

Virtual Memory II

CSE 351 Spring 2022

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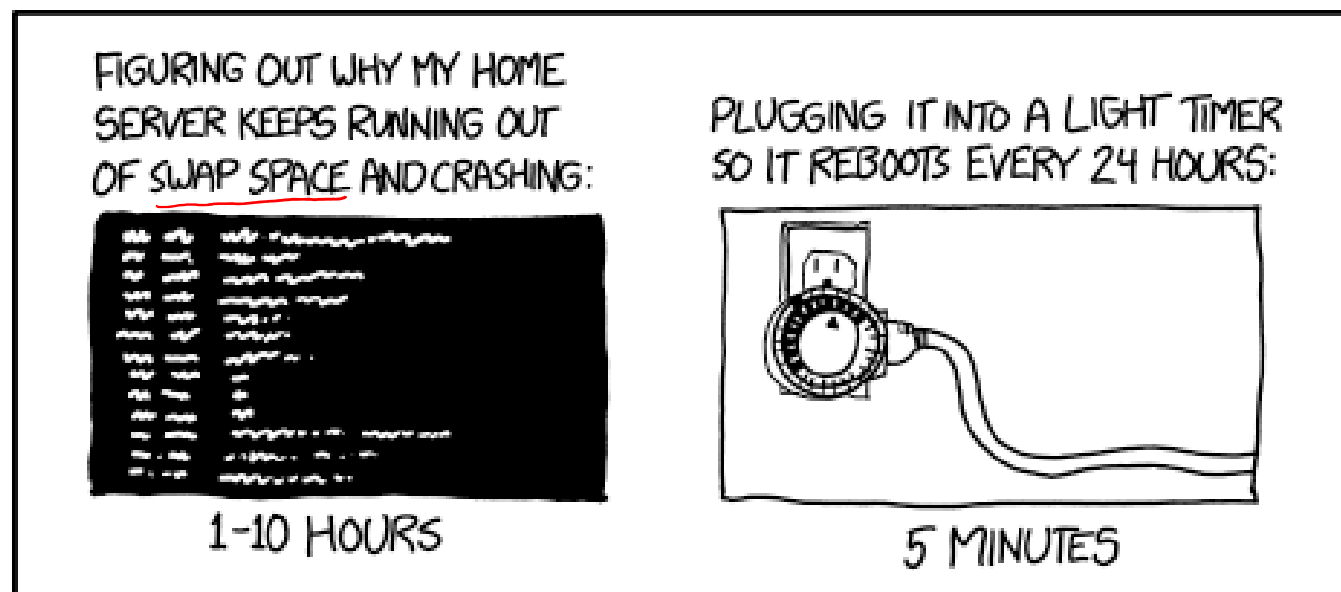
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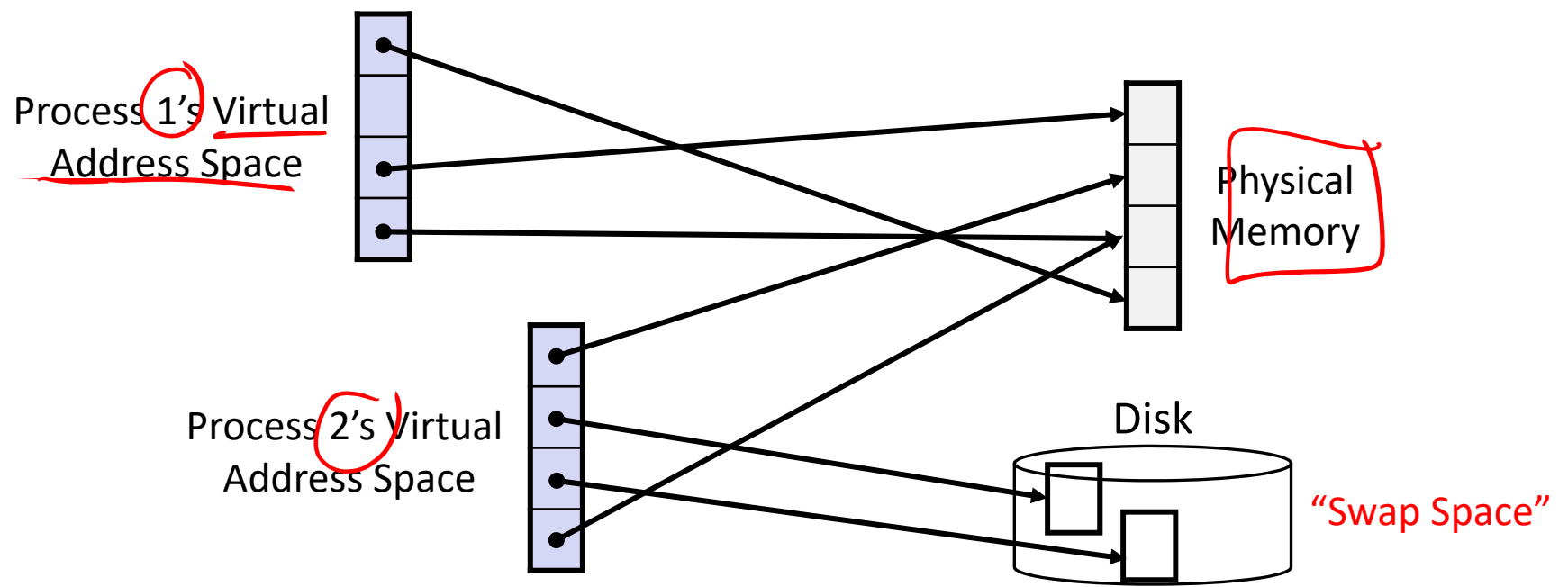
<https://xkcd.com/1495/>

Relevant Course Information

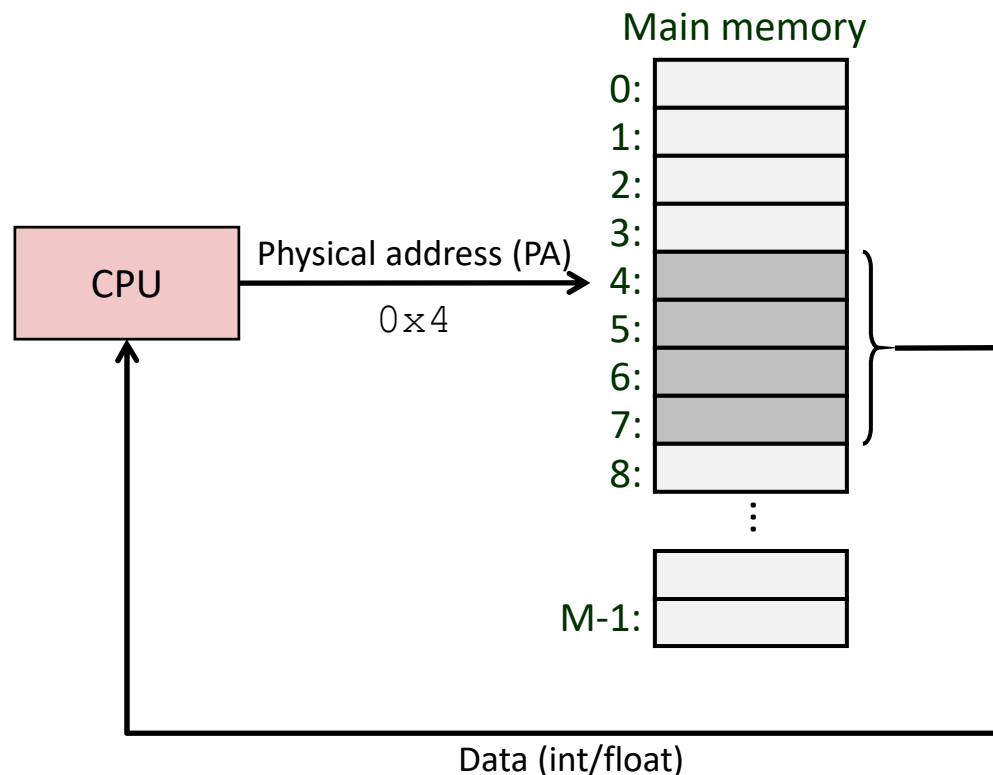
- ❖ hw19 due Monday (5/16)
 - Lab 4 preparation
- ❖ hw20 due Wednesday (5/18)
- ❖ hw21 due Friday (5/20)
- ❖ Lab 4 due Friday (5/20)
 - Cache parameter puzzles and code optimizations

