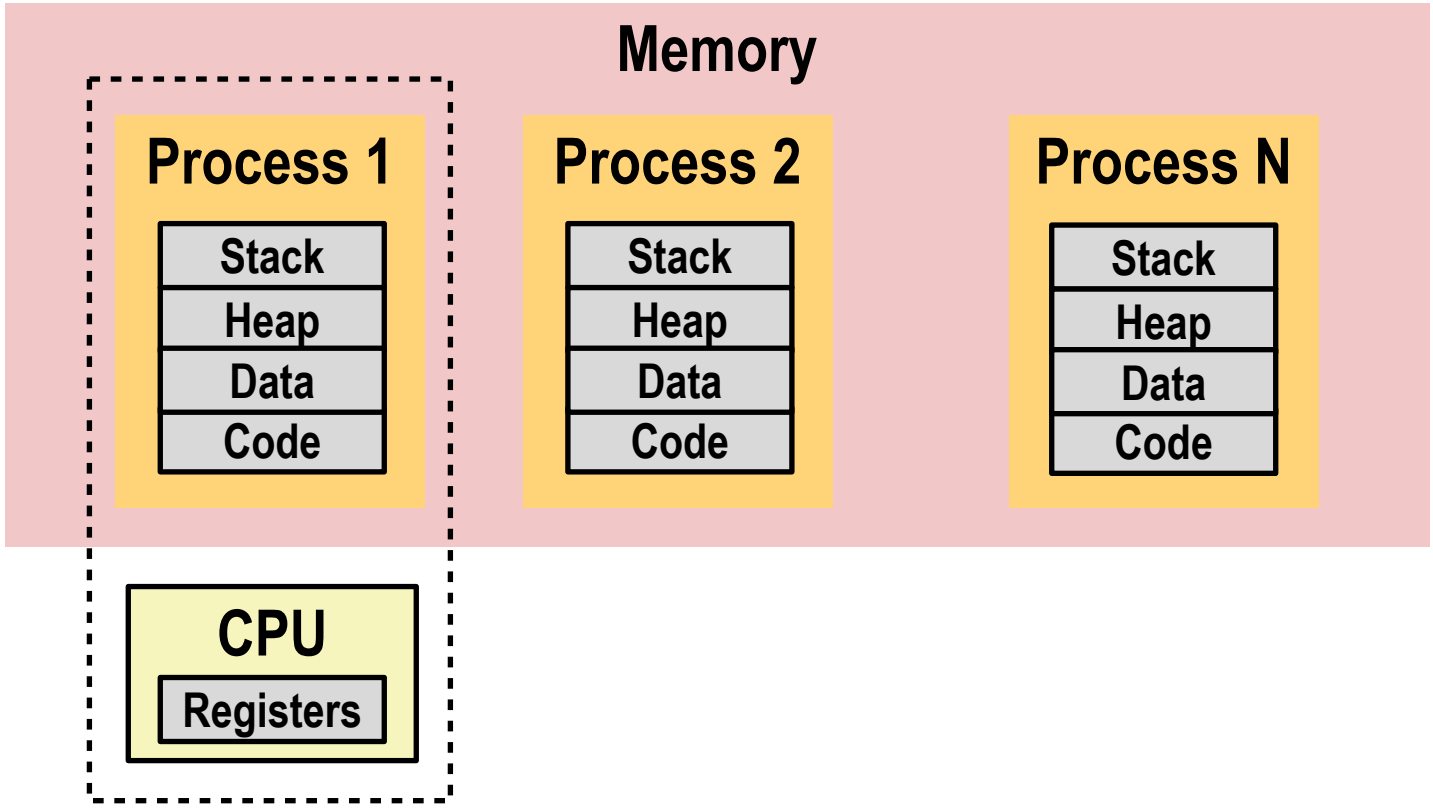
CSC 252/452: Computer Organization
Fall 2025: Lecture 20

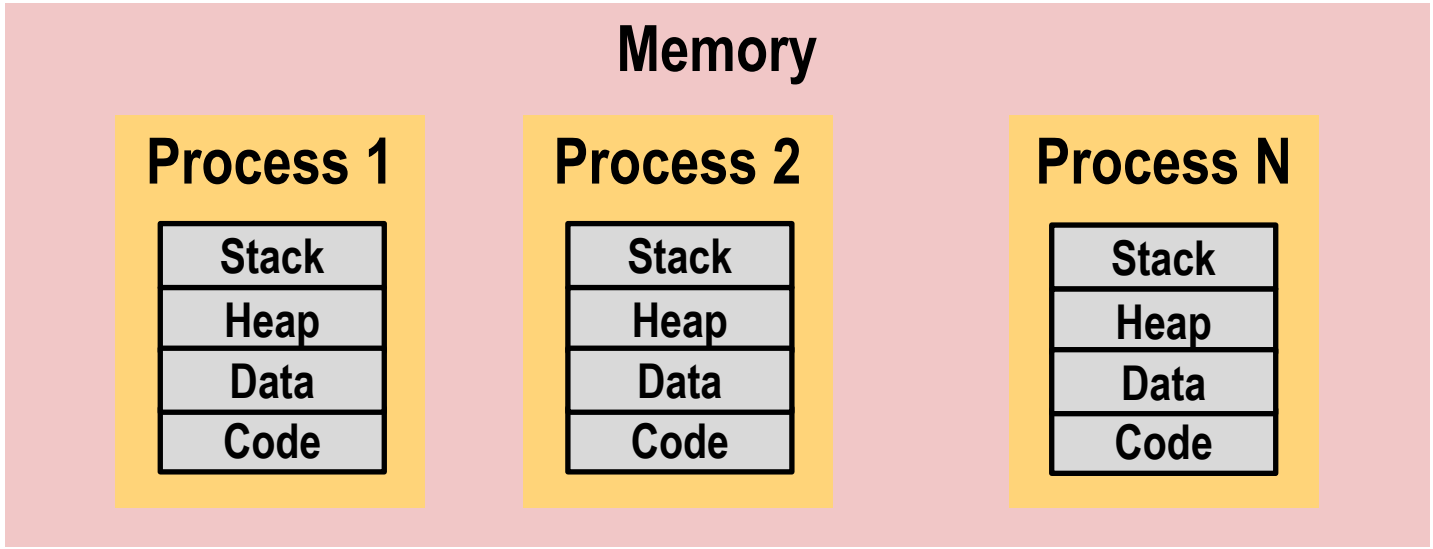
Instructor: Yanan Guo

Department of Computer Science
University of Rochester

Multiprocessing Illustration



Problem 1: Space



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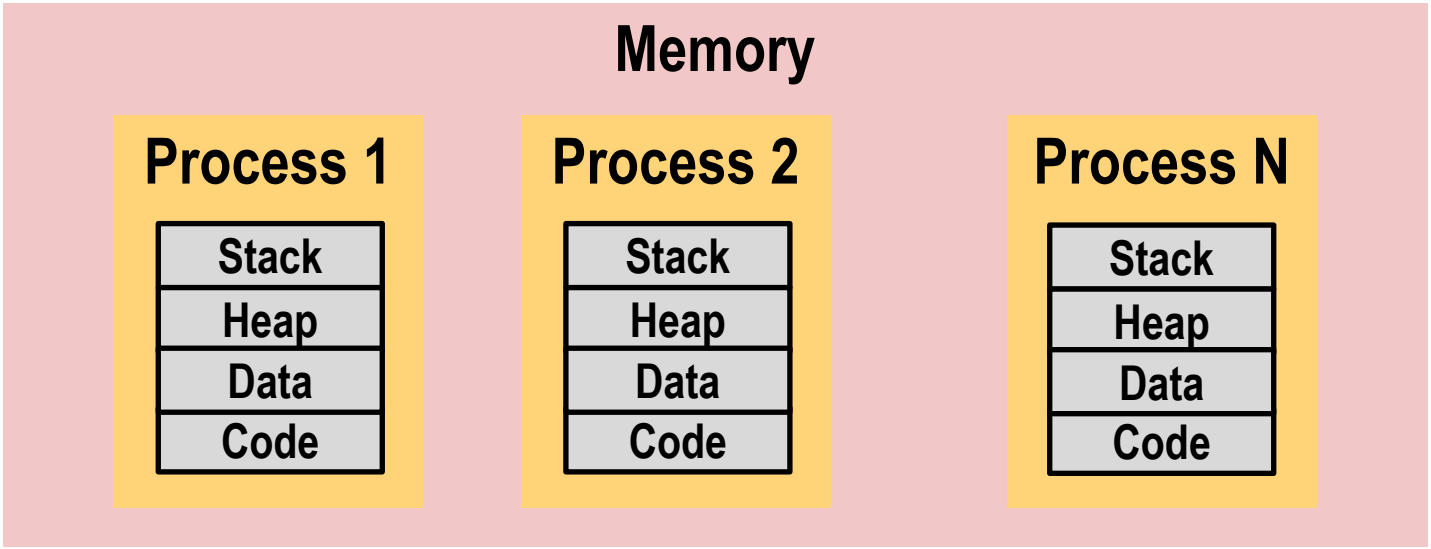
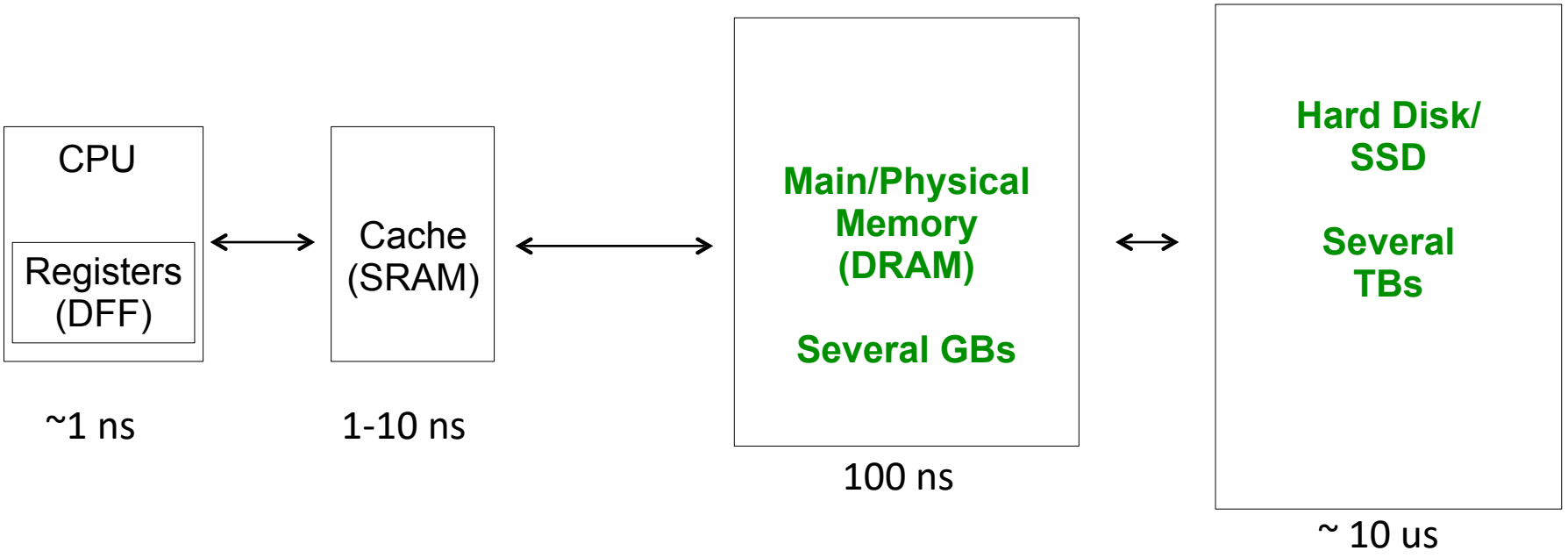


- Space:
  - Each process's address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
  - 2^48 bytes is 256 TB
  - There are multiple processes, increasing the storage requirement further

Recall: Memory Hierarchy

- Solution: store all the data in disk (several TBs typically), and use memory only for most recently used data
  - Of course if a process uses all its address space that won't be enough, but usually a process won't use all 64 bits. So it's OK.



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- Solution: store all the data in disk (several TBs typically), and use memory only for most recently used data
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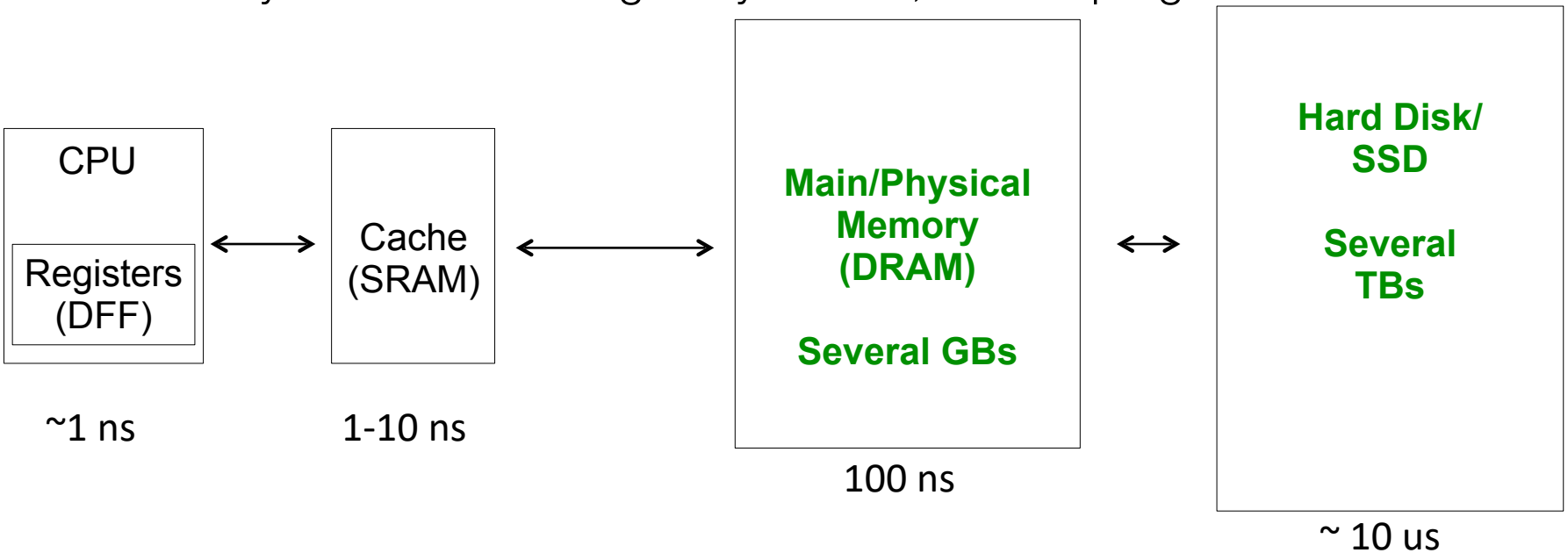
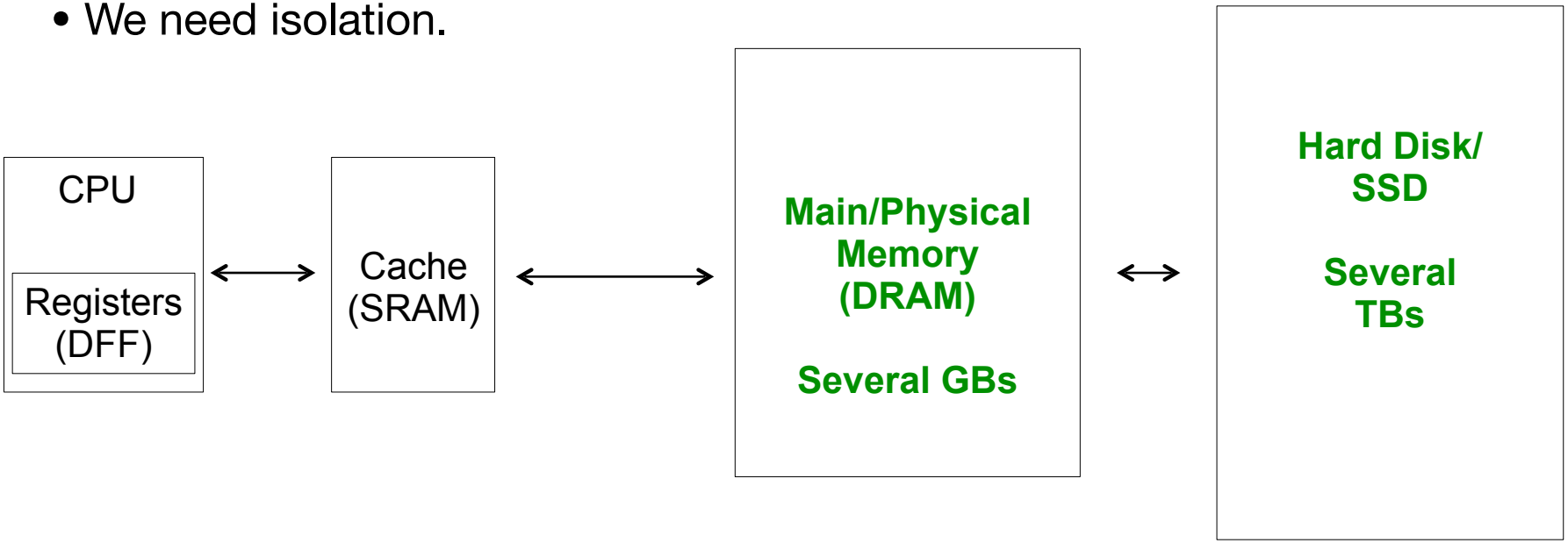
- Challange: who is moving data back and forth between the DRAM/main memory/physical memory and the disk?
  - Ideally should be managed by the OS, not the programmer.



