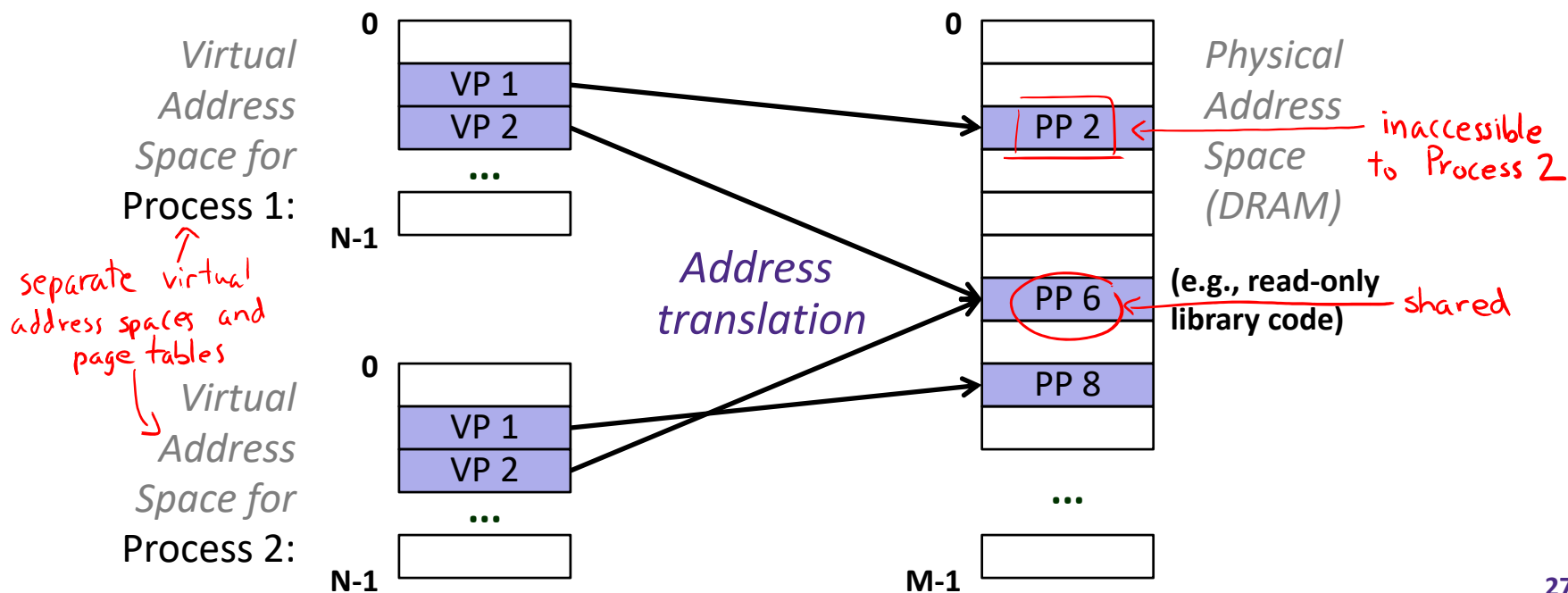


Virtual Memory (VM)

- ❖ 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**

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!