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

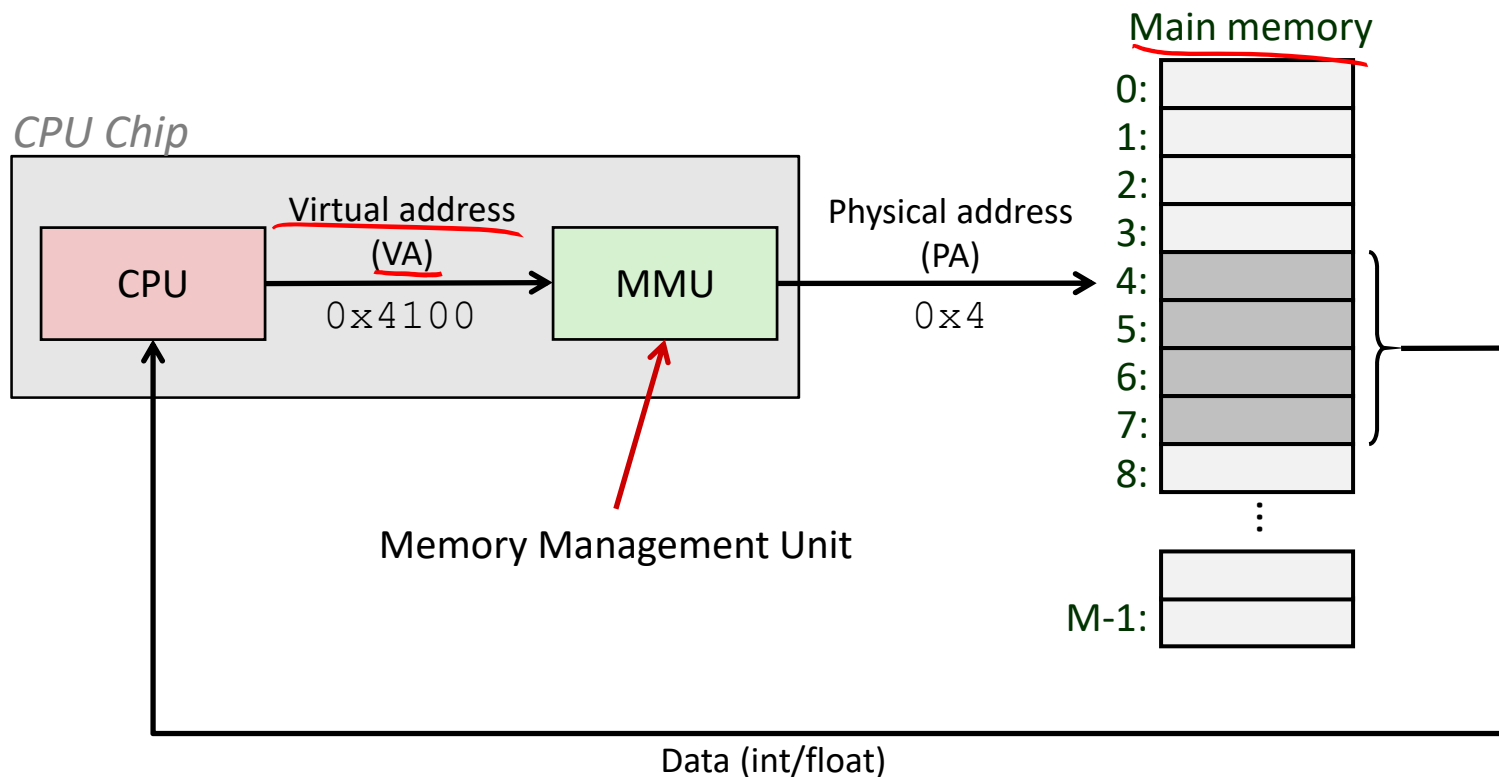


A System Using Physical Addressing



- ❖ 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

caching
VM

<i>Block #</i>	<i>Block offset</i>
----------------	---------------------

■ page offset width

block offset width

<i>VPN</i>	<i>page offset</i>
<i>PPN</i>	<i>page offset</i>

■ virtual page number

block number

■ physical page number

block number, cache set

■ page table entry

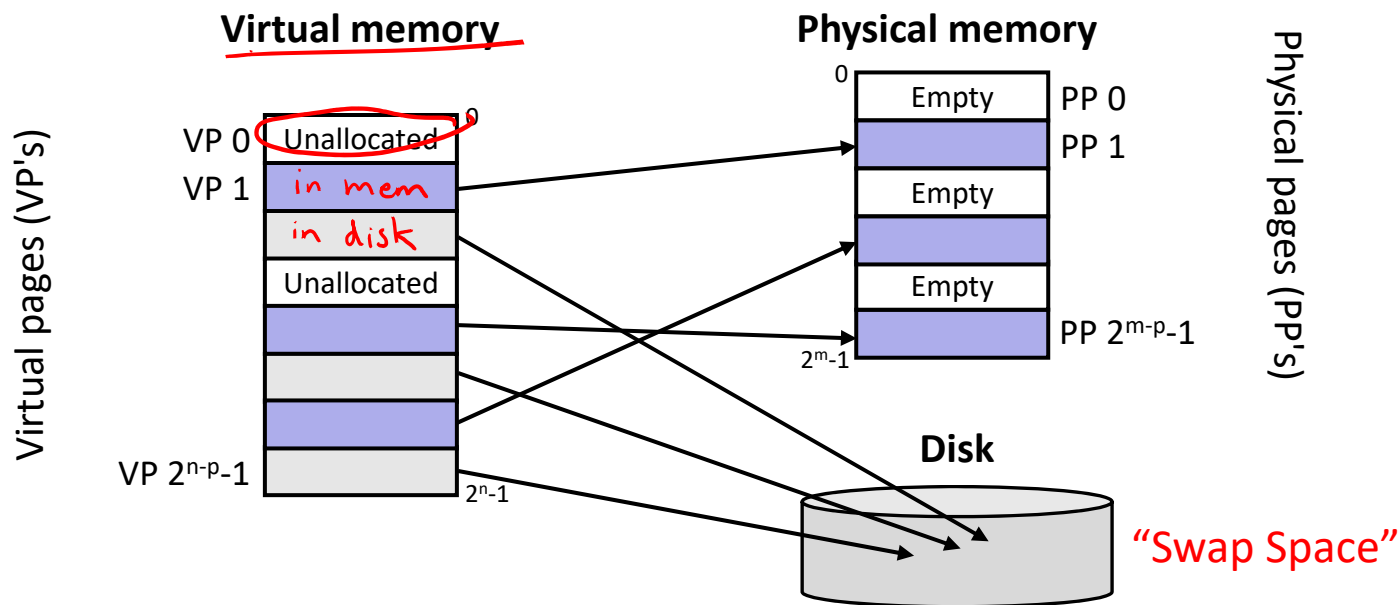
cache line

■ access rights

management bits

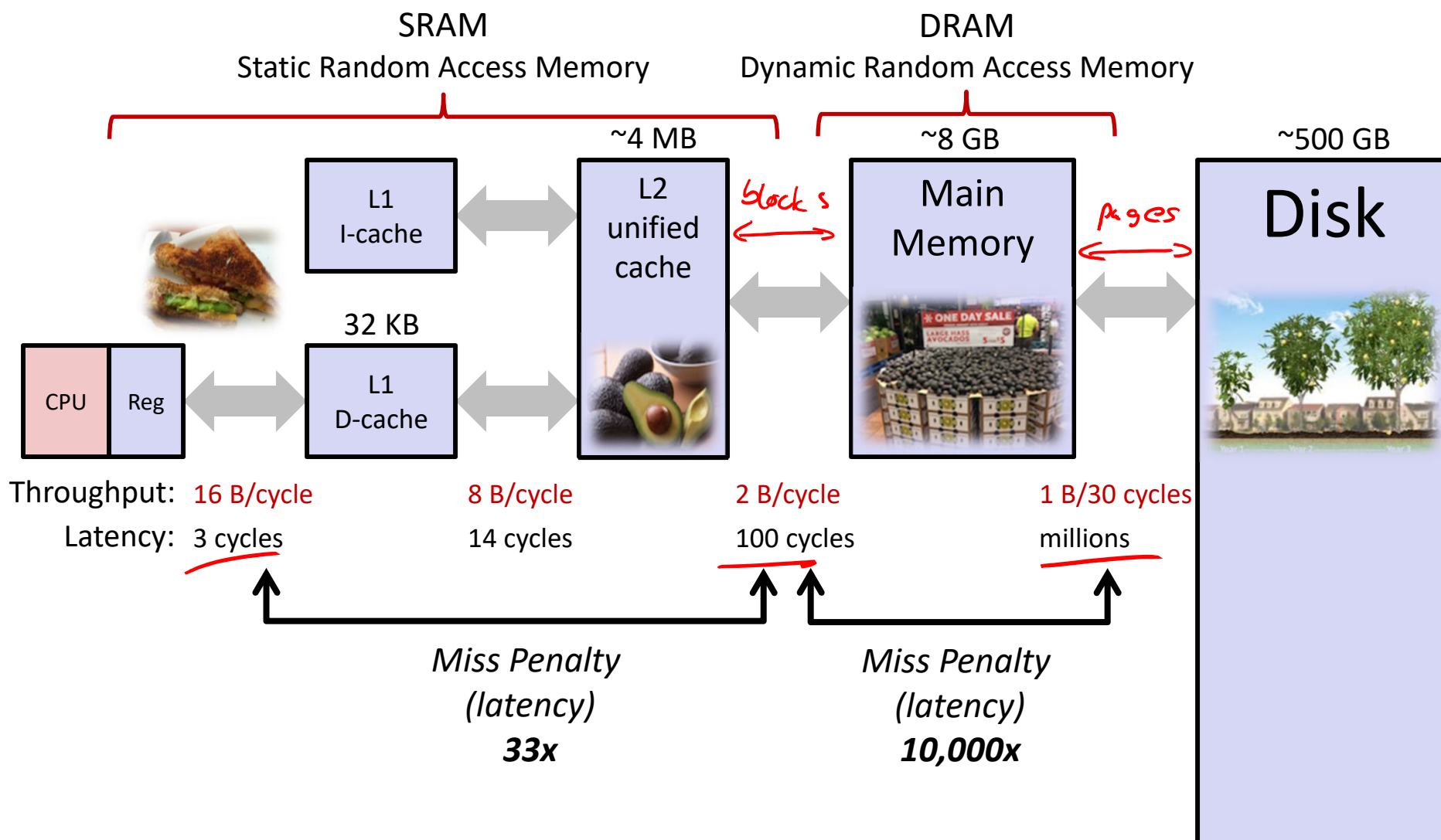
VM and the Memory Hierarchy

- ❖ 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 ^{later} rather than *write-through* *(track dirty pages)*