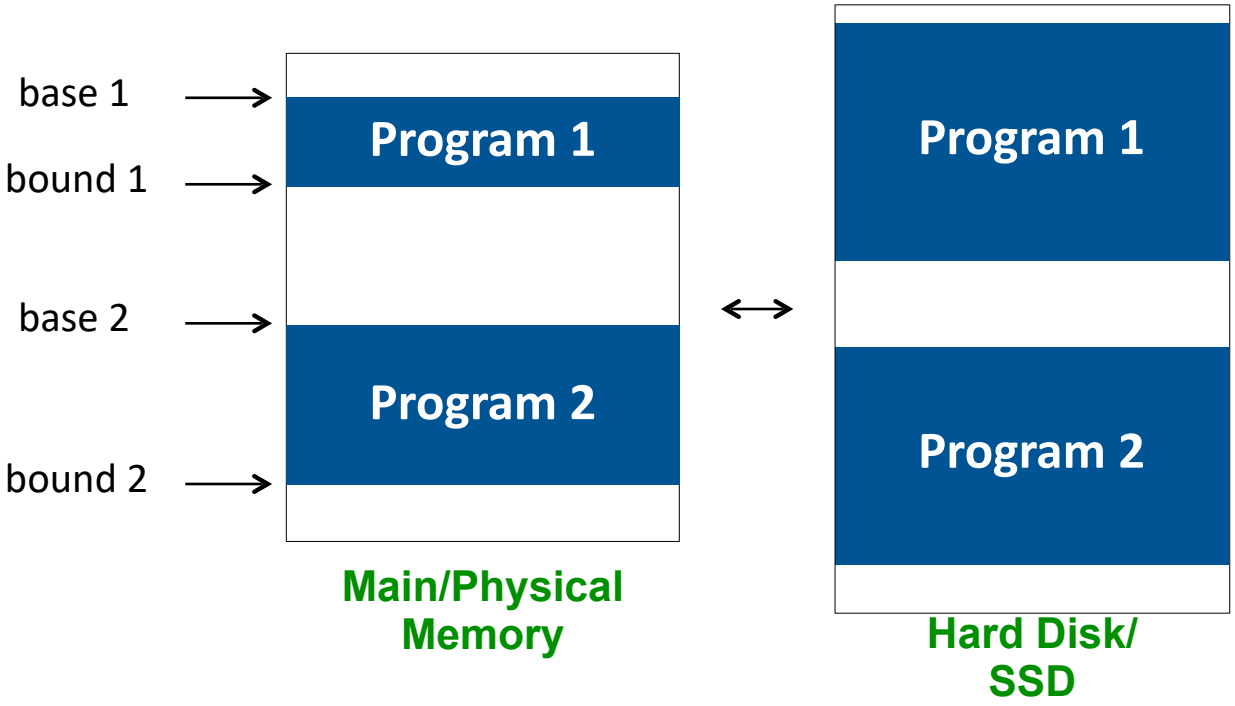
Problem 2: Security

- Different programs/processes will share the same physical memory
  - Or even different uses. A CSUG machine is accessed by all students, but there is one single physical memory!
- What if a malicious program steals/modifies data from your program?
  - If the malicious program get the address of the memory that stores your password, should it be able to access it? If not, how to prevent it?
- We need isolation.



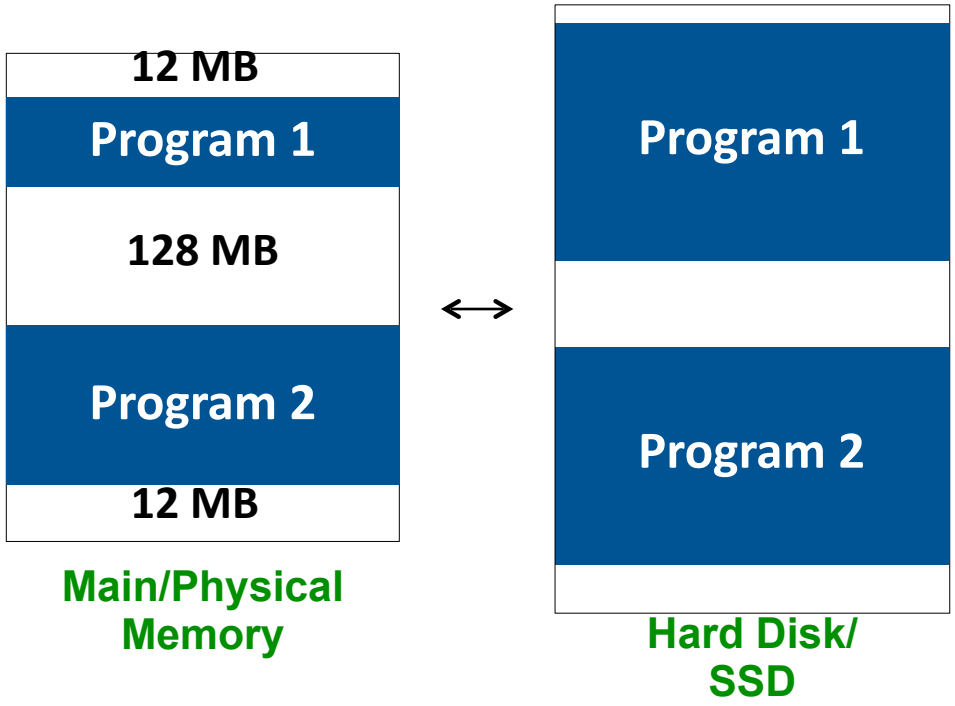
One Way to Isolate: Segments

- Different processes will have exclusive access to just one part of the physical memory.
- This is called ***Segments***.
  - Need a base register and a bound register for each process. Not widely used today. x86 still supports it (backward compatibility!)
  - Fast but not inflexible. Makes benign sharing hard.



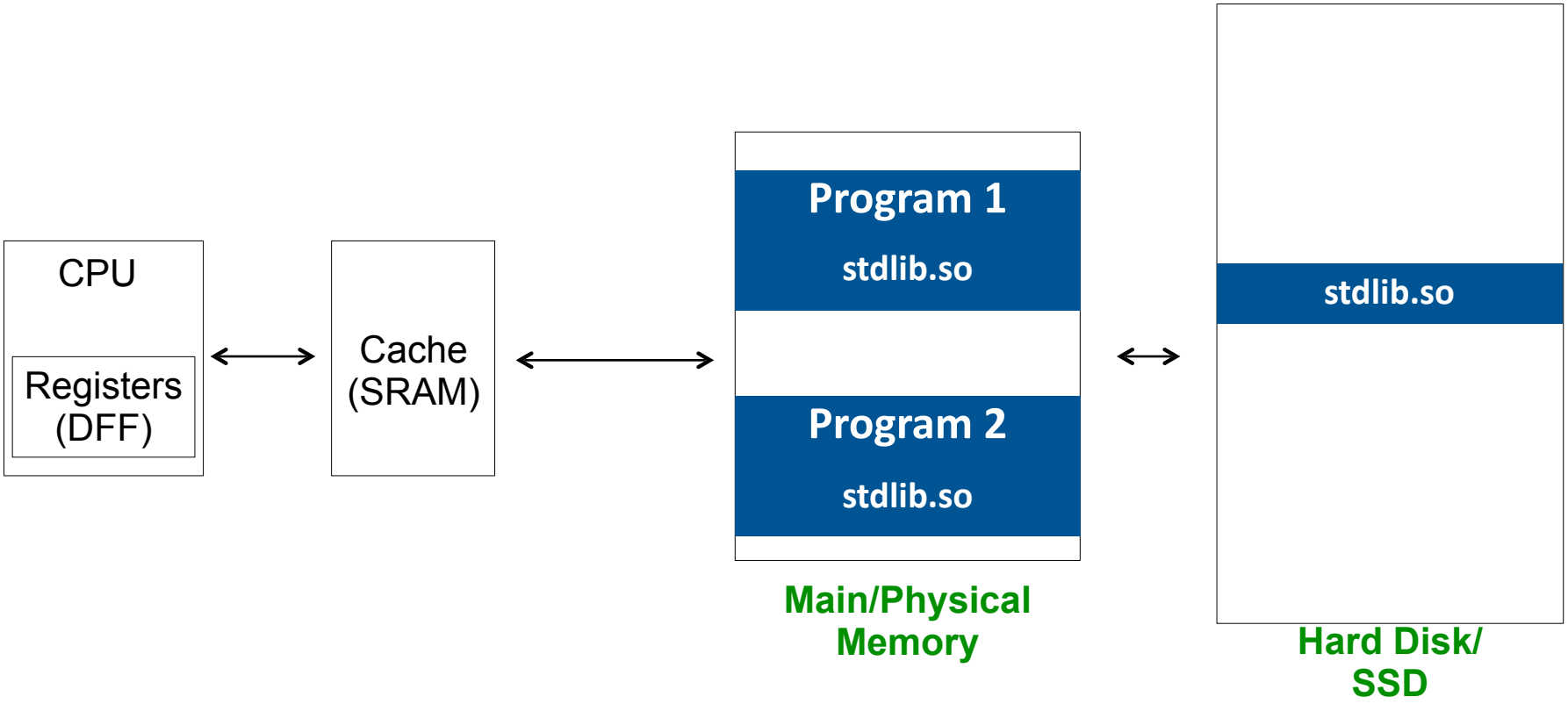
Problem 3: Fragmentation (with Segments)

- Each process gets a continuous chunk of memory. Inflexible.
- What if a process requests more space than any continuous chunk in memory but smaller than the total free memory?
  - This is called “fragmentation”; will talk about this more later.
- Need to allow assigning discontinuous chunks of memory to processes.

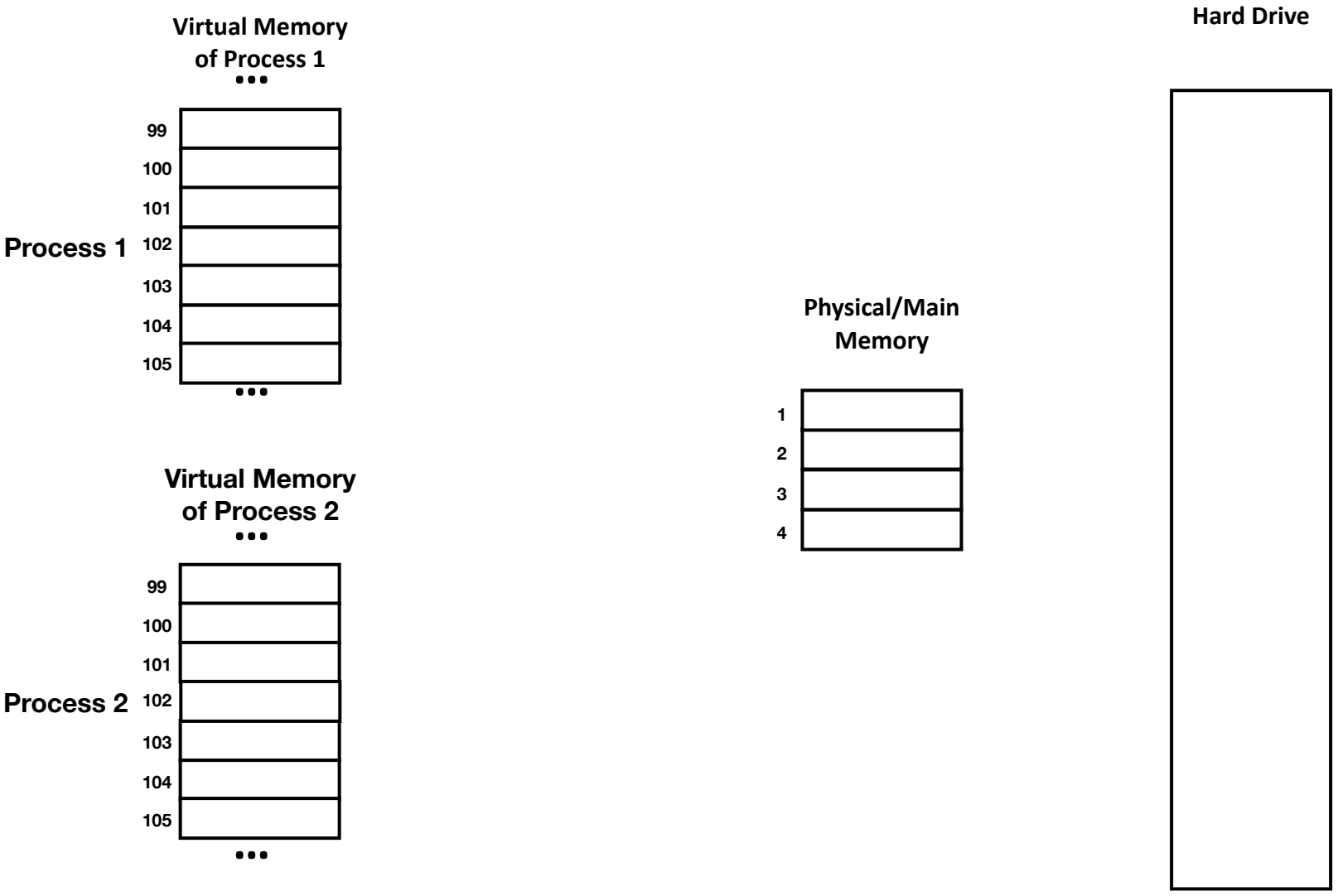


Problem 4: Benign Sharing (with Segments)

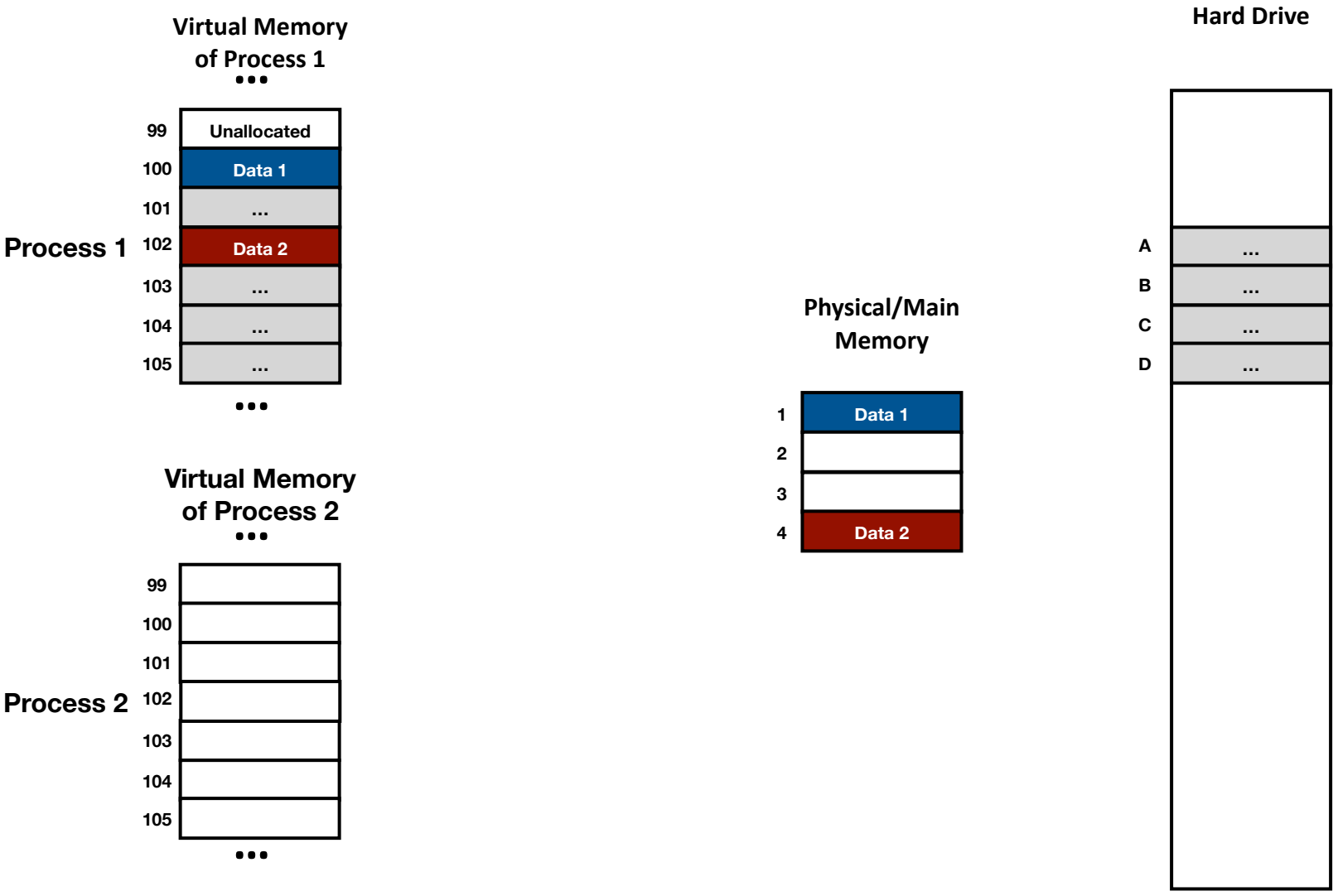
- Different programs/processes will share same data: files, libraries, etc.
- No need to have separate copies in the physical memory.
- Would be good to let other processes access part of the current's process' memory based on the "permission".