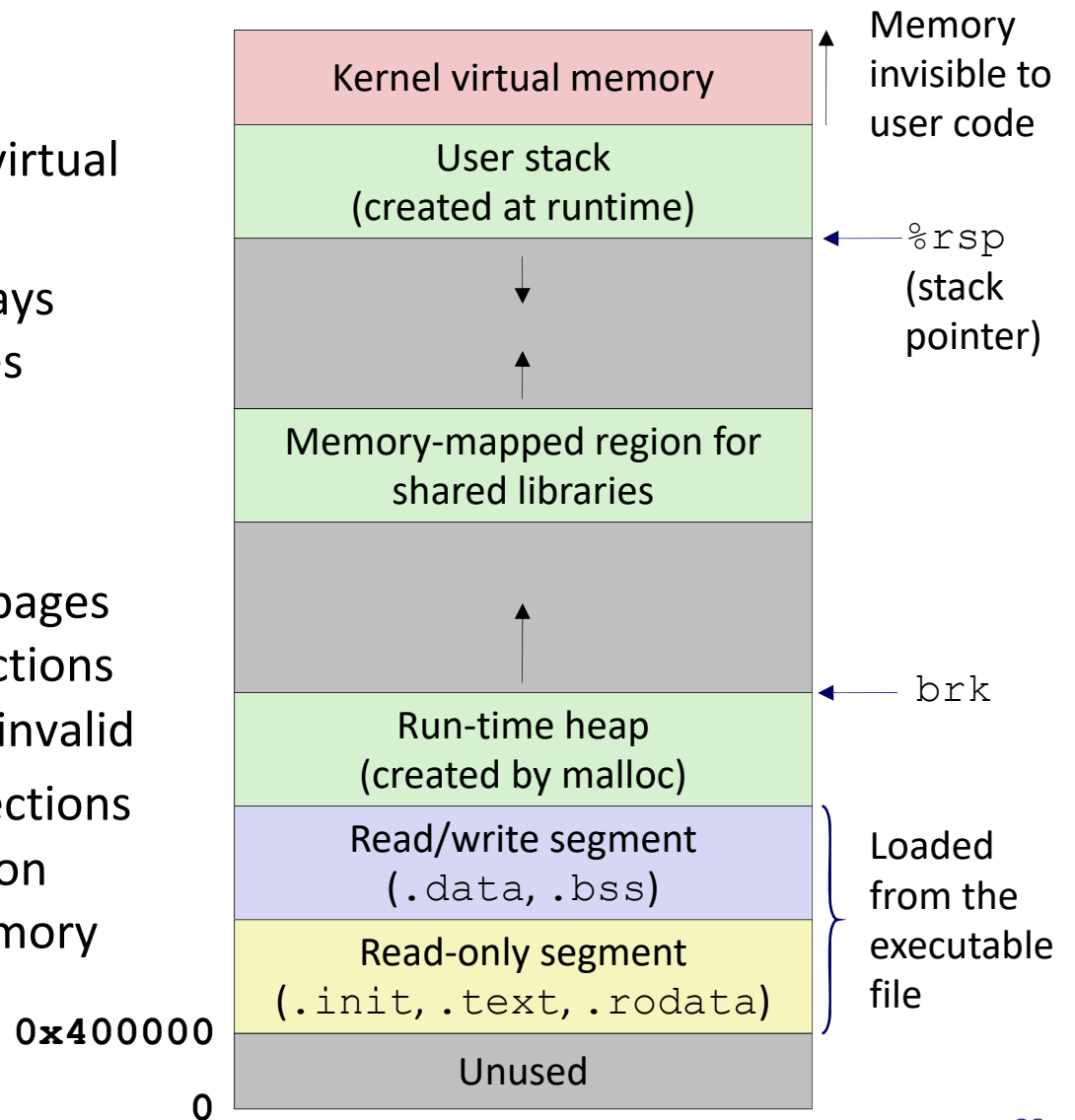
Simplifying Linking and Loading

❖ Linking

- Each program has similar virtual address space
- Code, Data, and Heap always start at the same addresses