 - 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?

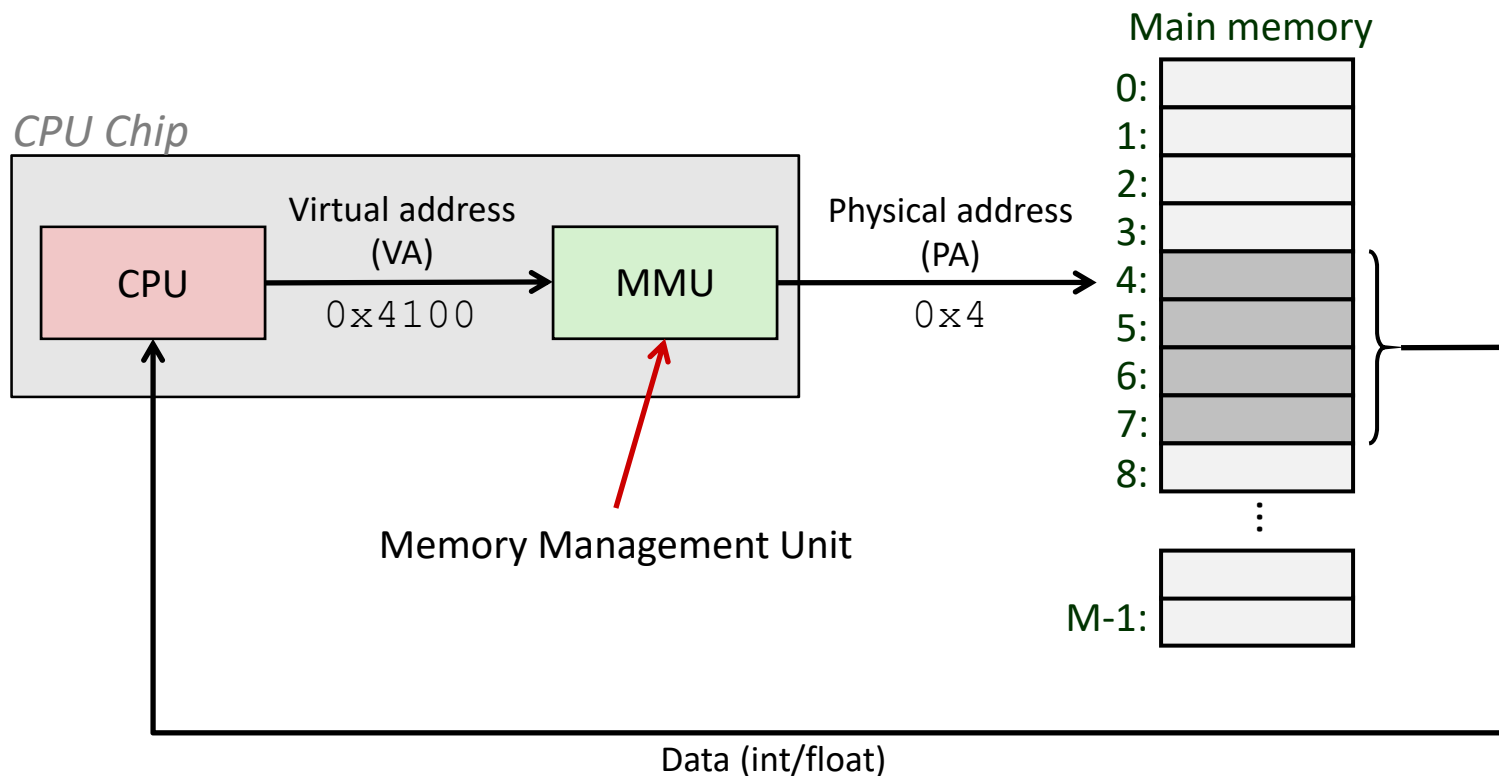
- ❖ Avoids disk accesses because of *locality*
 - Same reason that L1 / L2 / L3 caches work
- ❖ The set of virtual pages that a program is “actively” accessing at any point in time is called its *working set*
 - If (*working set of one process* \leq *physical memory*):
 - Good performance for one process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



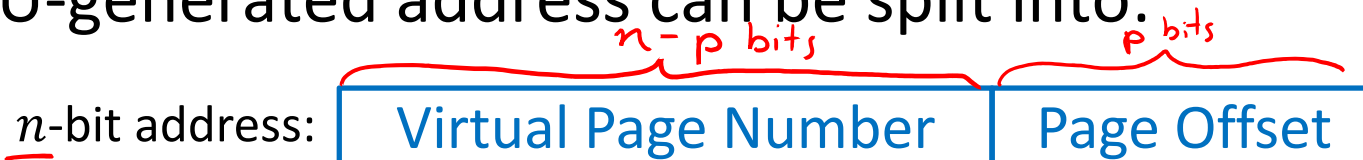
Address Translation: Page Tables

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:



analogous to: block number | block offset for caches

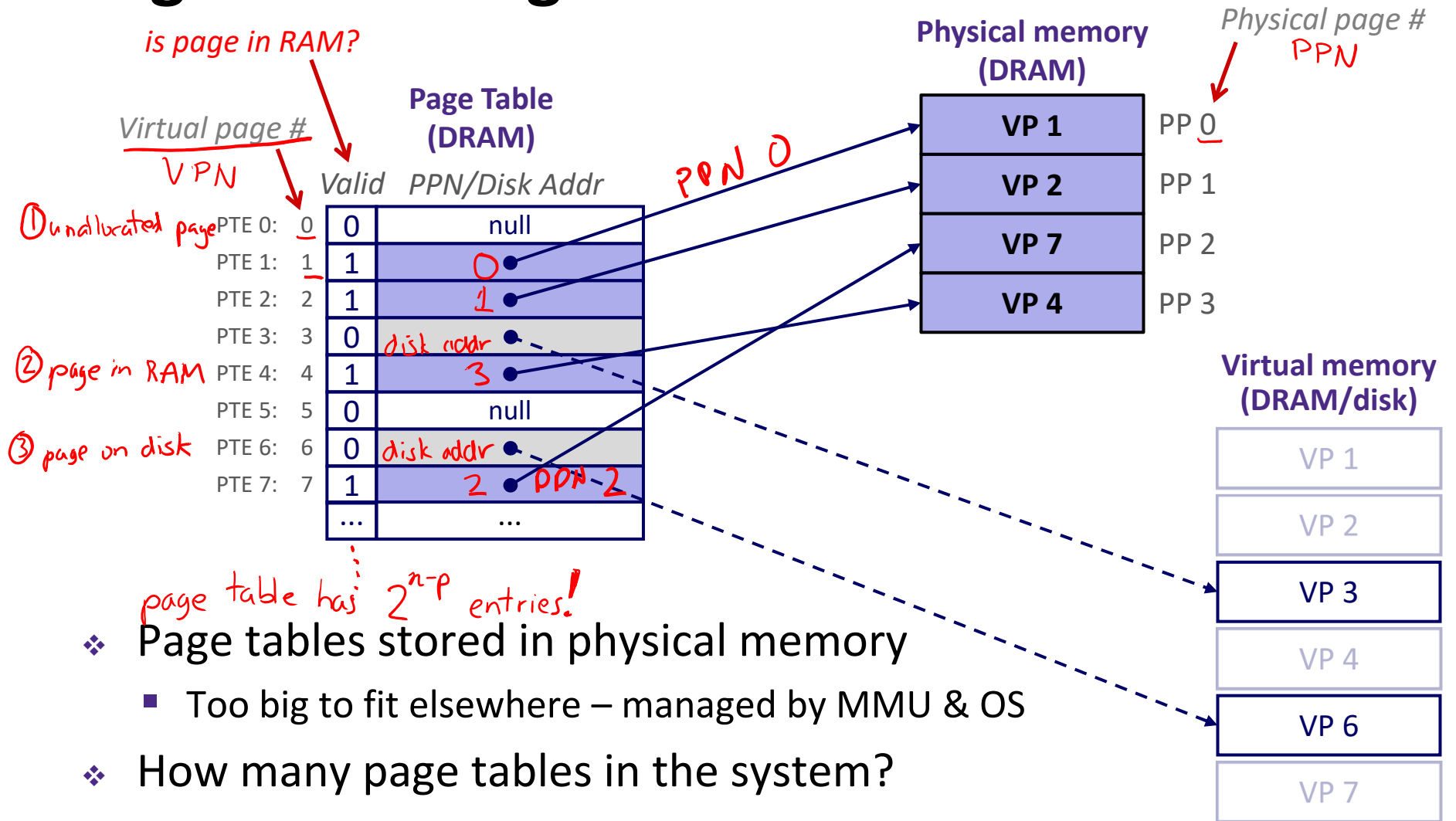
- Request is Virtual Address (VA), want Physical Address (PA)
- Note that Physical Offset = Virtual Offset (page-aligned)