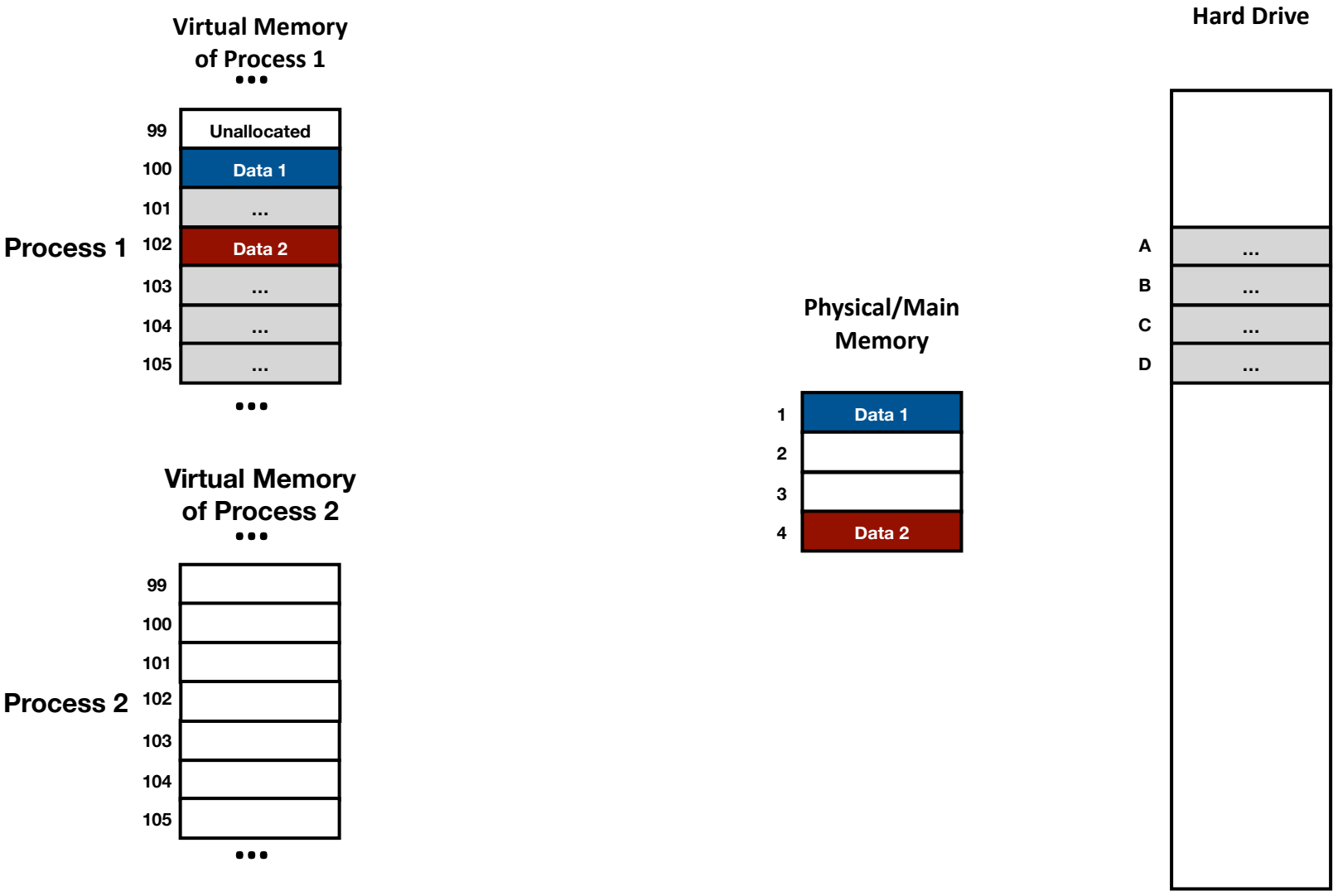
The Big Idea: Virtual Memory



“Cache” Data in Physical Memory



Allow Using Discontinuous Allocation



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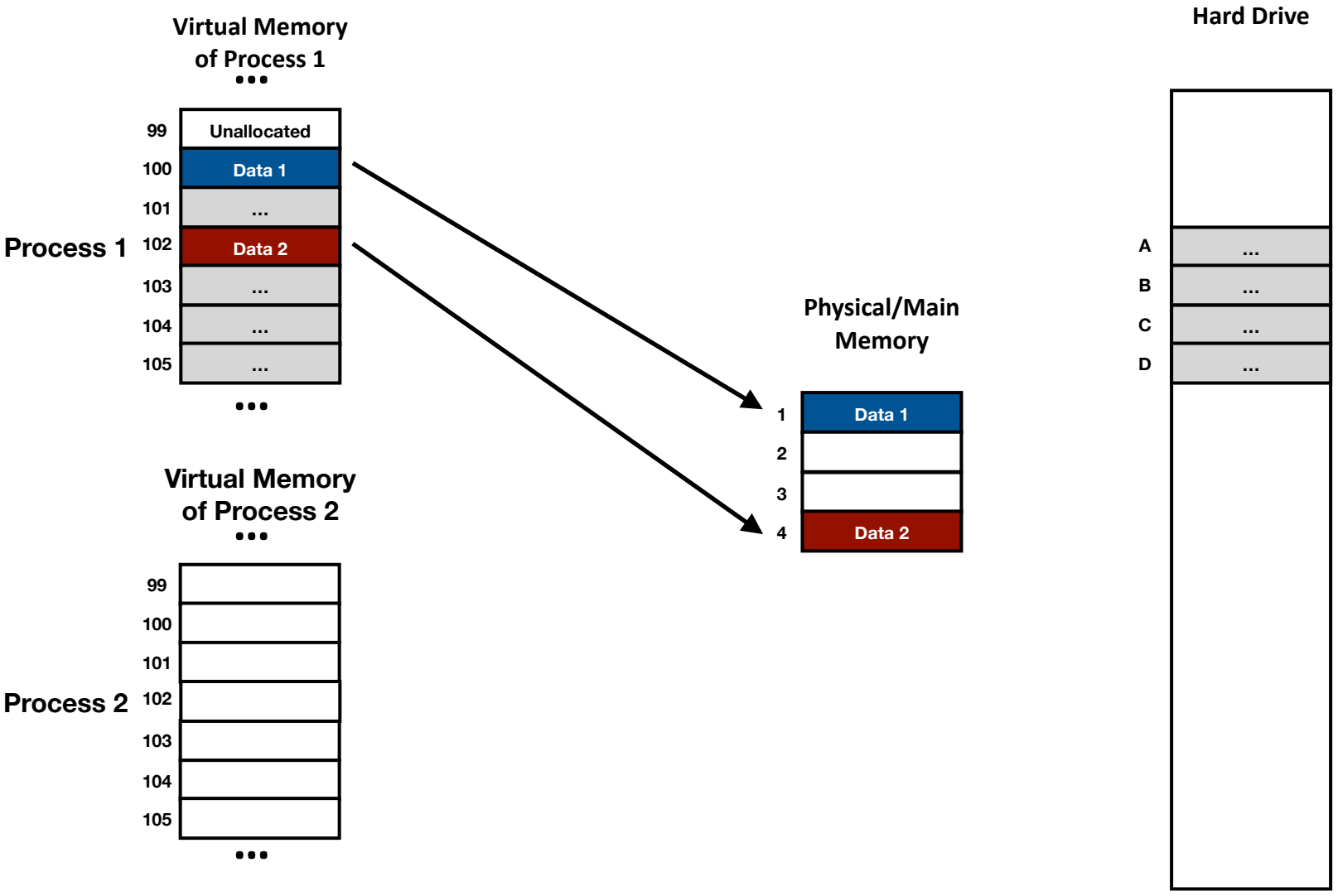
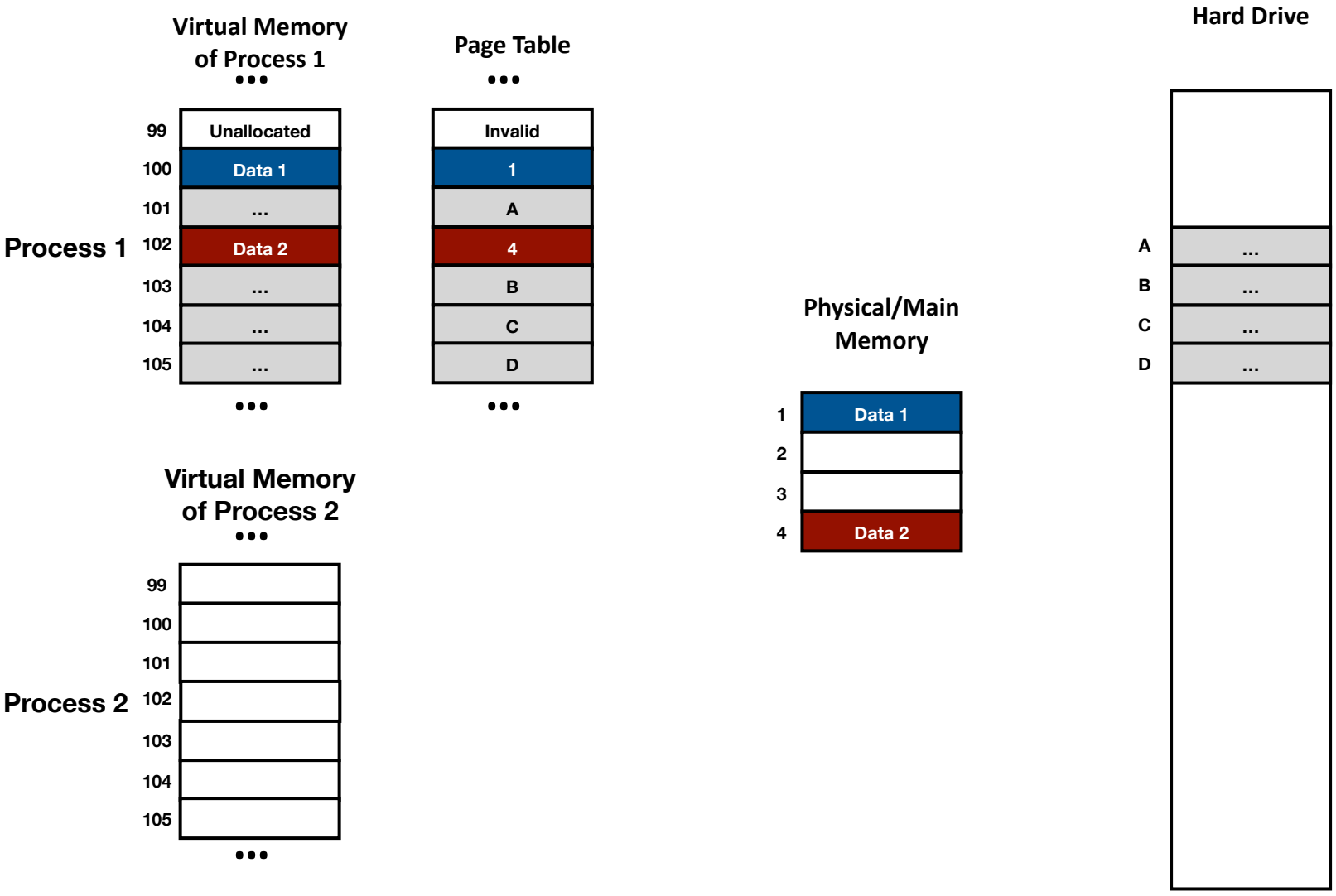
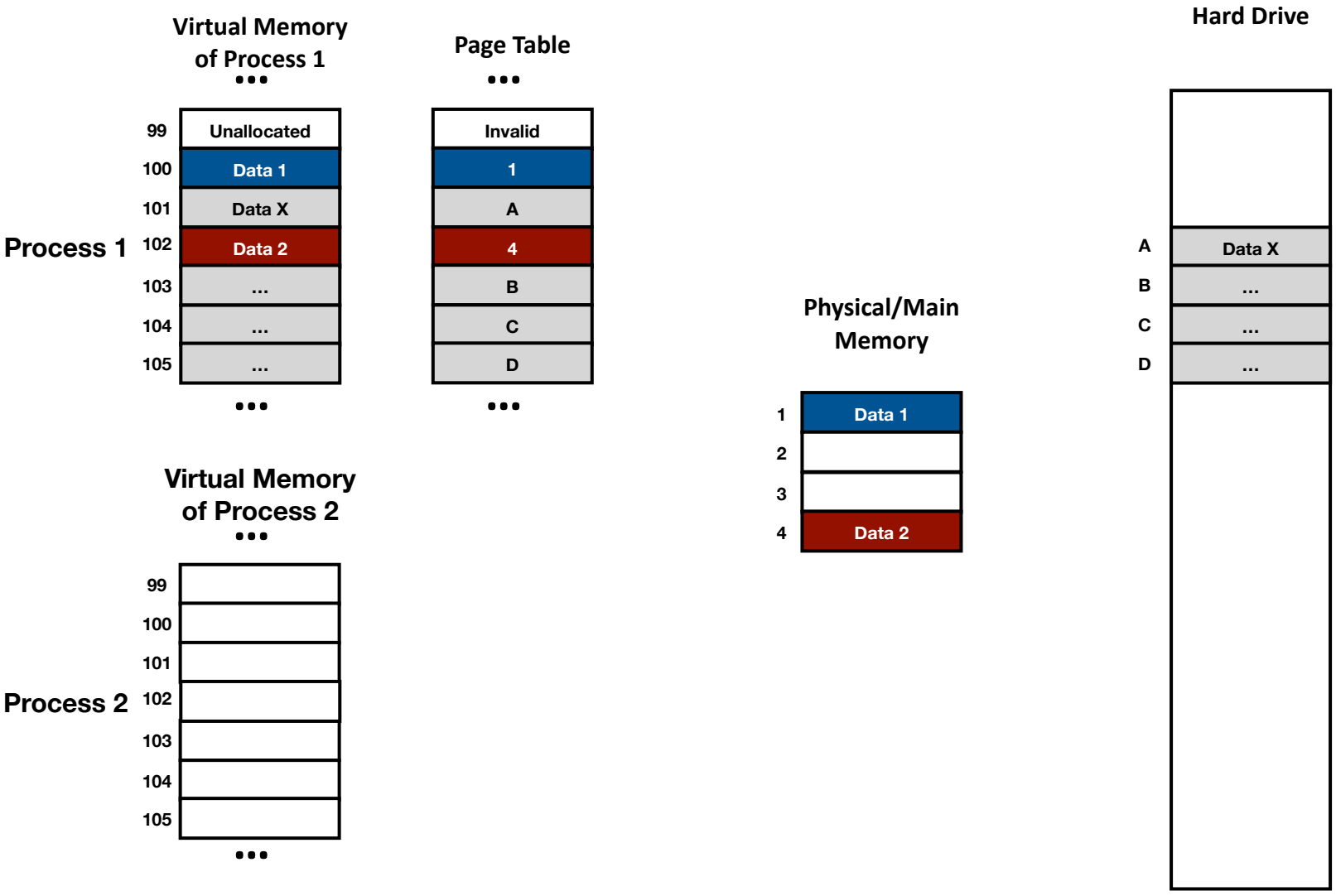


Page Table


Virtual Memory of Process 1
Page Table
Process 1
99
100
101
102
103
104
105
Unallocated
Data 1
...
Data 2
...
...
...
Invalid
1
A
4
B
C
D
Physical/Main Memory
1
2
3
4
Data 1
Data 2
Hard Drive
A
B
C
D
...
...
...
...
Virtual Memory of Process 2
Process 2
99
100
101
102
103
104
105

Demand Paging



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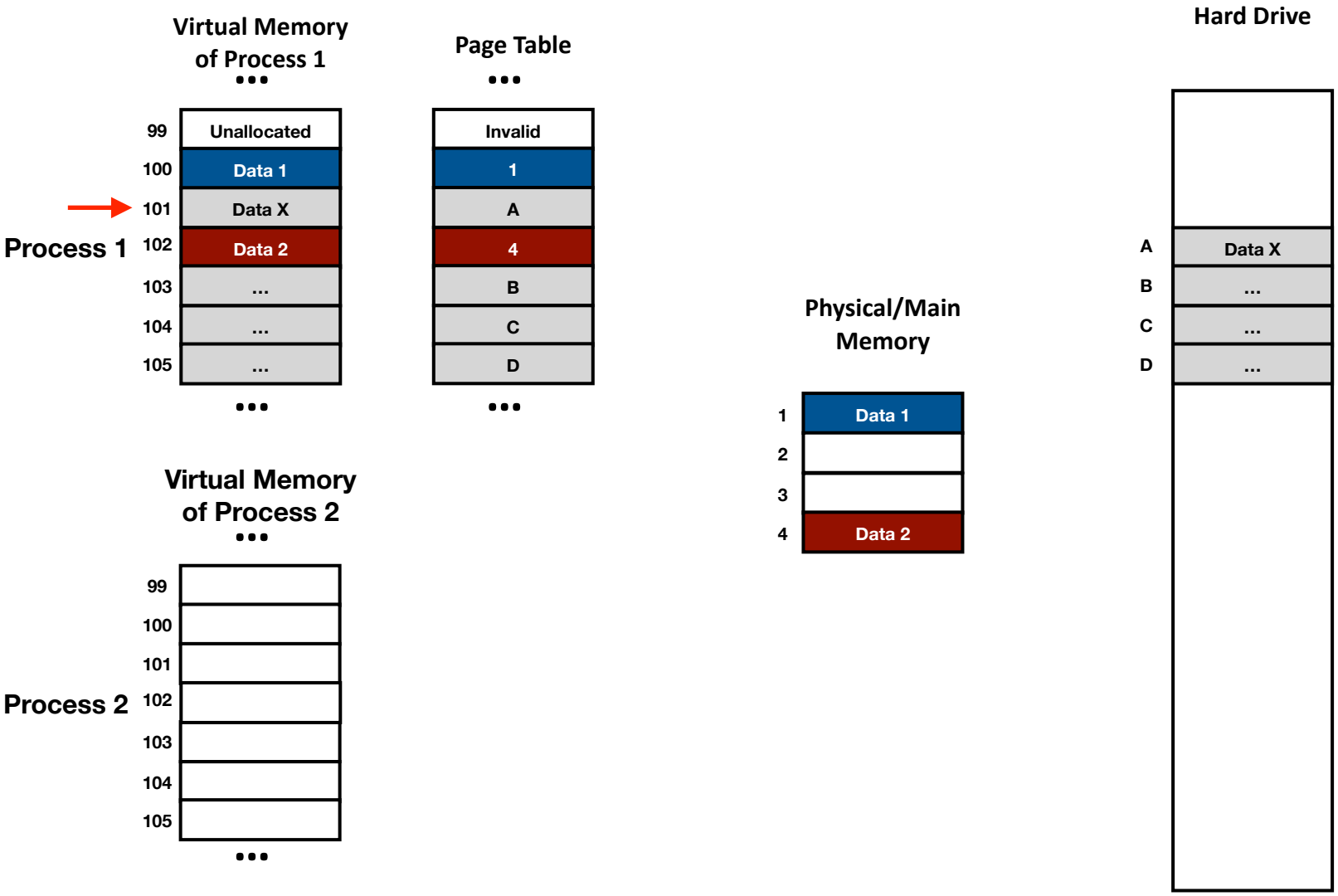

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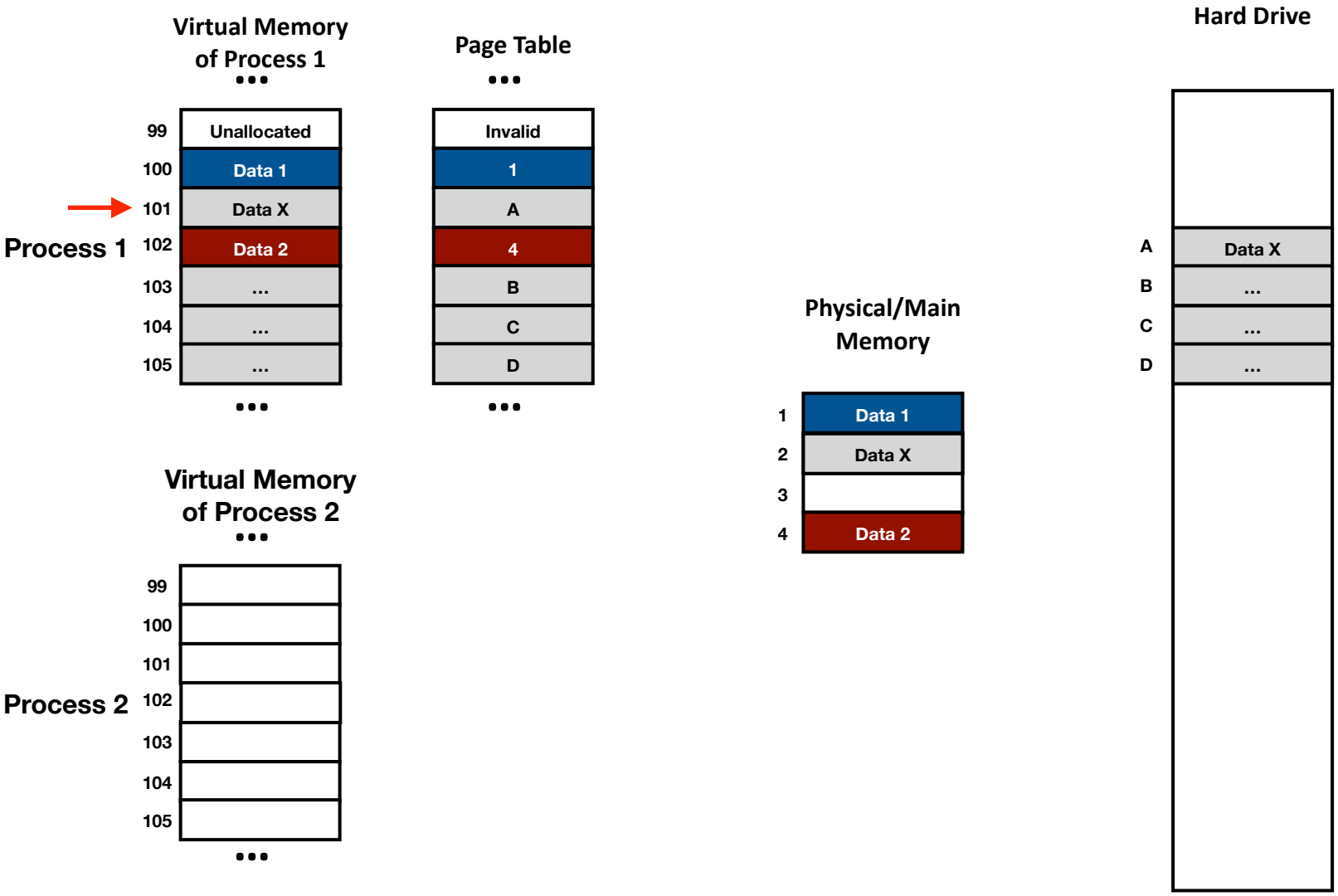