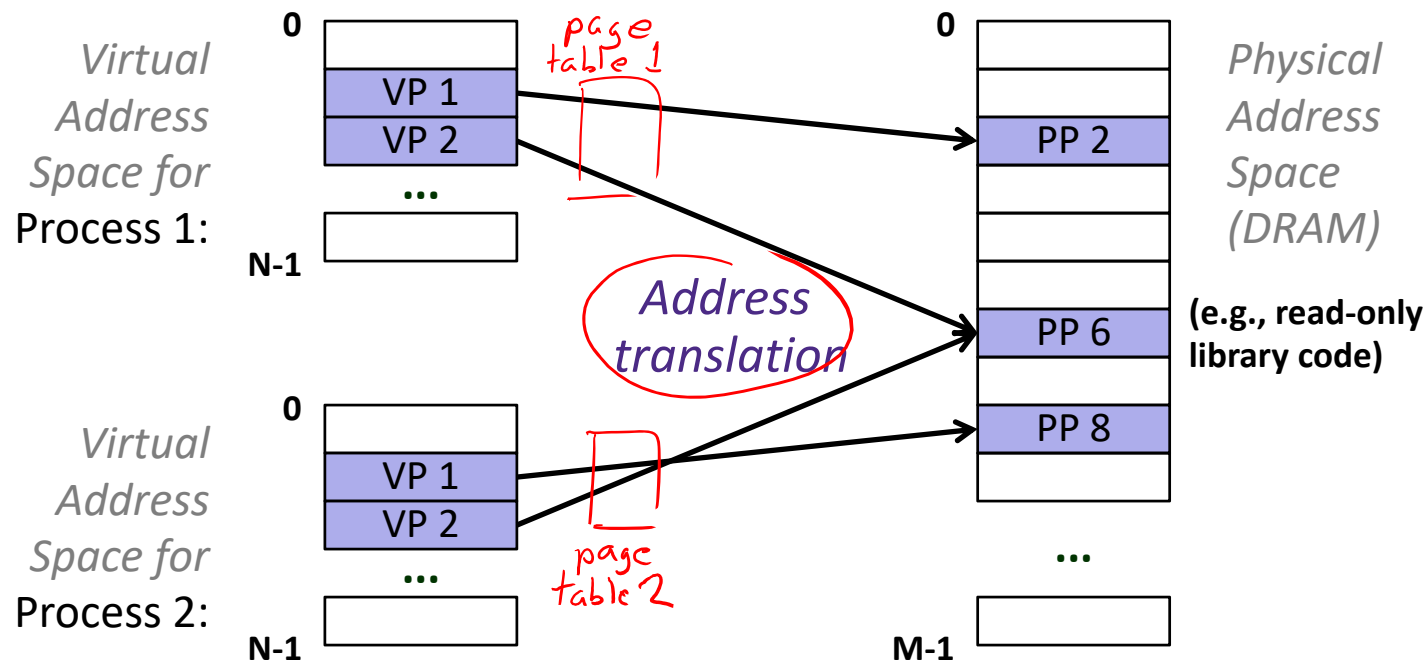
❖ Loading

- `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



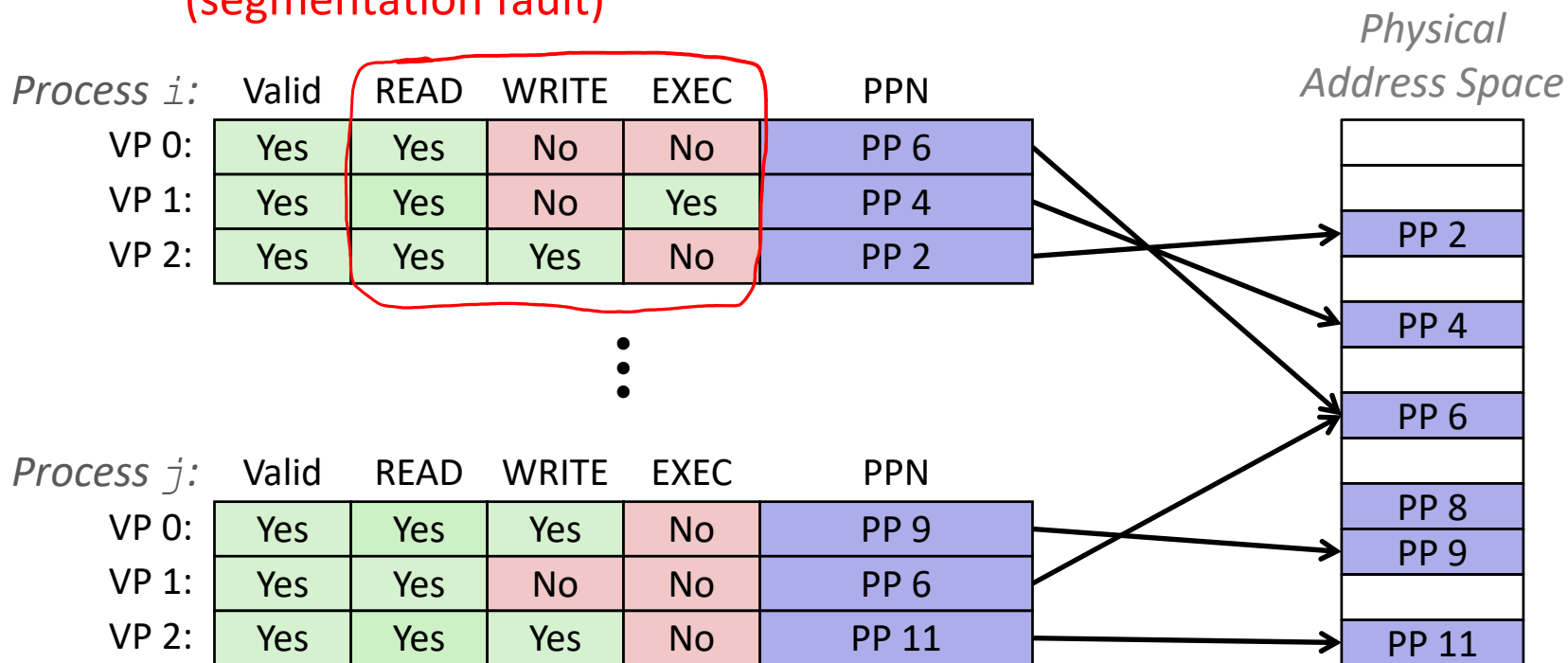
VM for Protection and Sharing

- ❖ 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 *(extra management 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	1	1	0
Heap	1	1	0
Static Data	1	1	0
Literals	1	0 (constants)	0
Instructions	1	0 (don't alter code)	1 (only instructions should be executable)

static in size →