❖ 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)

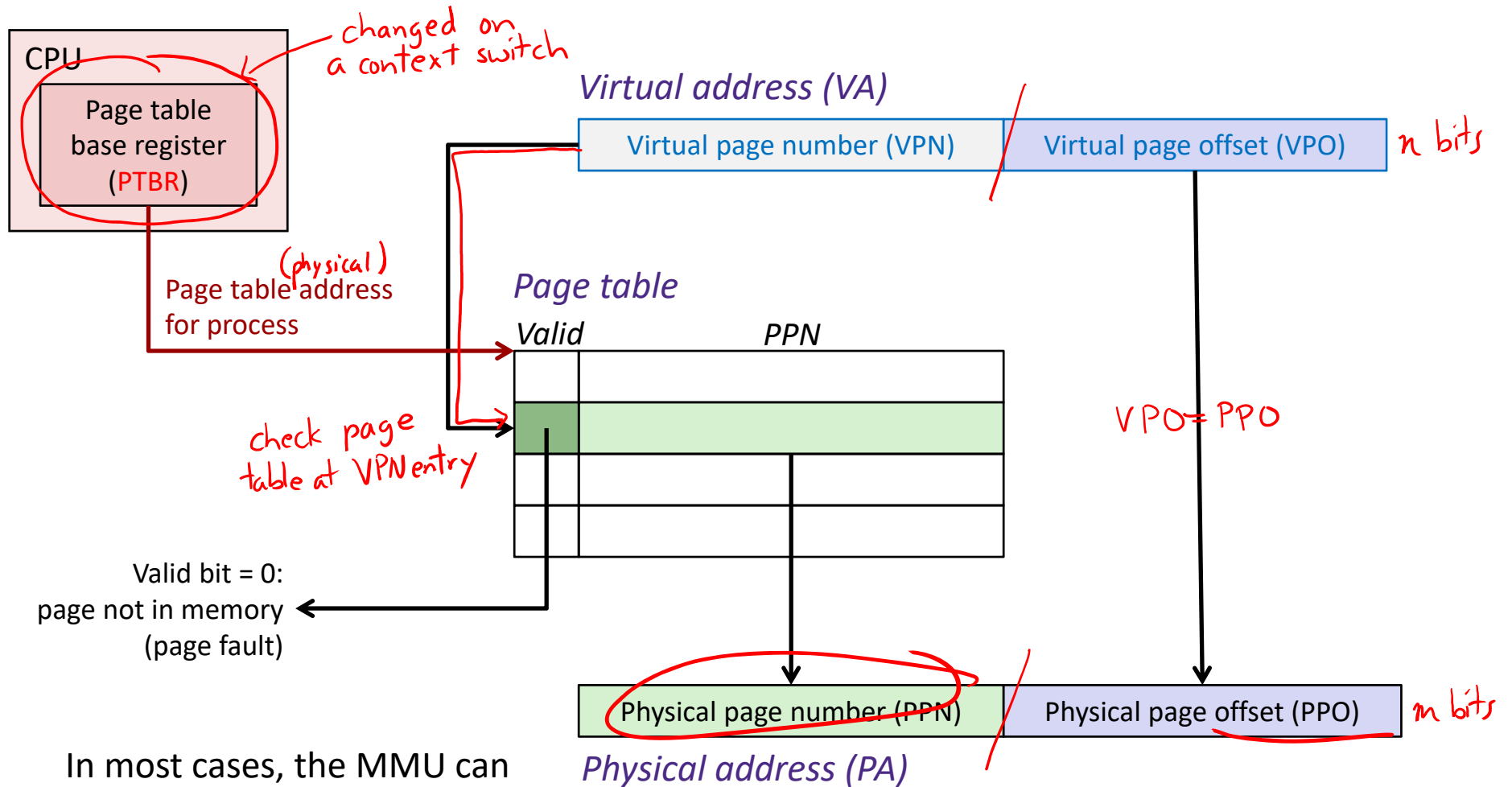
★ Has an entry for every virtual page

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

Page = 2^{14} Bytes 14 bits page offset
 $48 \text{ bits} - 14 \text{ bits} = 34 \text{ bits}$ VPN

2^{34} Bytes

$34 \text{ bits} - 14 \text{ bits} = 20 \text{ bits}$ PPN



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

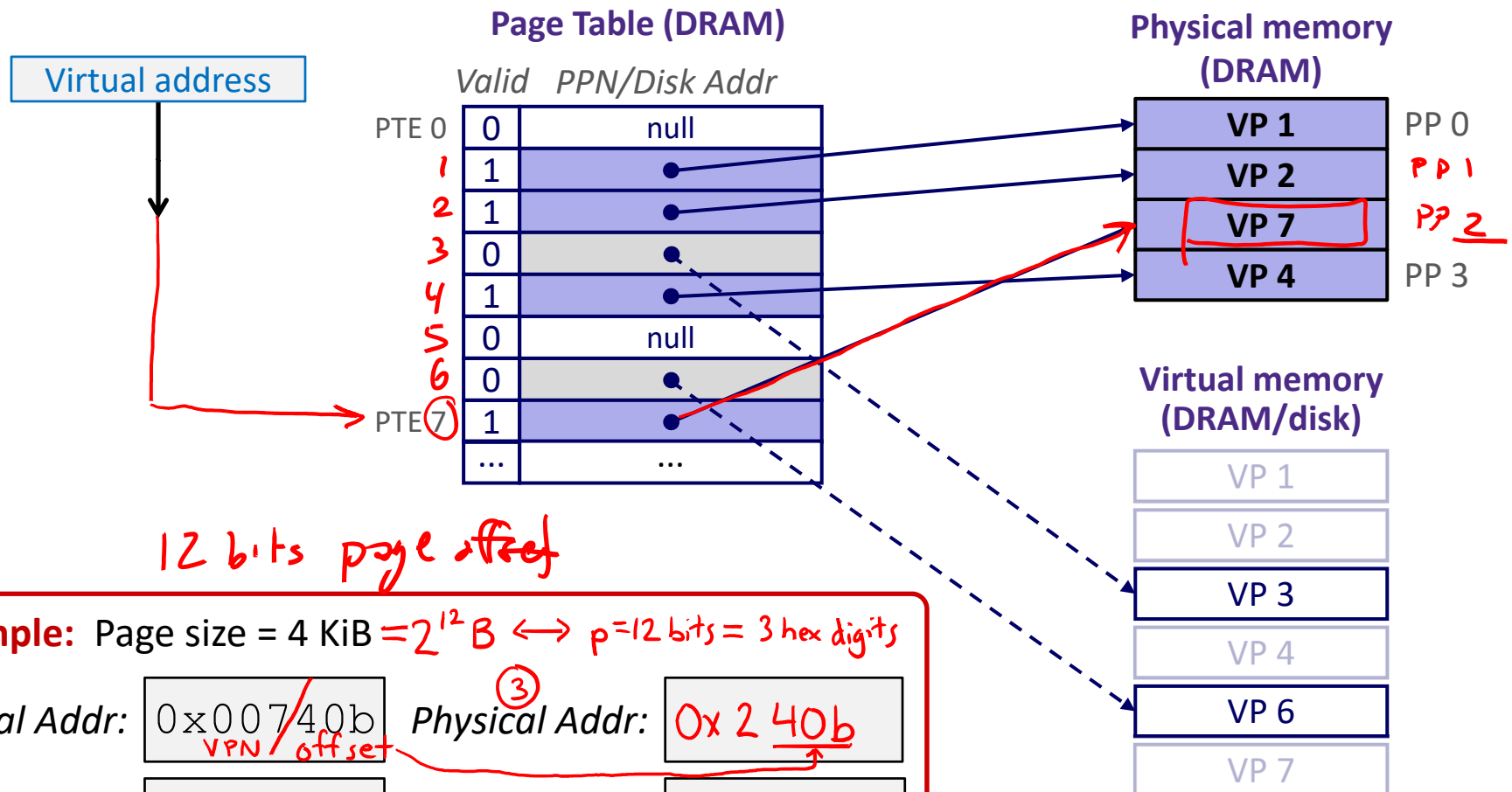


$PPN = m - p = 20 \text{ bits} \leftrightarrow 2^{20}$ pages in physical address space