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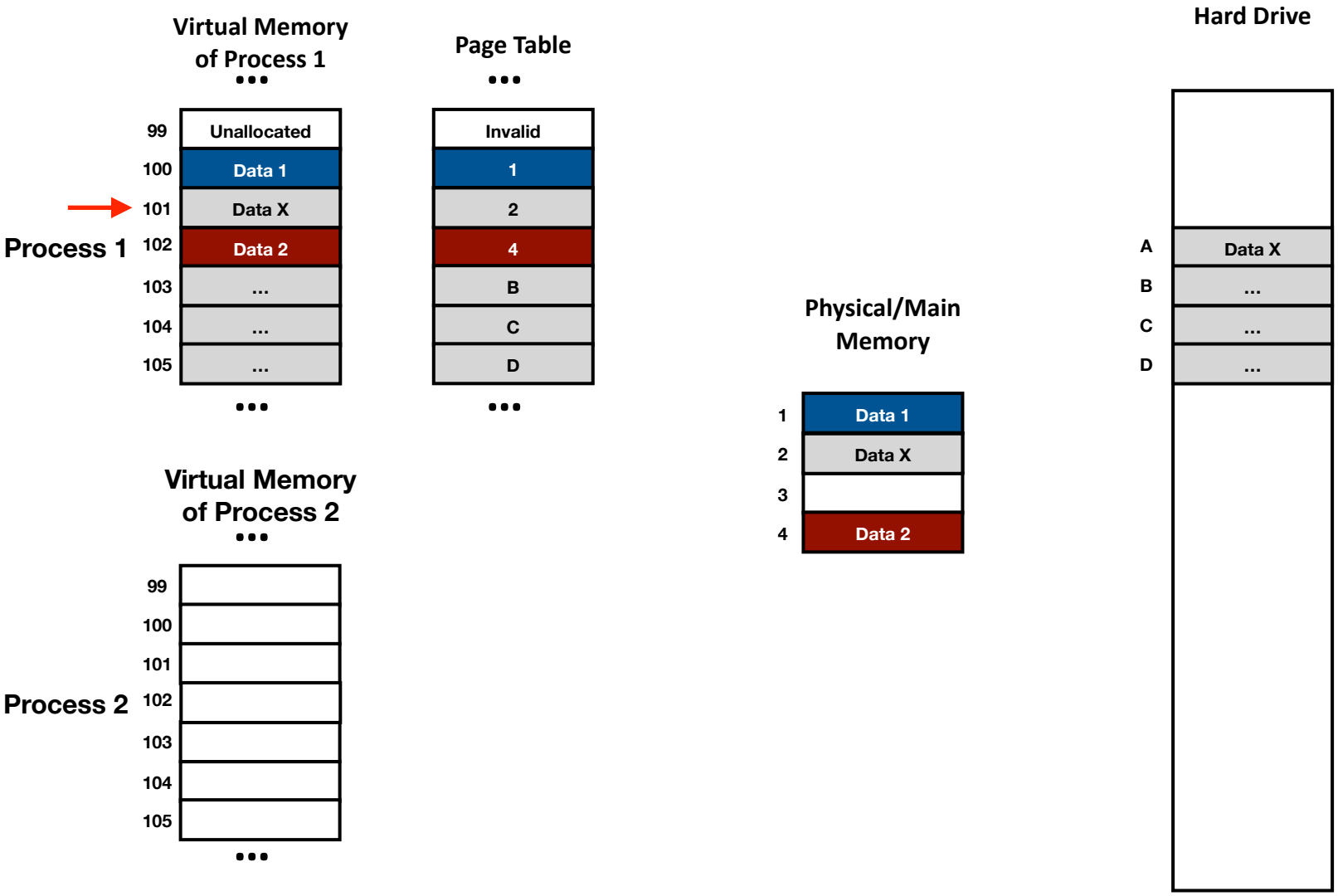
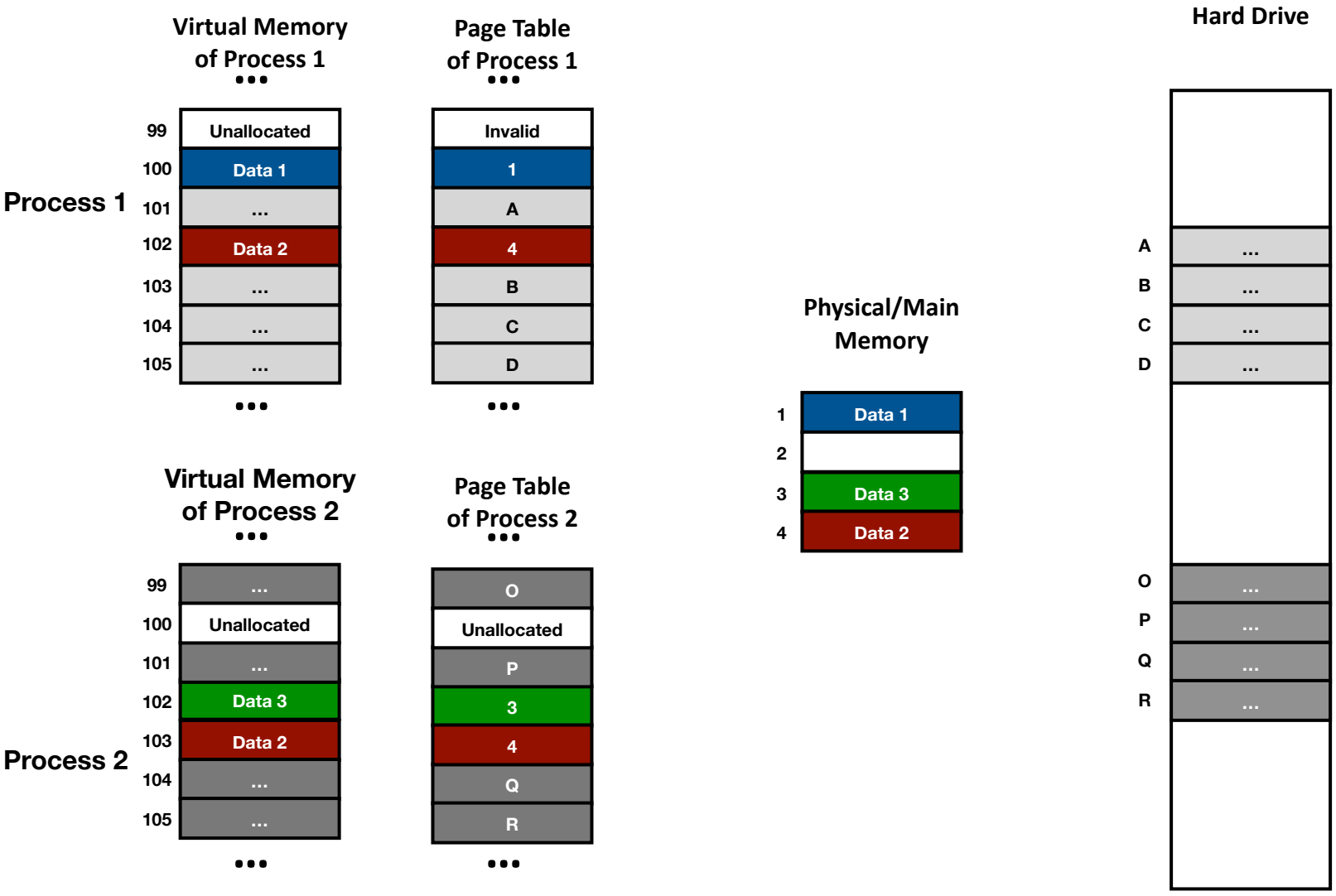


Prevent Unwanted Sharing



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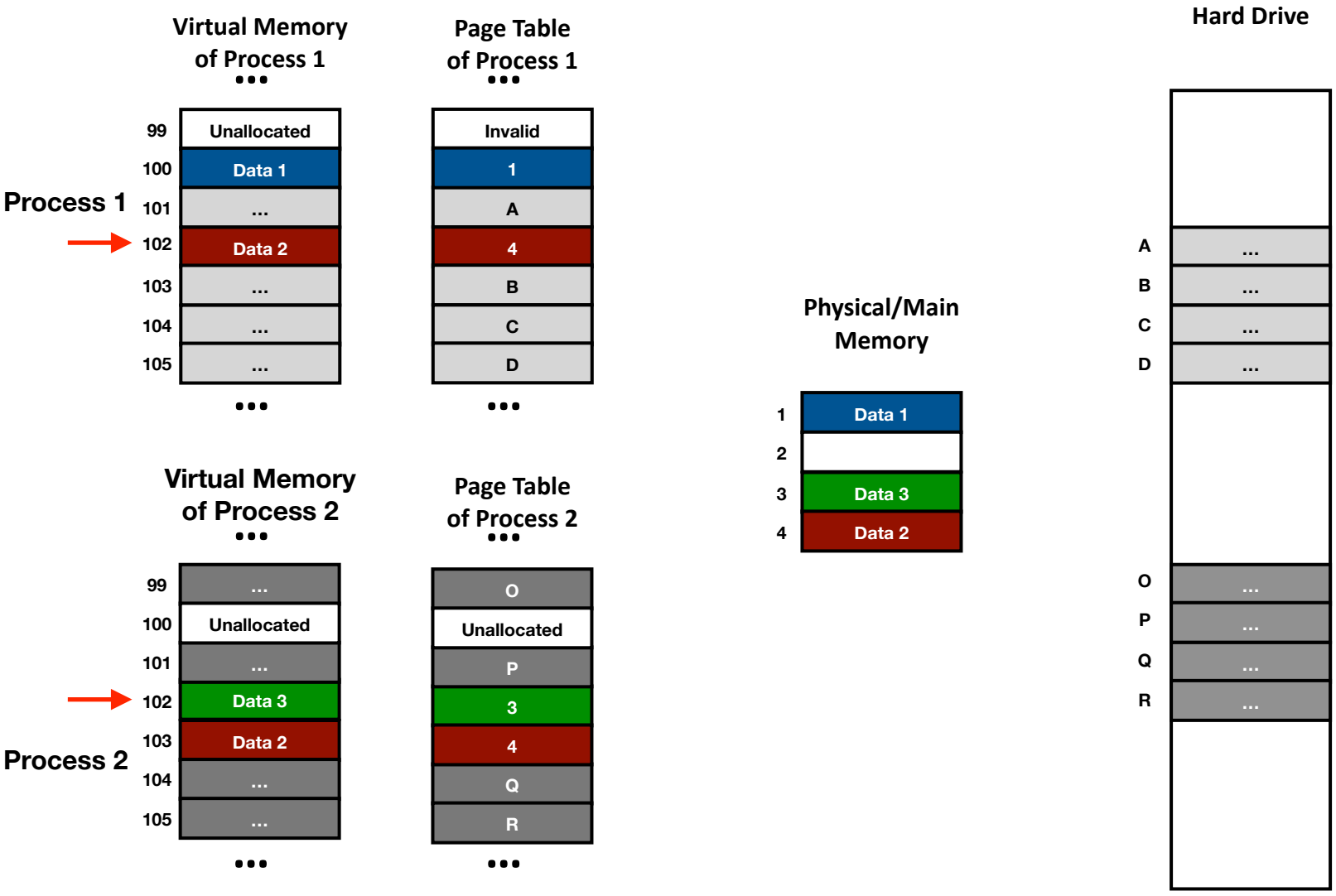
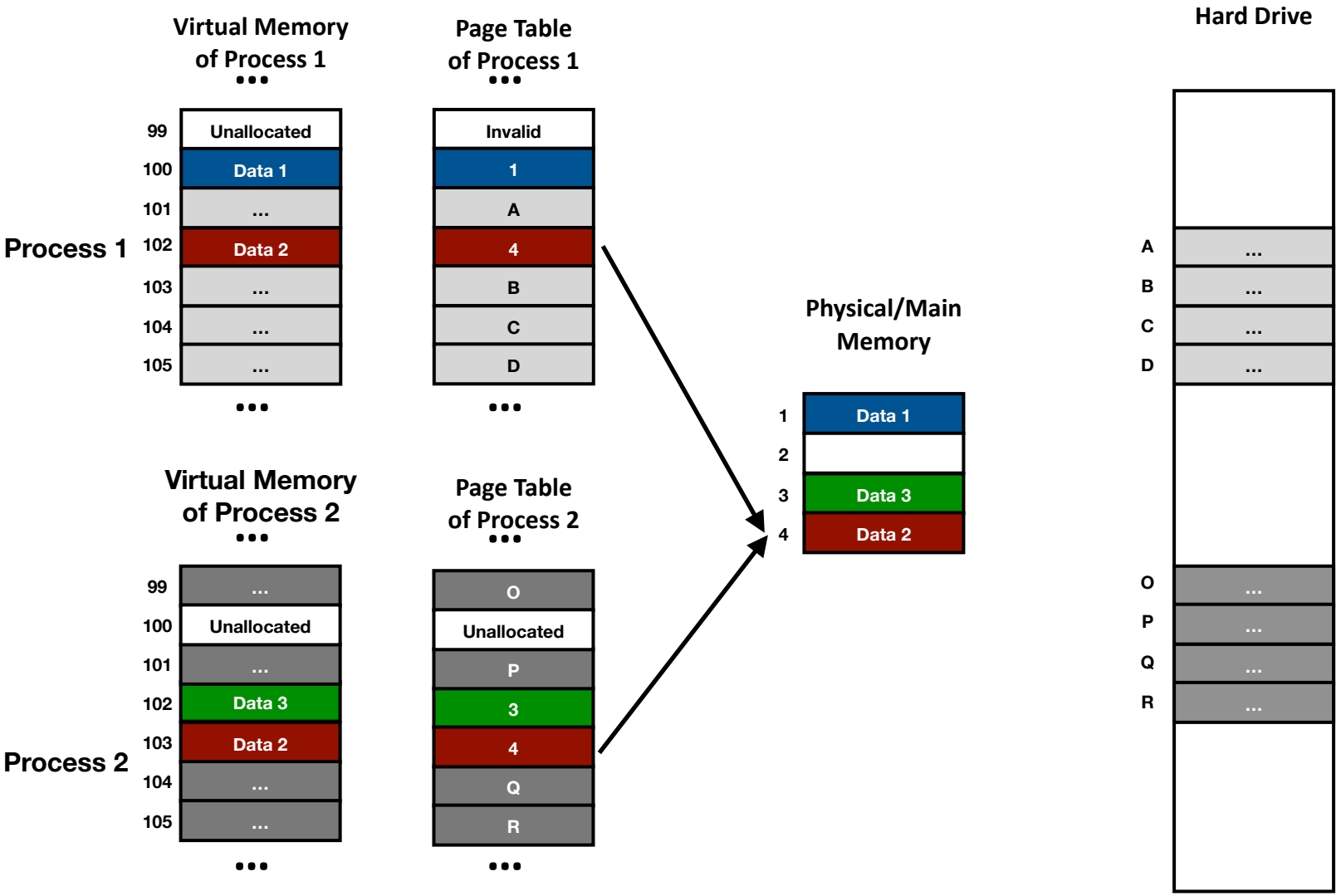


Enable Benign Sharing



Analogy for Virtual Memory: A Secure Hotel

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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
  - Guest's name is a virtual address
  - Room number is physical address
  - Front desk is doing address translation!