	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

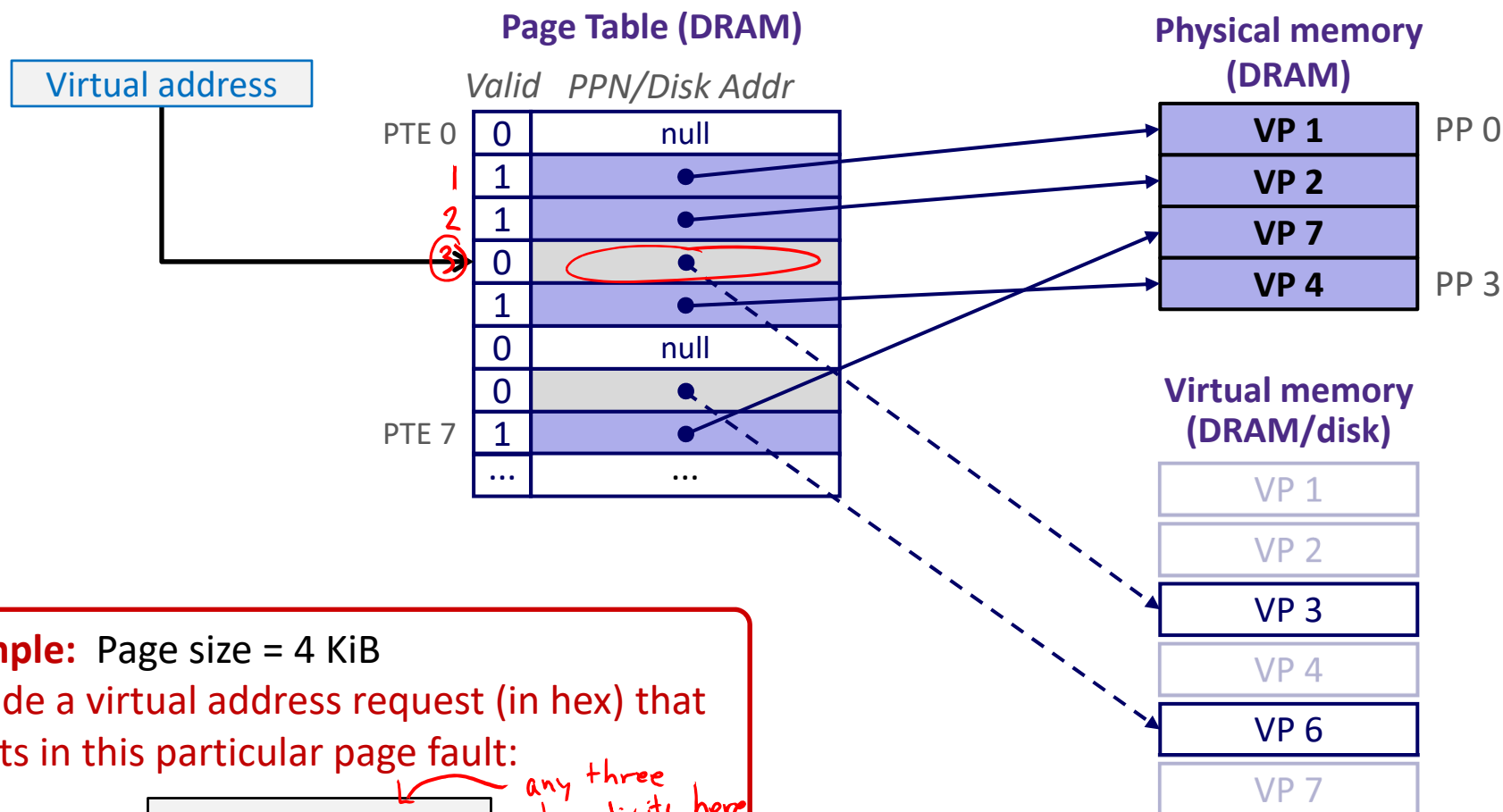
Virtual Addr: $0x007/40b$
VPN / offset

Physical Addr: $0x240b$
③

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:

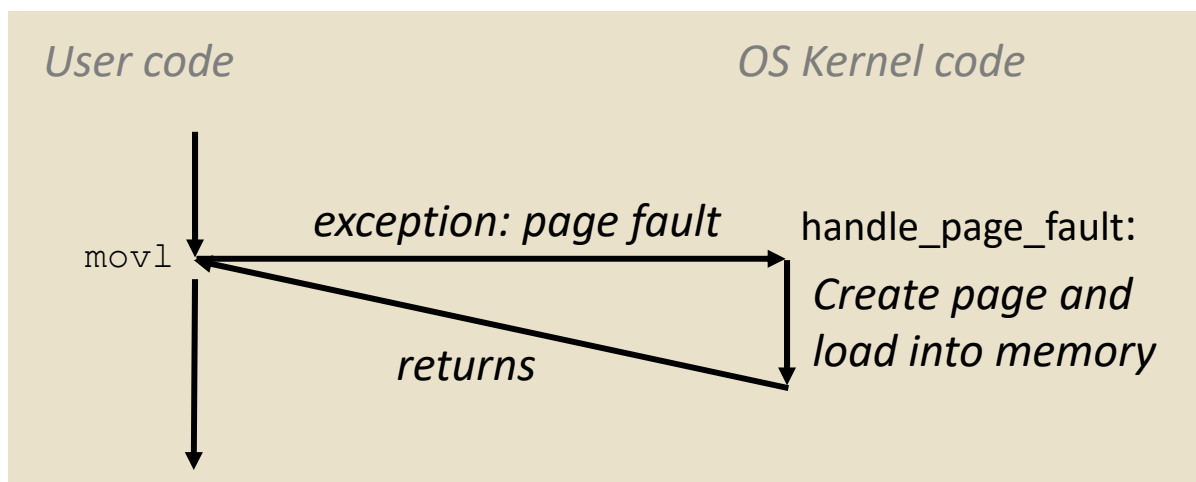
Virtual Addr: 0x003--- *any three hex digits here*