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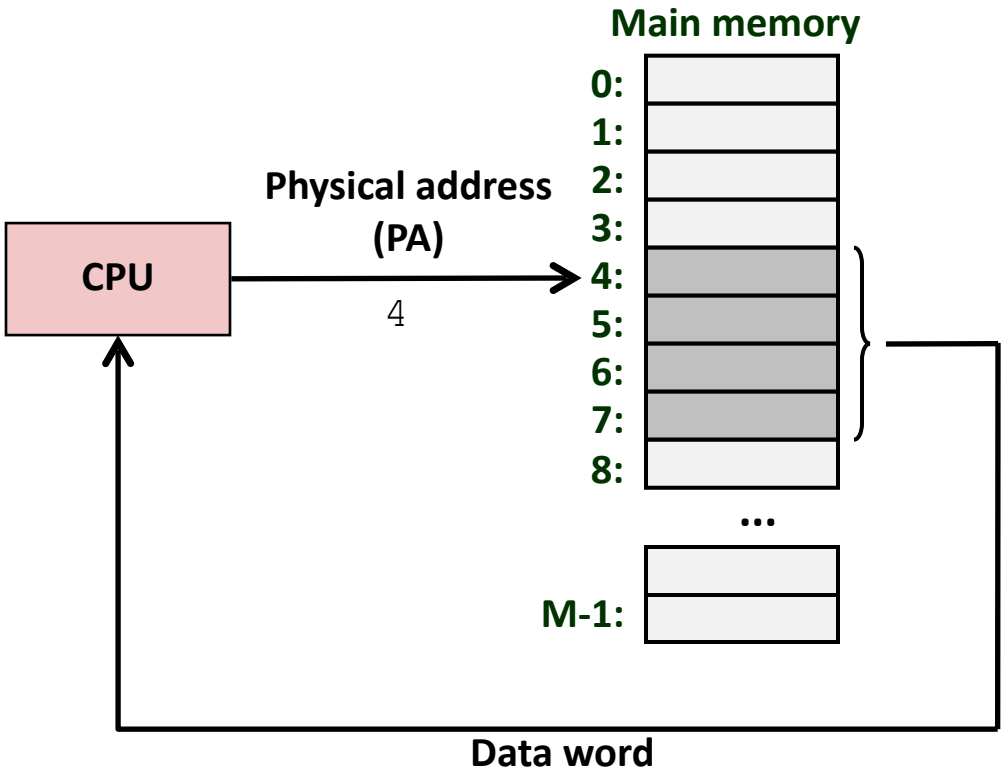
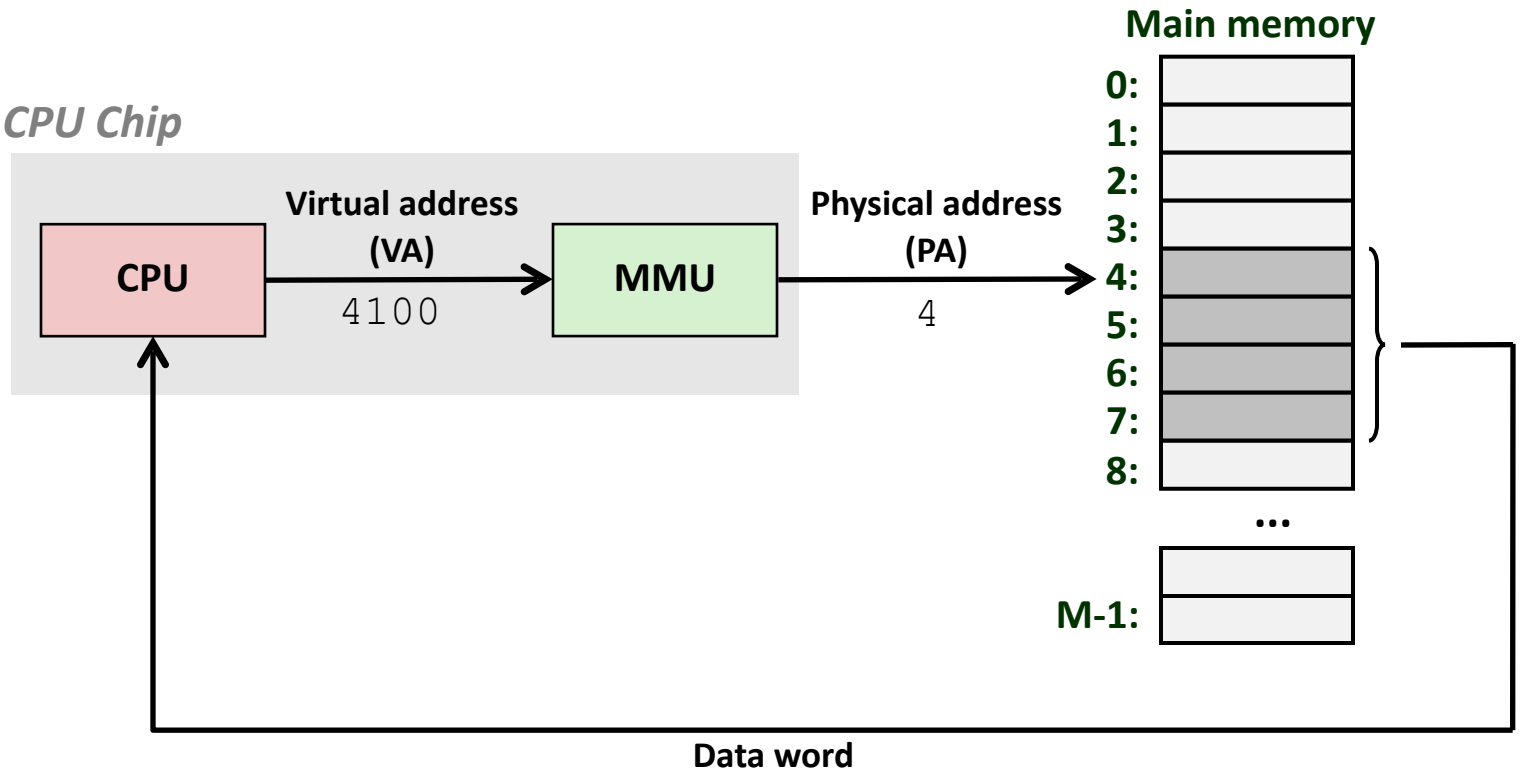
- Benefits
  - **Ease of management**: Guest could change rooms (physical address). You can still find her without knowing it
  - **Protection**: Guest could have block on calls, block on calls from specific callers (permissions)
  - **Sharing**: Multiple guests (virtual addresses) can share the same room (physical address)

A System Using Physical Memory Only



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

A System Using Virtual Memory



- Used in all modern servers, laptops, and smart phones
- One of the great ideas in computer science (back in the 60s)
- MMU: Memory Management Unit; part of the OS

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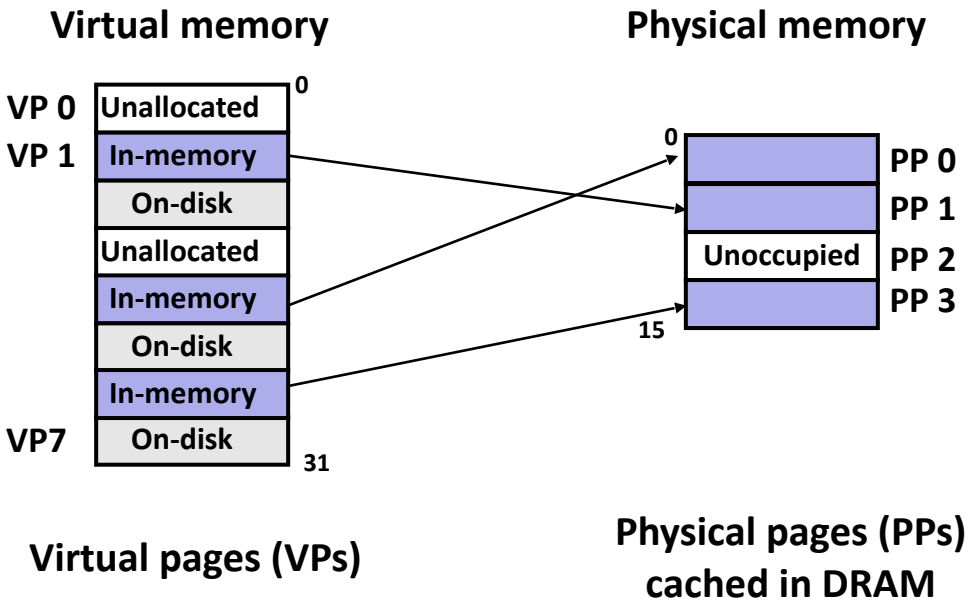
  - Infinitely large, infinitely fast memory
  - Strong isolation between processes to prevent unwanted sharing
  - Enable wanted sharing
- Virtual memory to the rescue
  - Present a large, uniform memory to programmers
  - Data in virtual memory by default stays in disk
  - Data moves to physical memory (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

- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

VM Concepts

- *Virtual memory* is an array of N contiguous *pages* (each page has a certain amount of continuous bytes).
- Physical memory is also divided into pages. Each physical page (sometimes called *frames*) has the same size as a virtual page. Physical memory has way fewer pages.
- A page can either be on the ("uncached") disk or in the physical memory ("cached").



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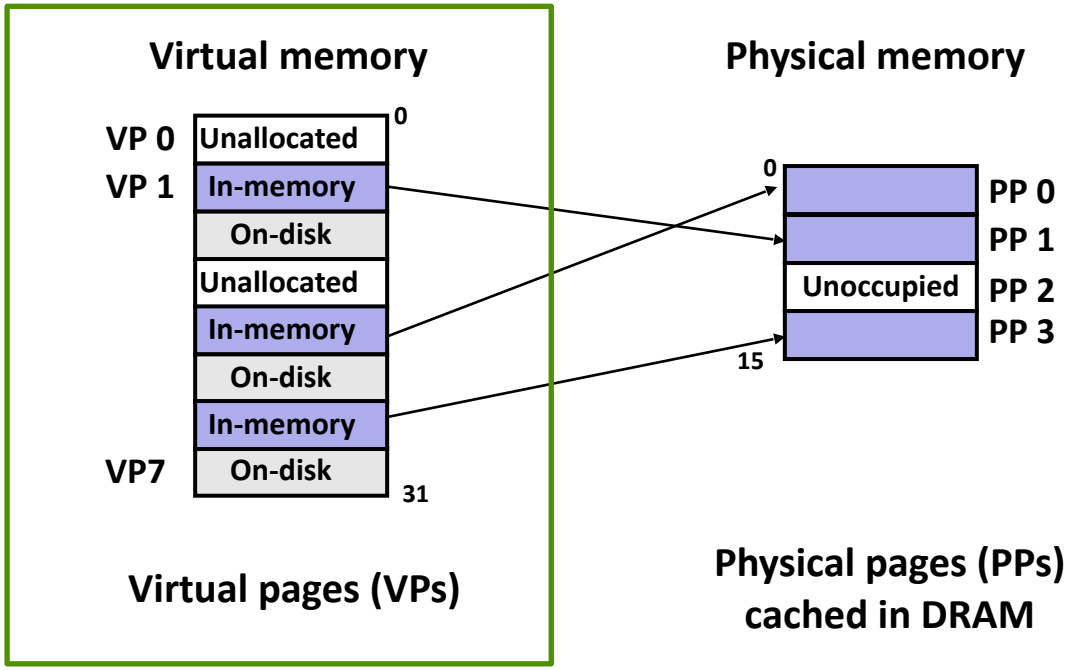

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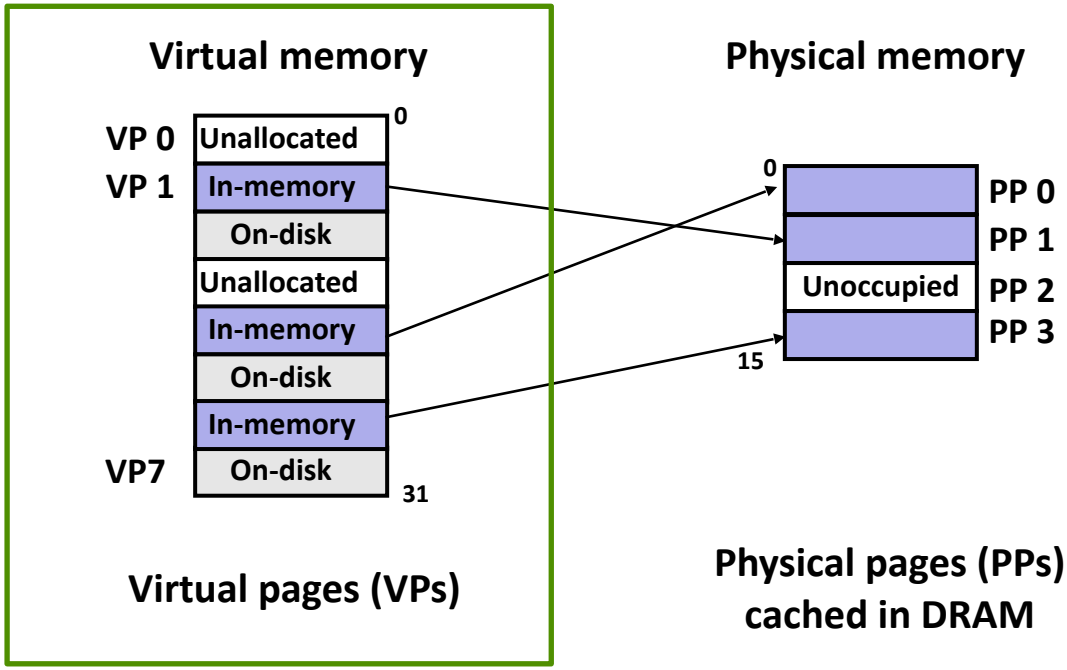

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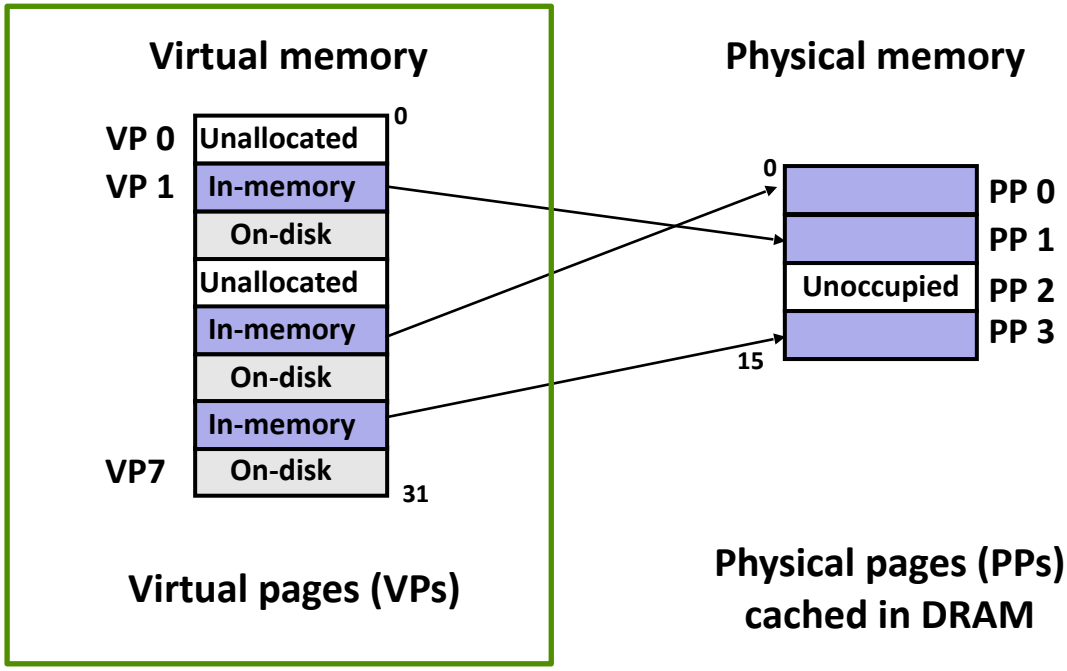

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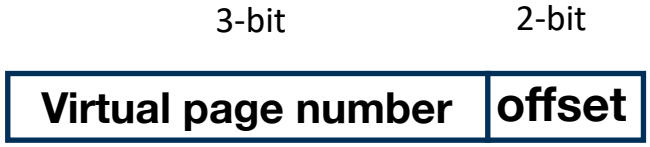

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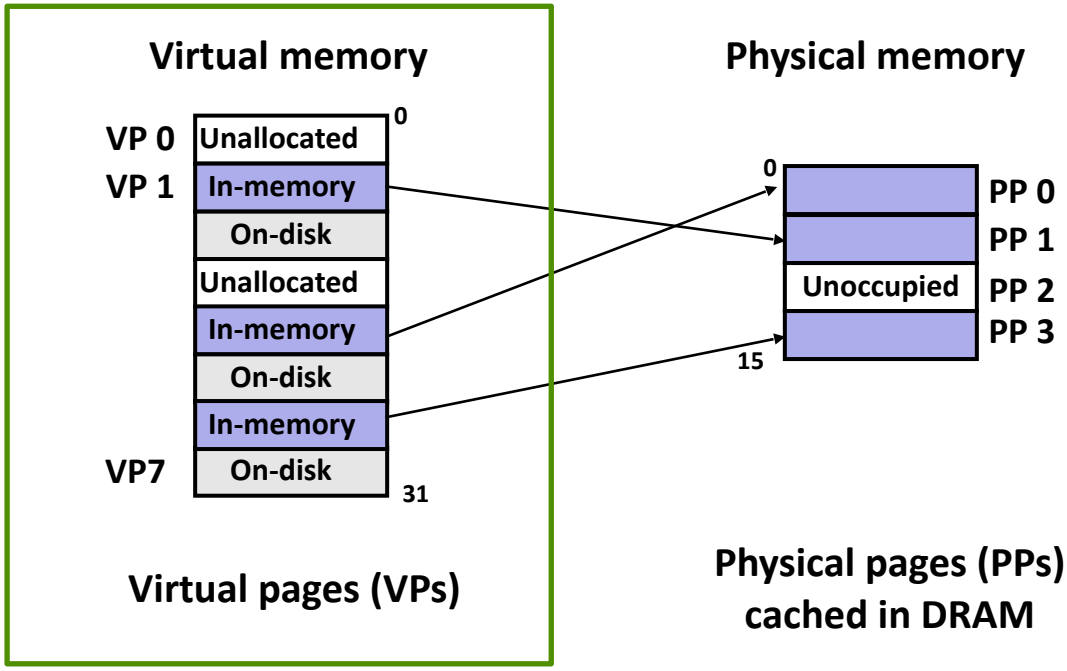

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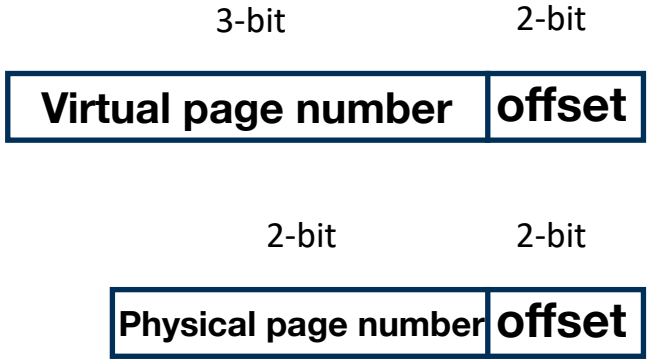

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- Do you need a page table for each process?
  - Per-process data structure; managed by the OS kernel

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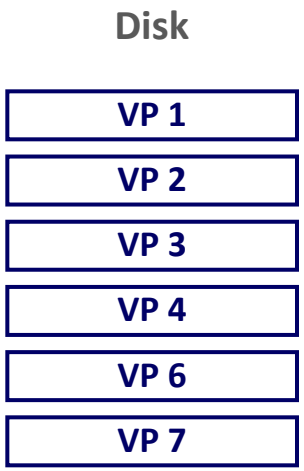

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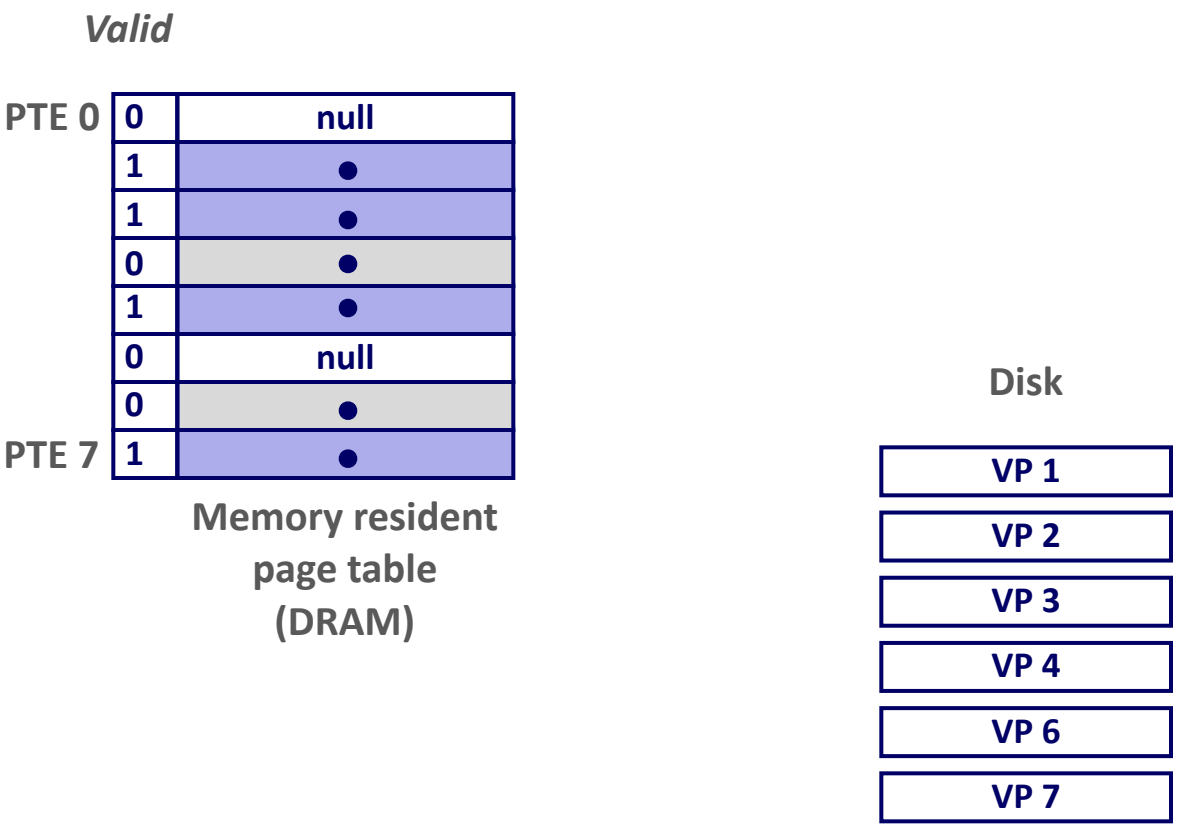