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;
}
```

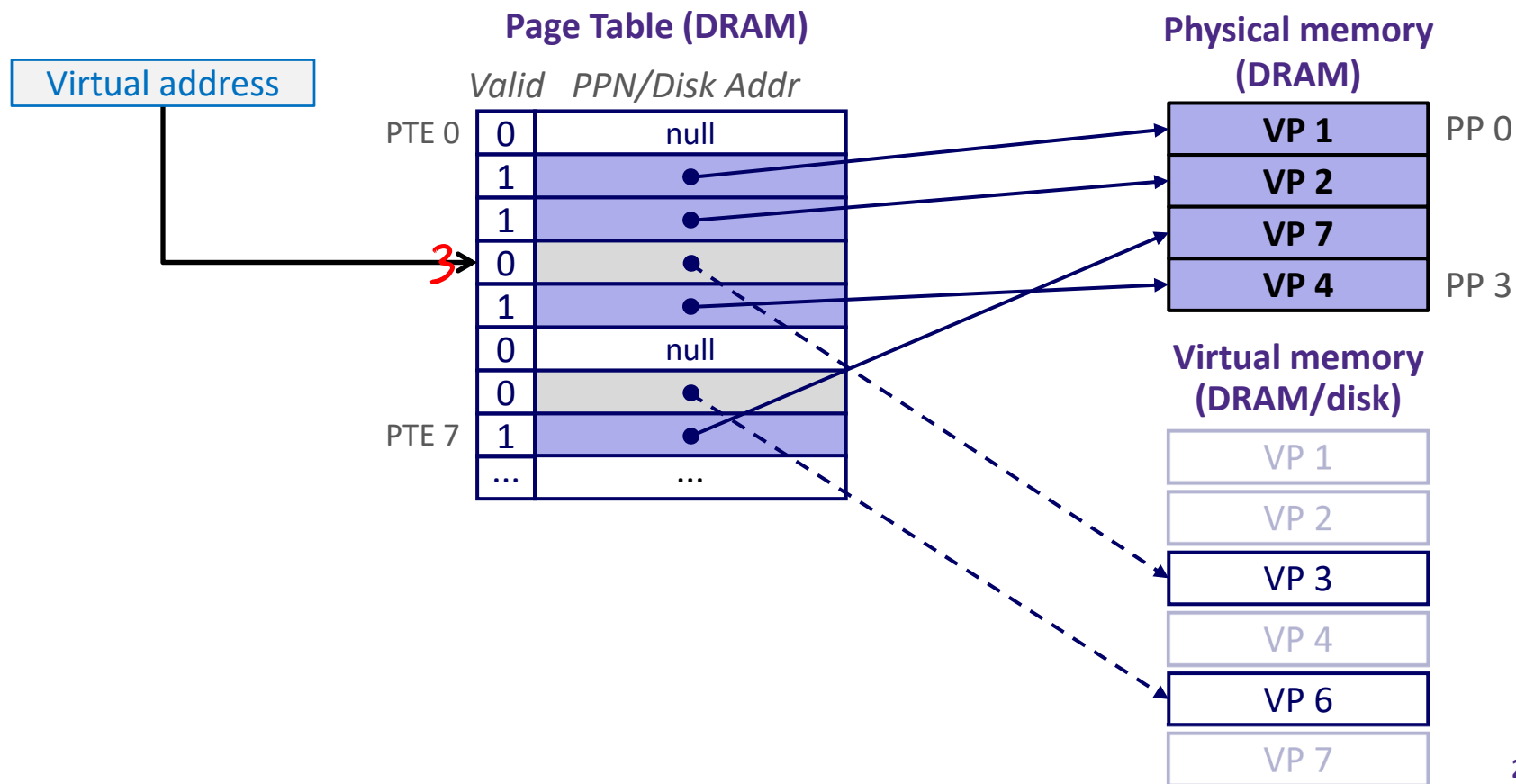
```
80483b7:      c7 05 10 9d 04 08 0d  movl   $0xd,0x8049d10
```



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

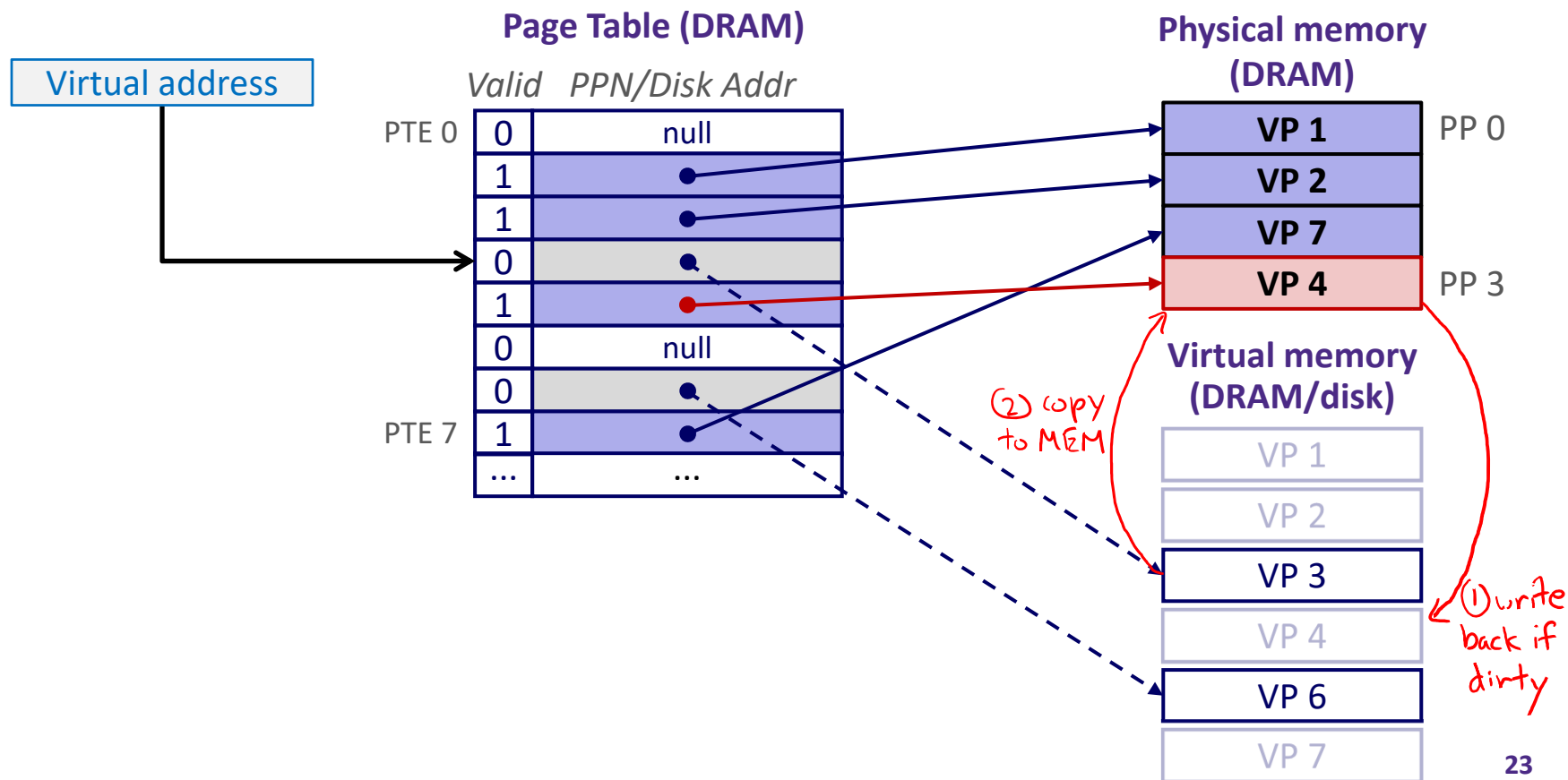
Handling a Page Fault

- ❖ Page miss causes page fault (an exception)



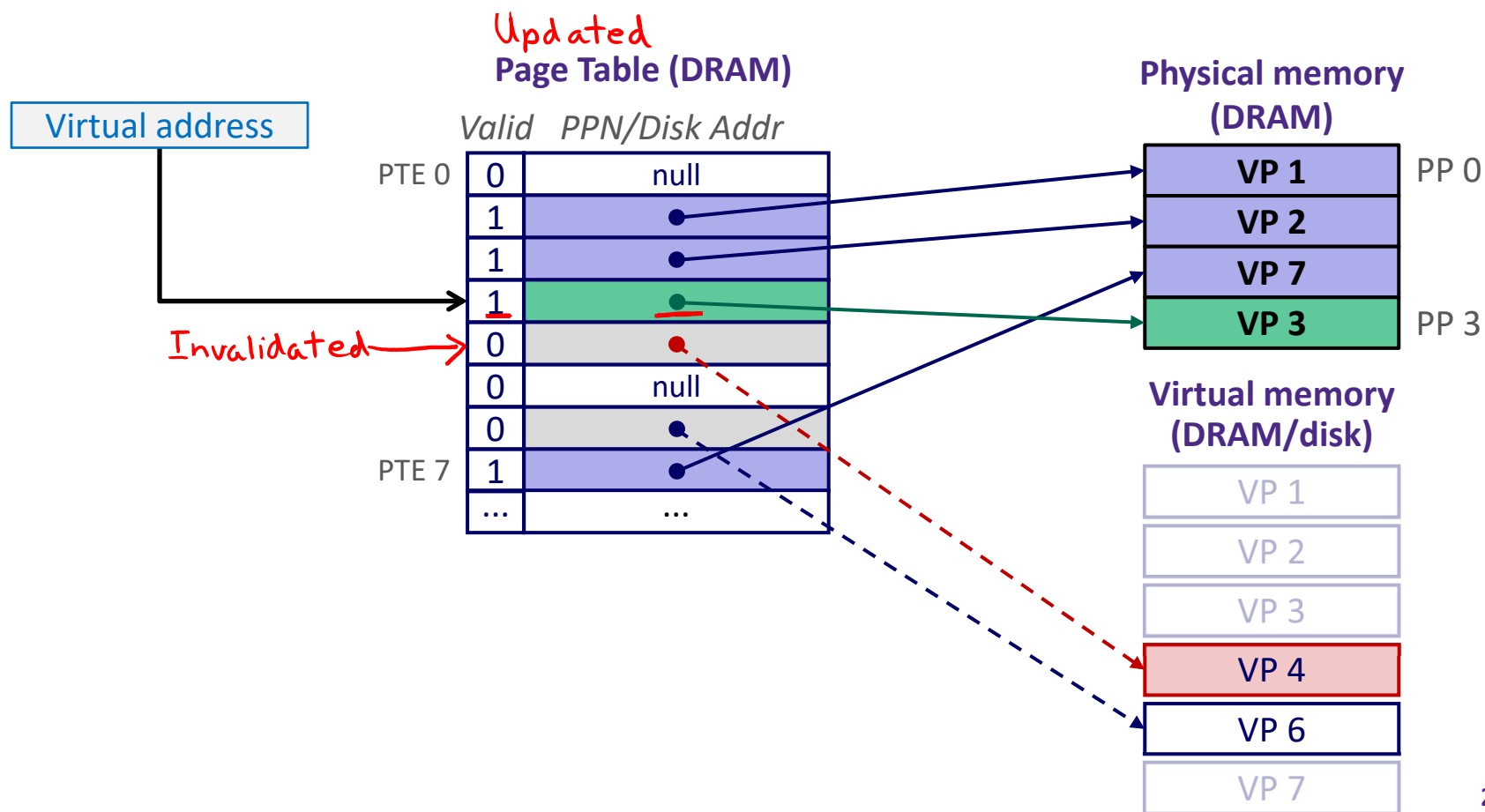
Handling a Page Fault

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



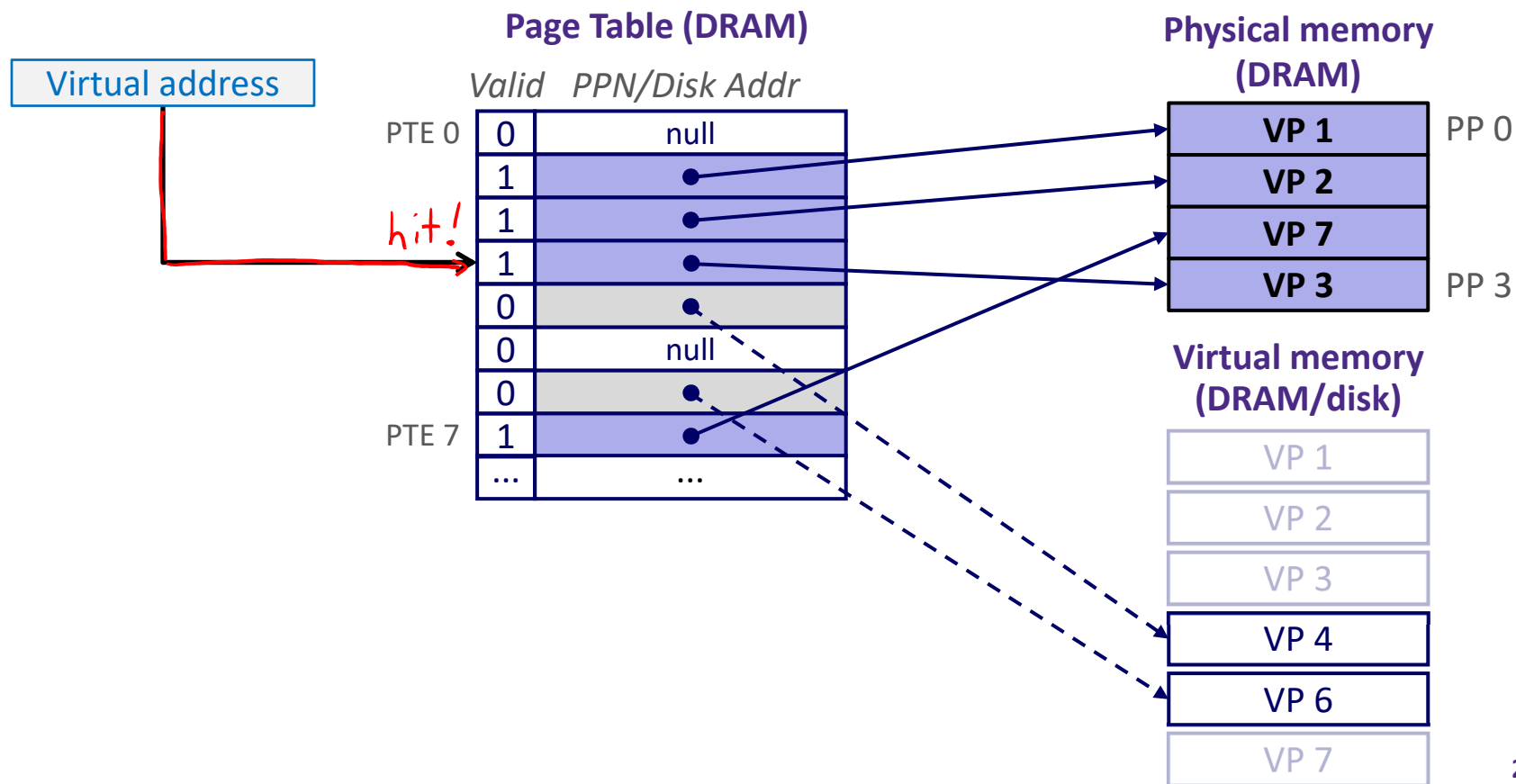
Handling a Page Fault

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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!**

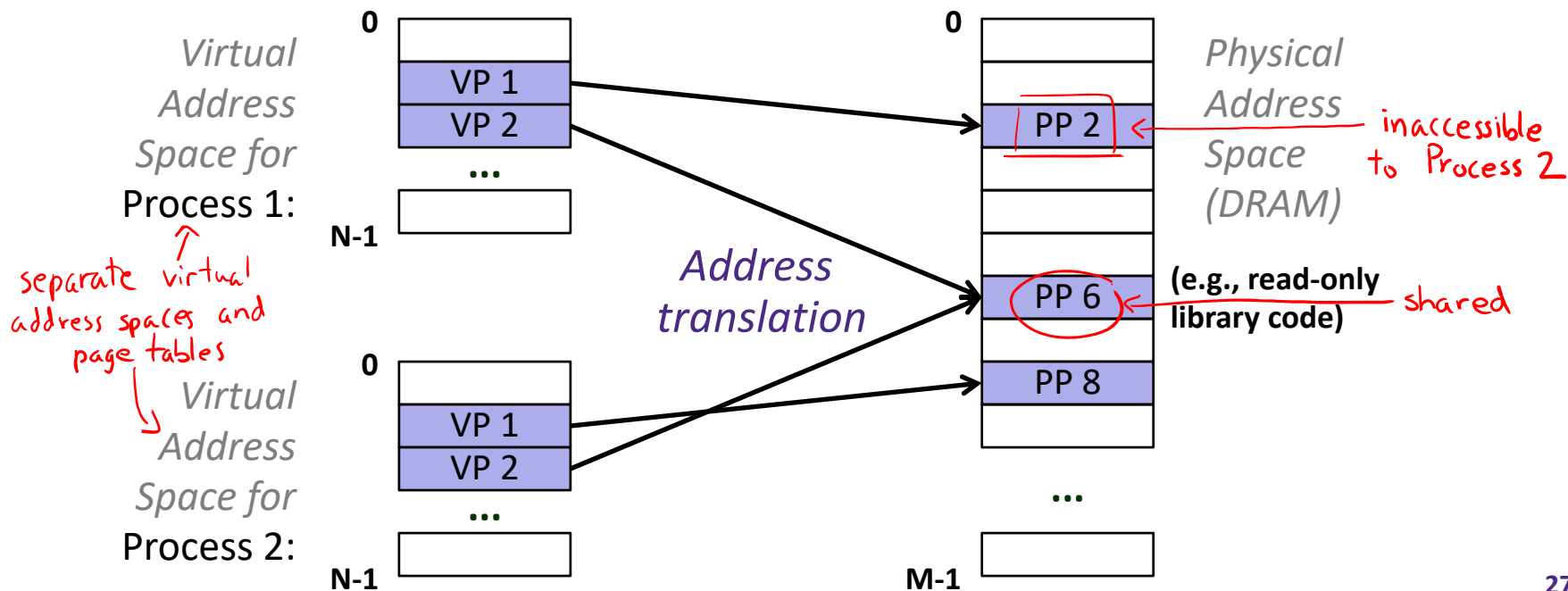


Virtual Memory (VM)

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- ❖ 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!