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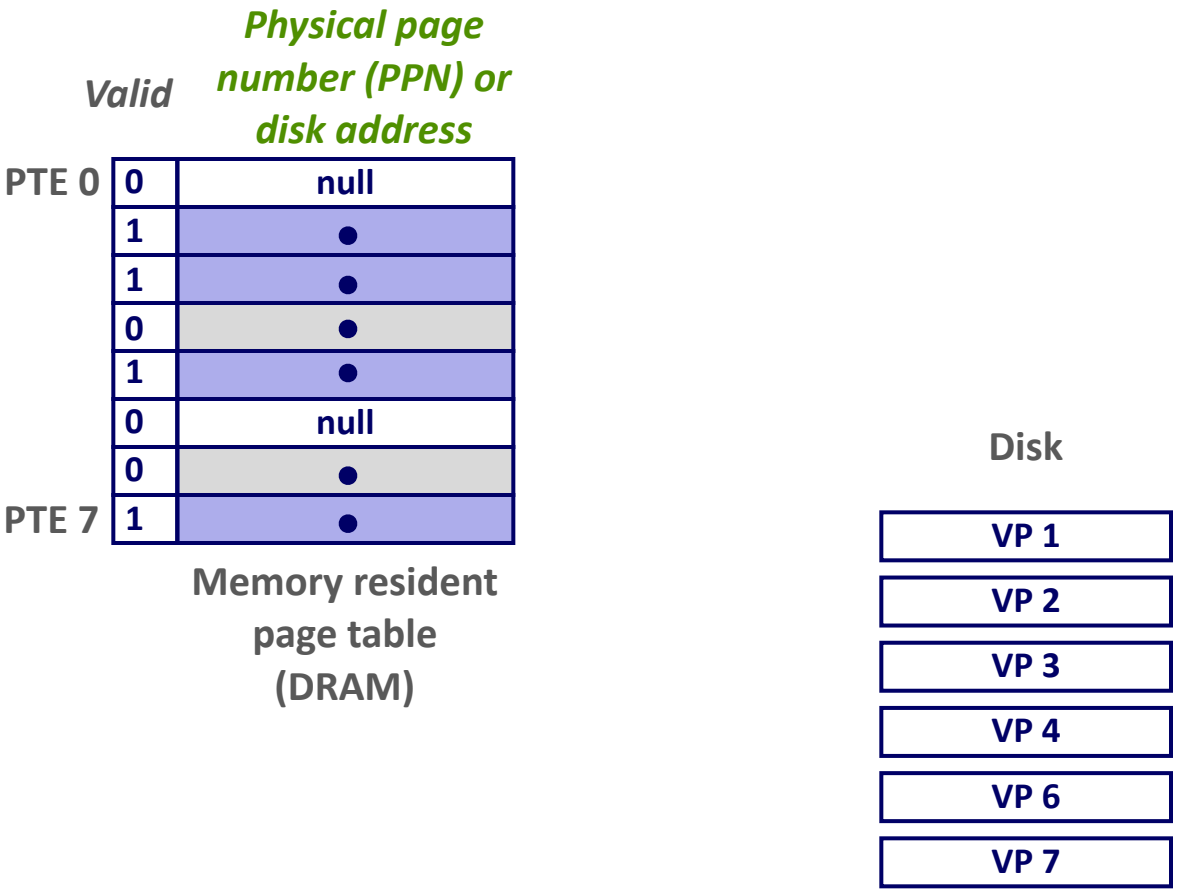

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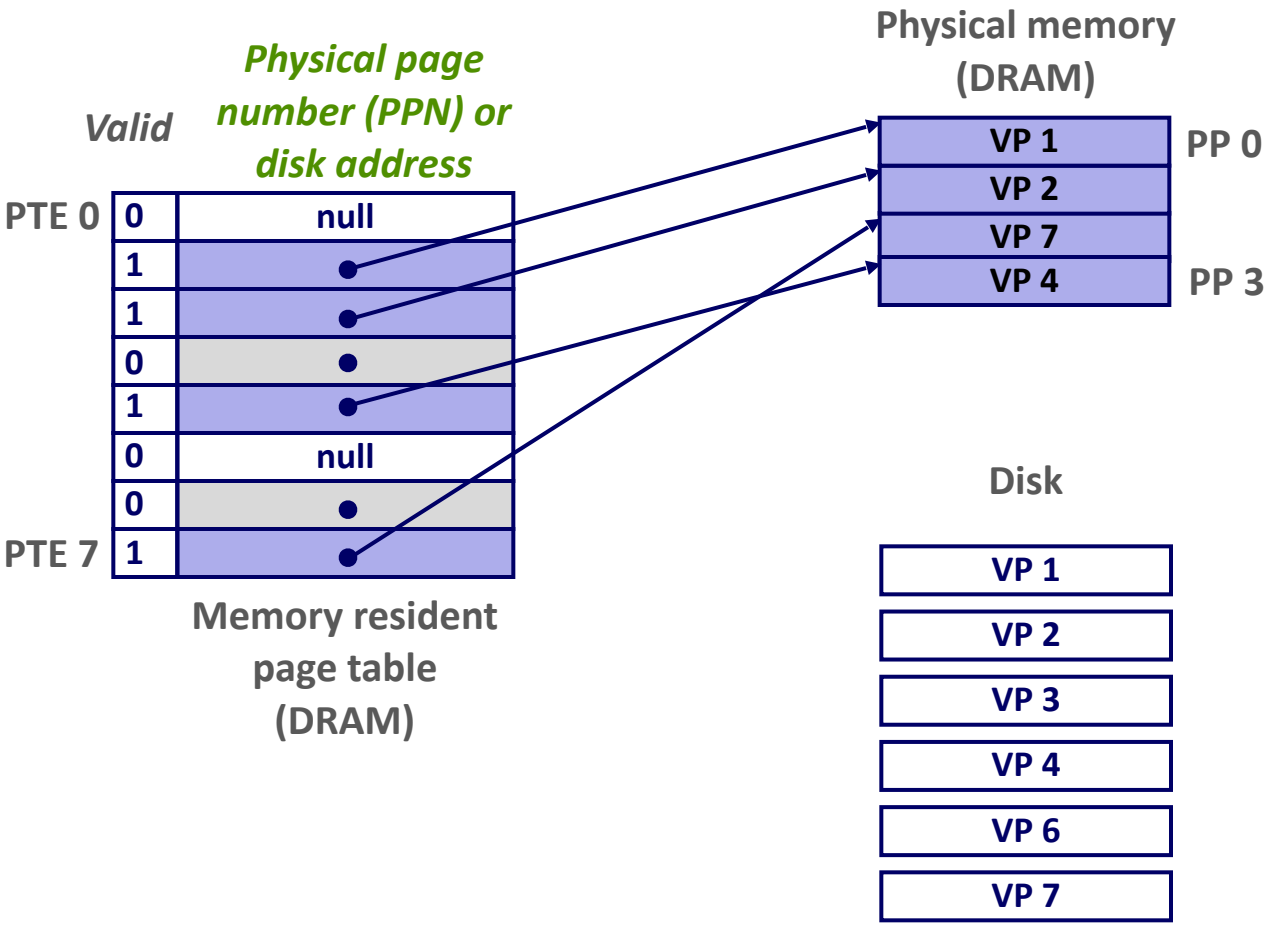

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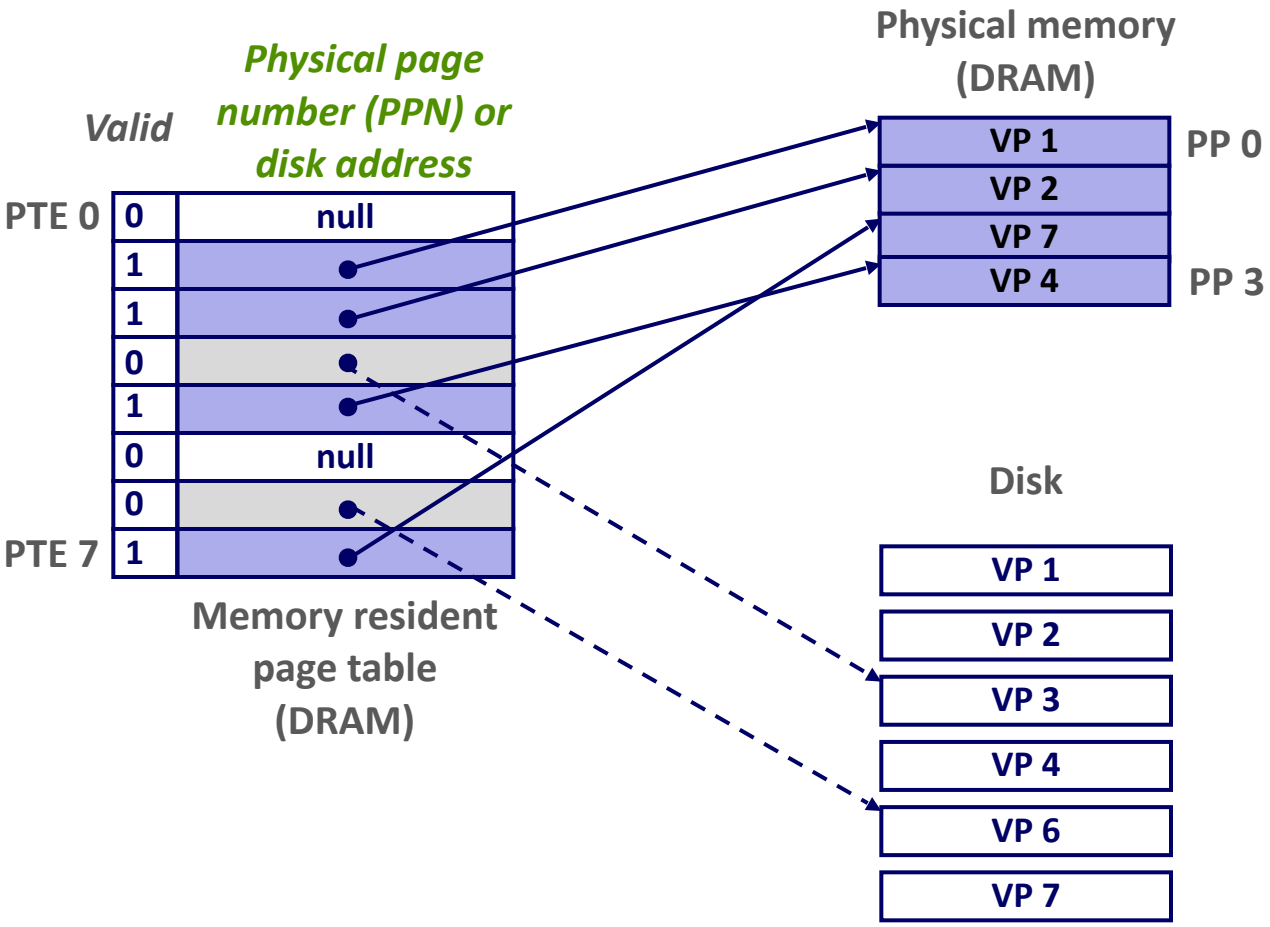
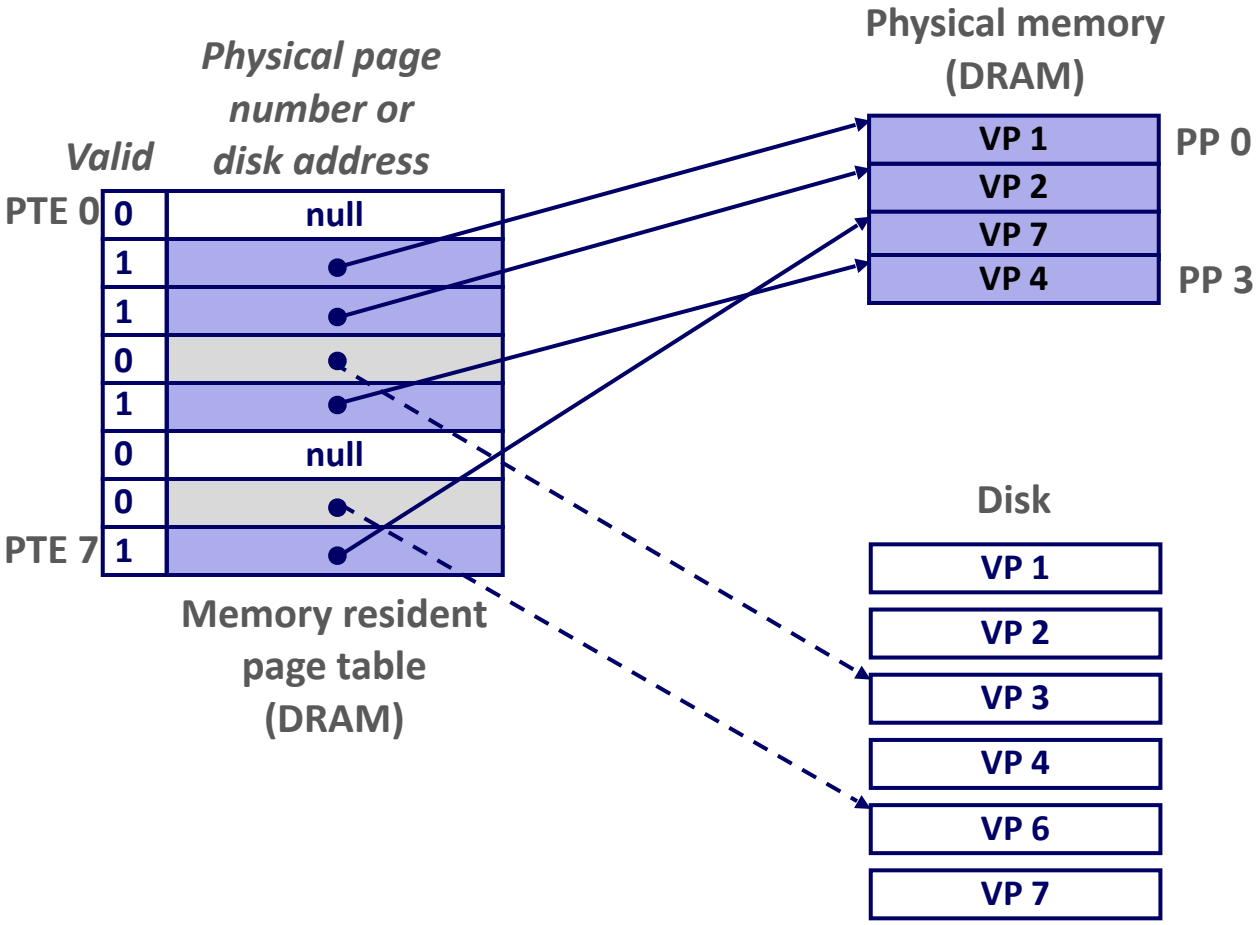


Page Hit

- *Page hit:* reference to VM word that is in physical memory



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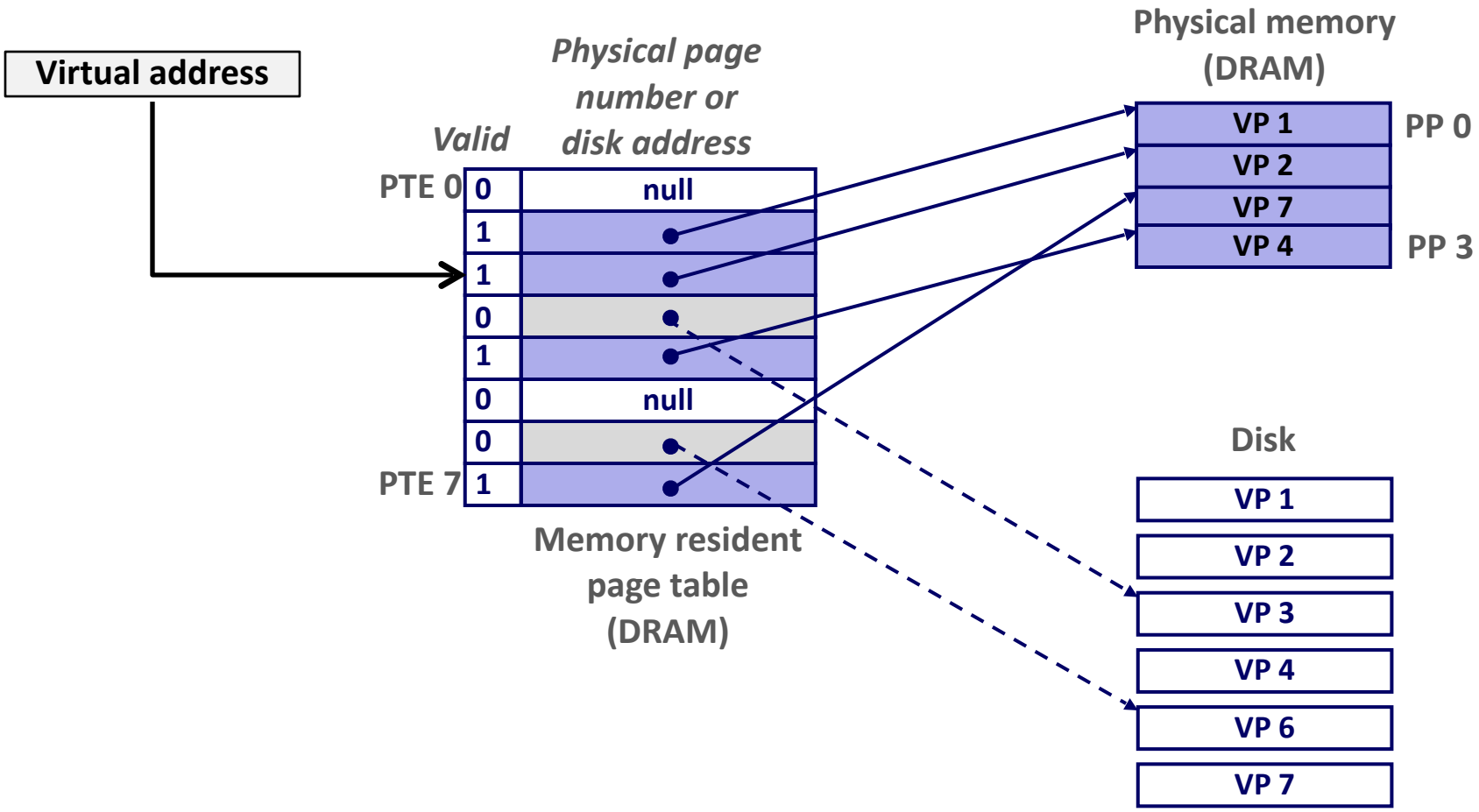