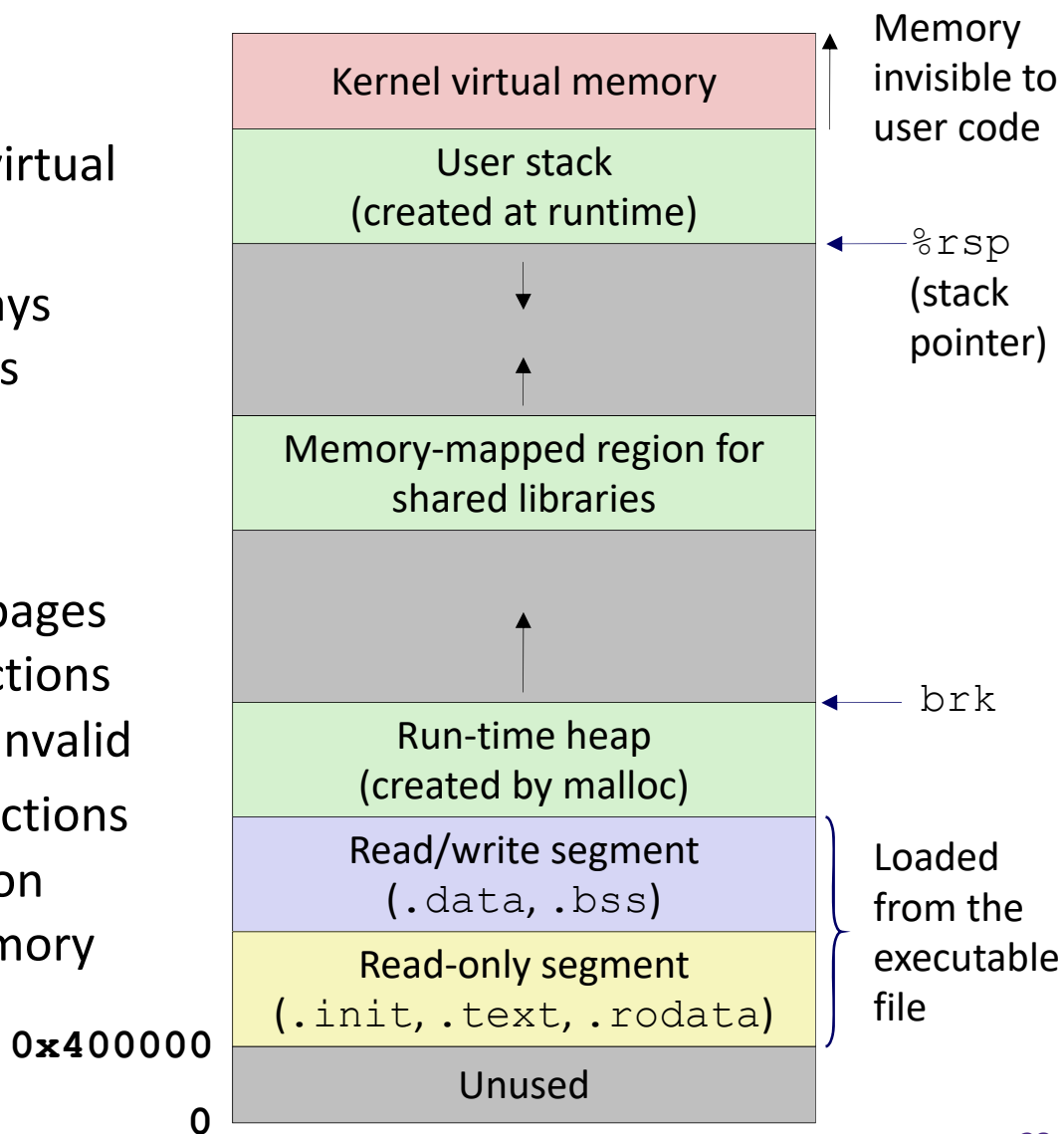
Simplifying Linking and Loading

❖ Linking

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

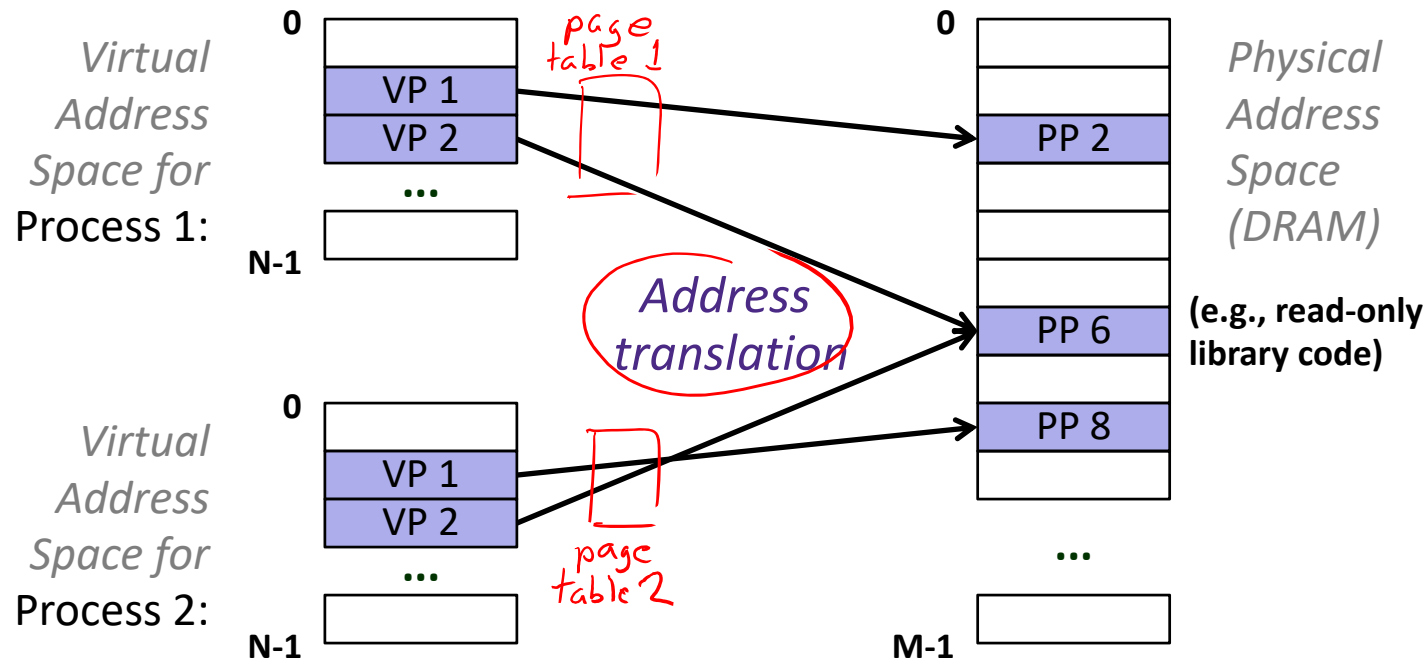
❖ Loading

- `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



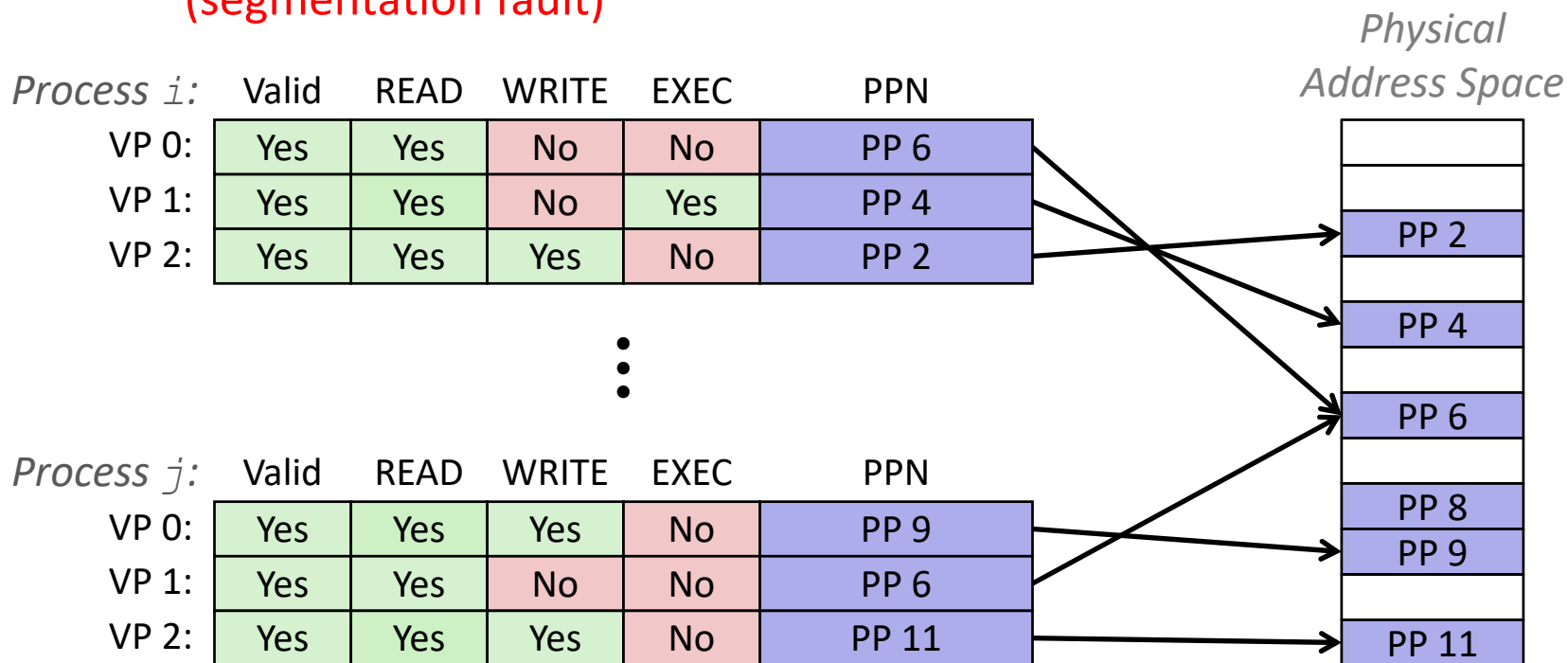
VM for Protection and Sharing

- ❖ 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 →