Page Fault

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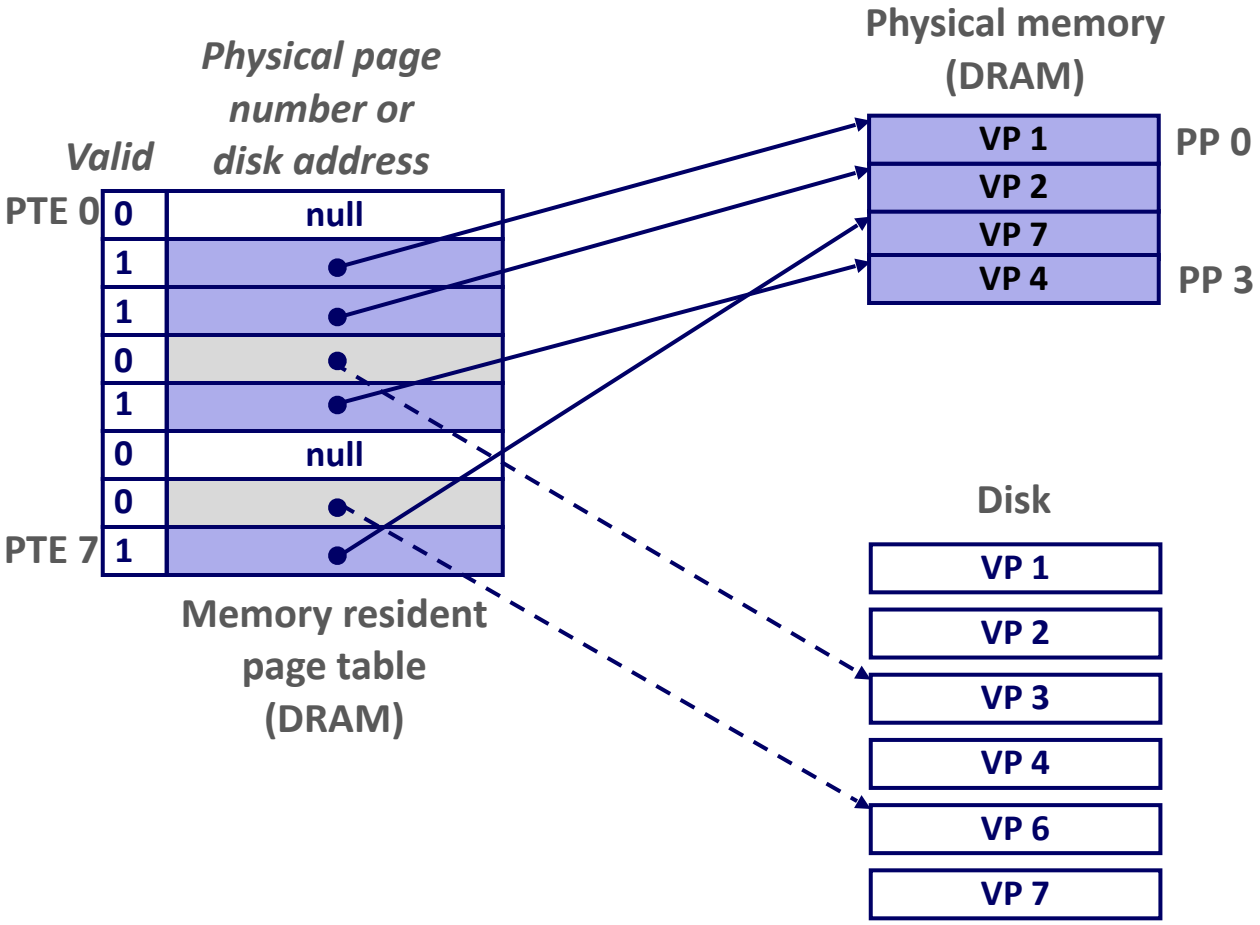

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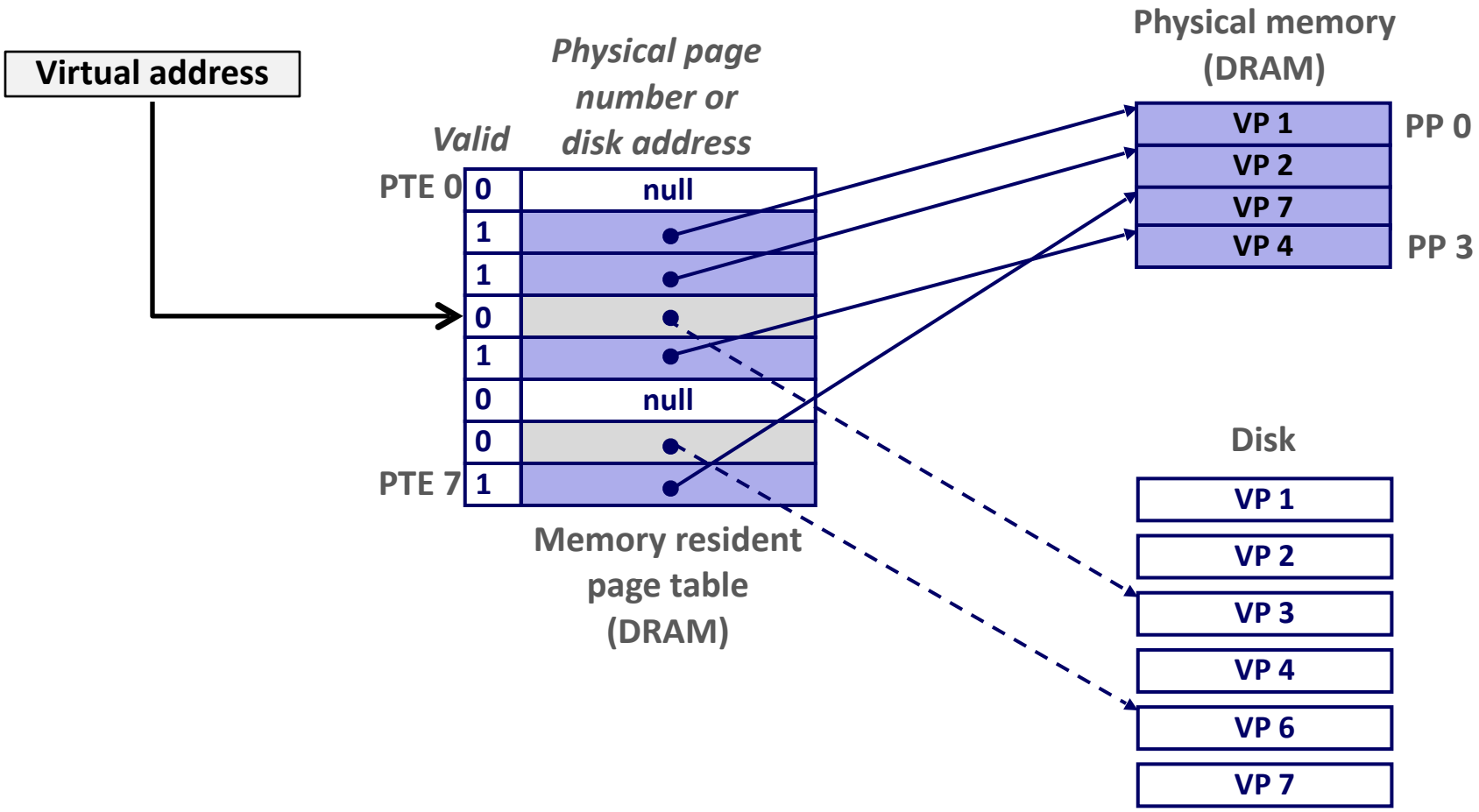
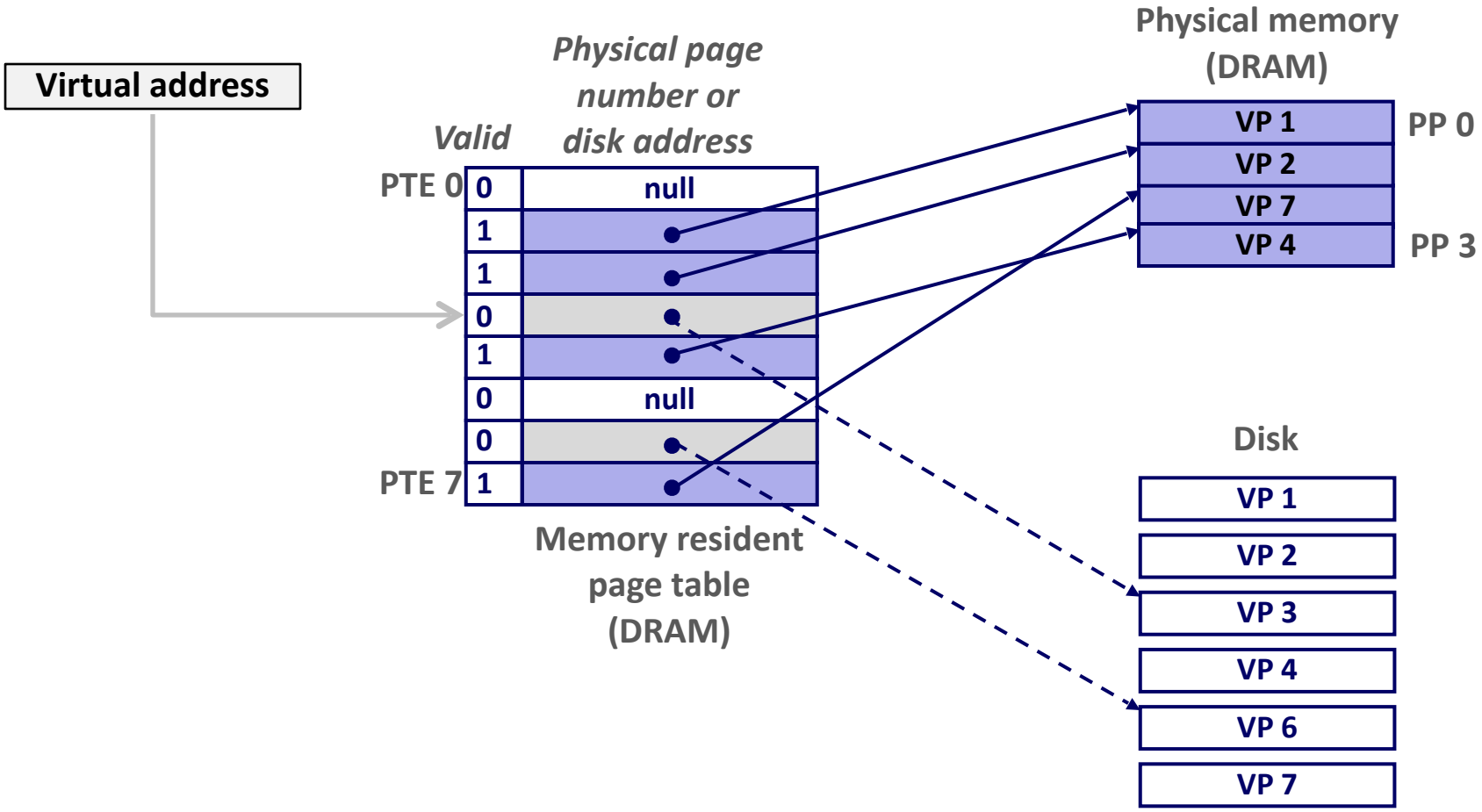


Handling Page Fault

- Page miss causes ***page fault (an exception)***



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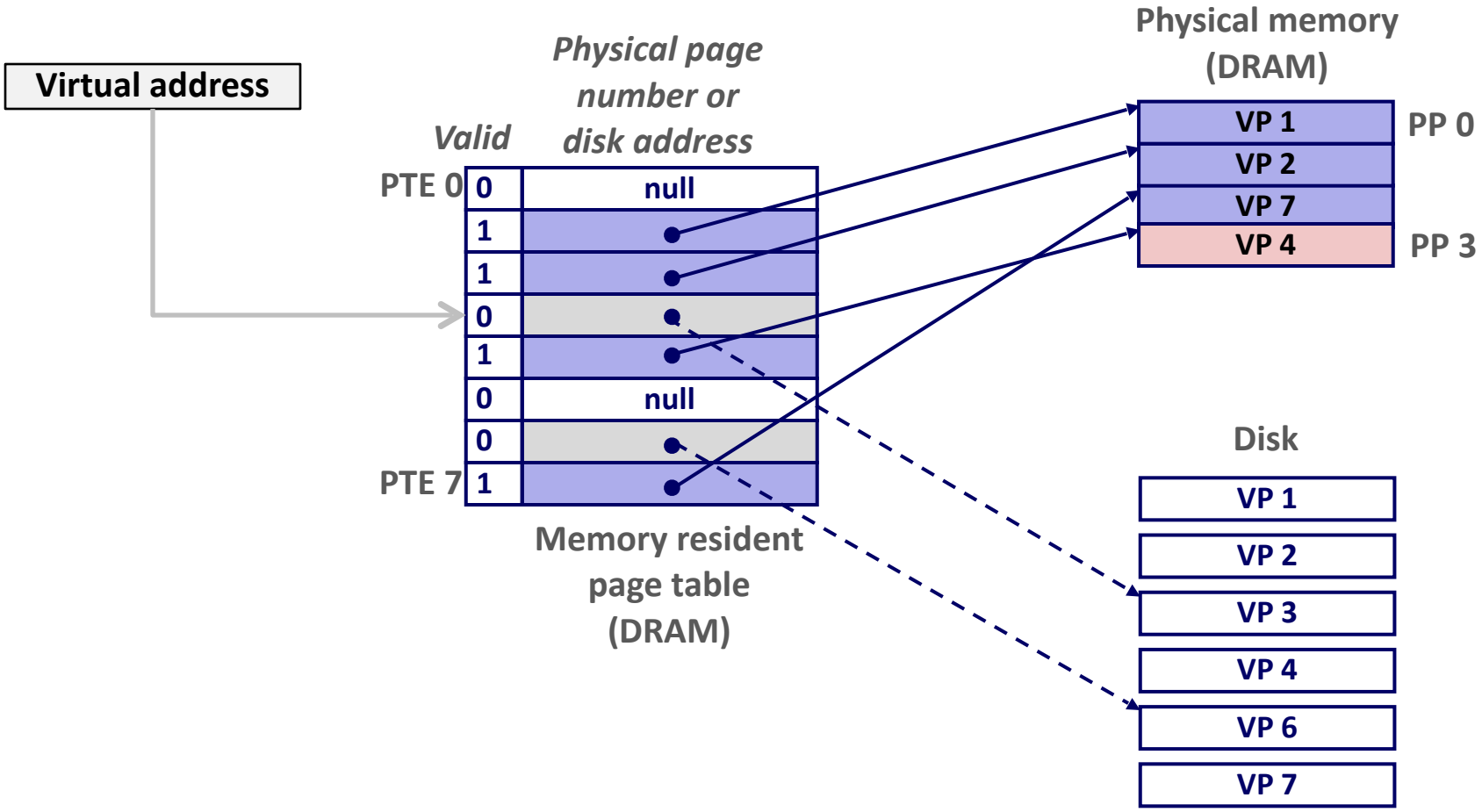

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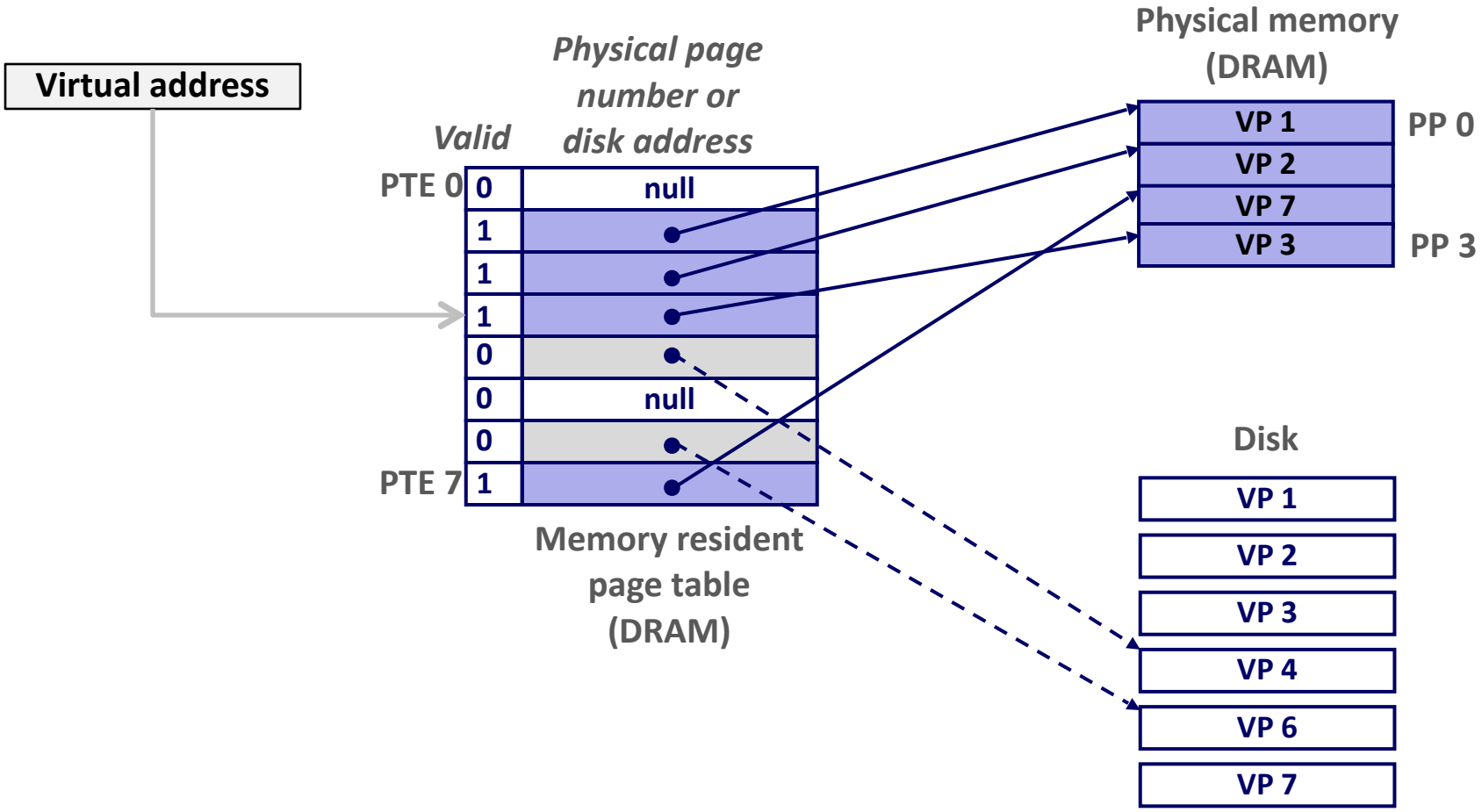

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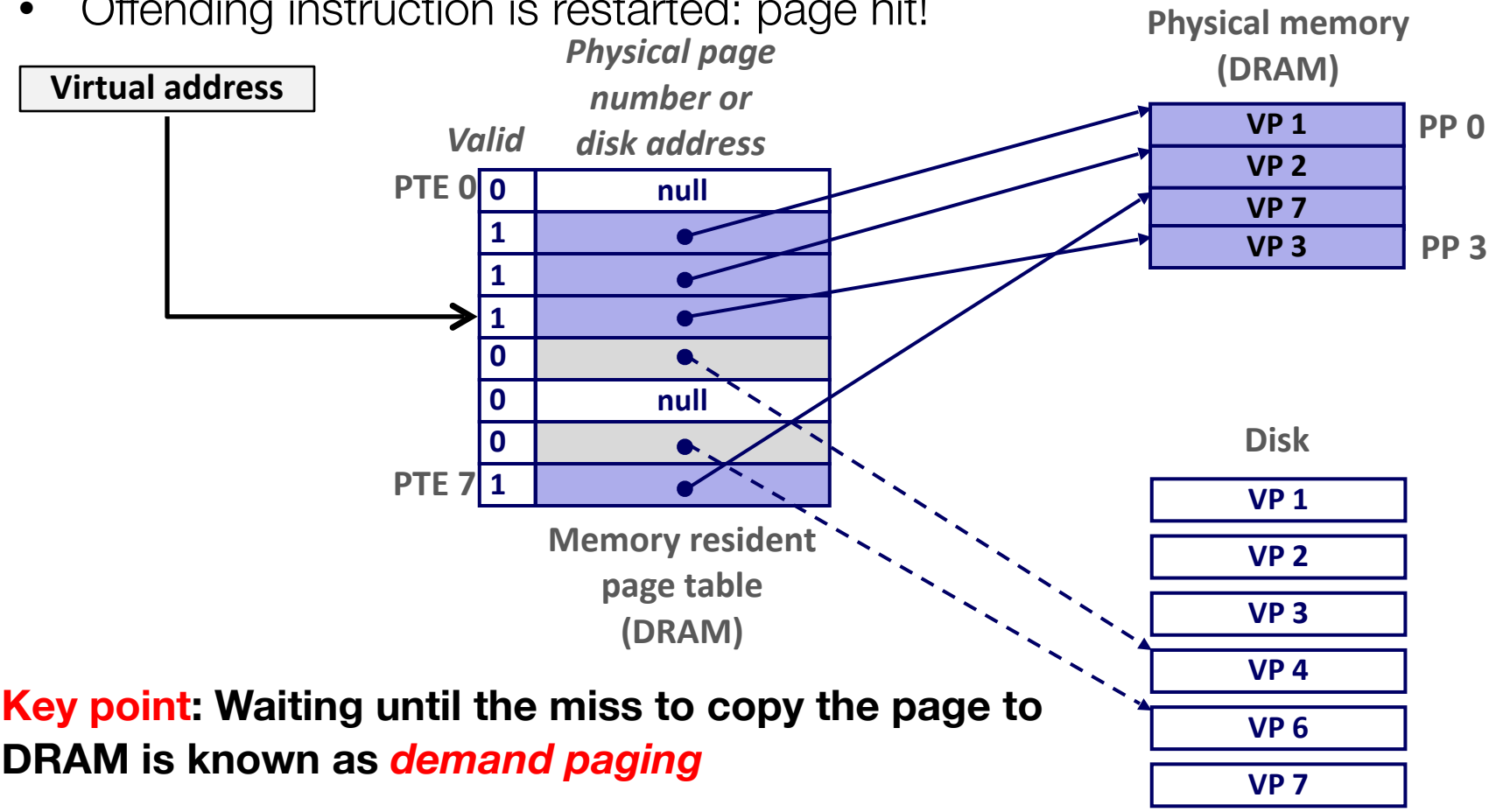
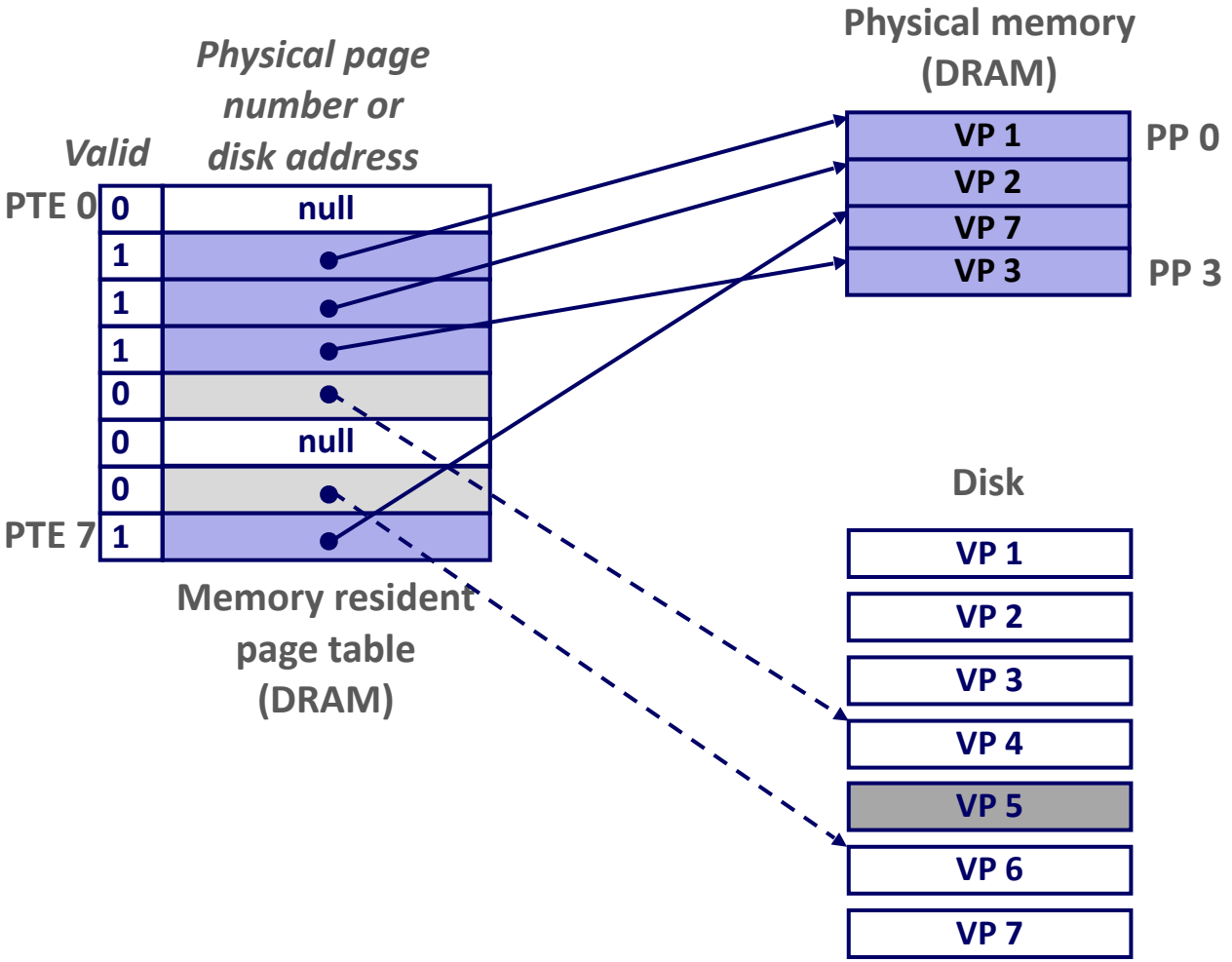
- Offending instruction is restarted: page hit!



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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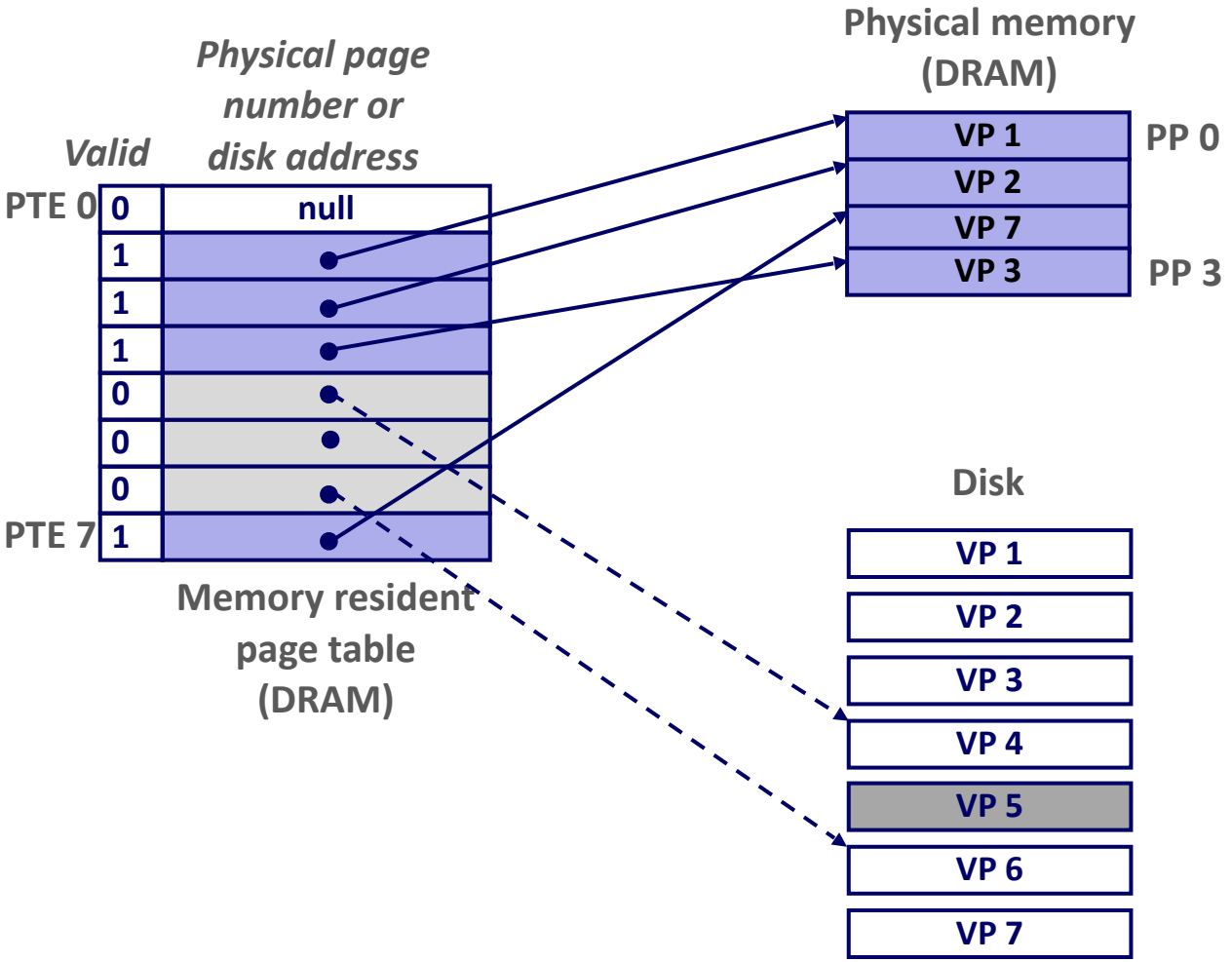

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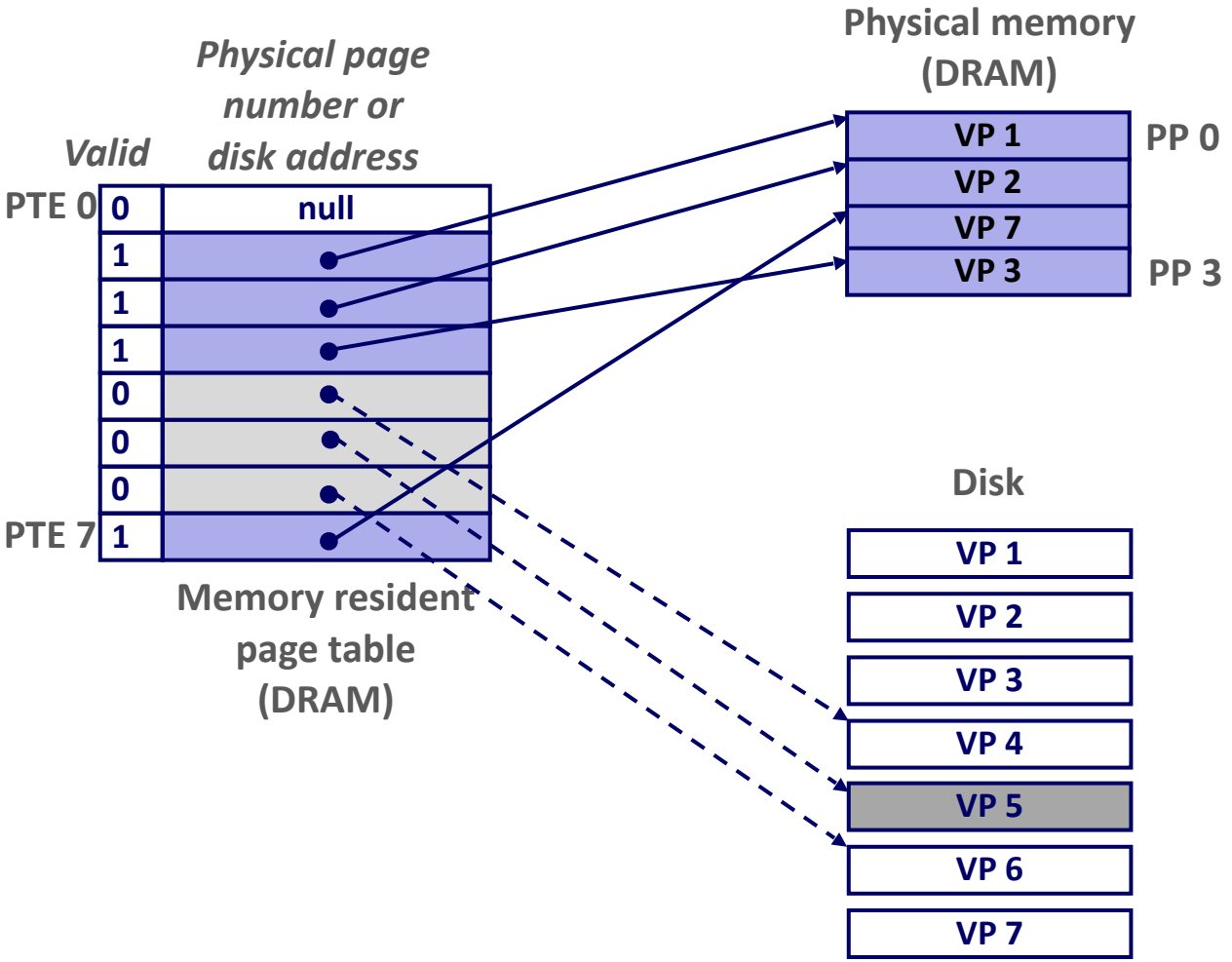

Virtual Memory Exploits Locality (Again!)

- 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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  - Some special SRAM?
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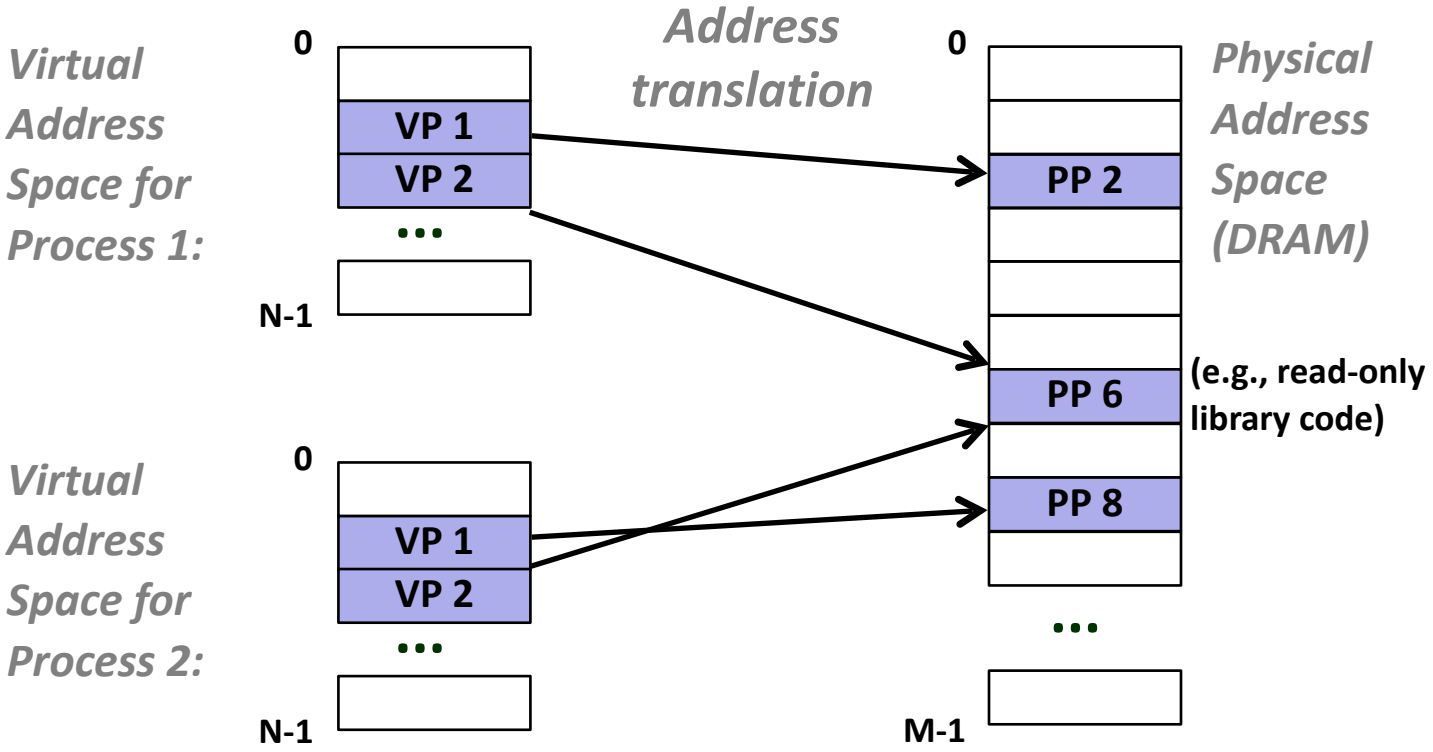
- ~MBs of a page table *per process*
  - Too big for on-chip SRAM (c.f., a L1 cache is ~32 KB)
  - Too slow to access in disk
  - Put the page table in DRAM, with its start address stored in a special register (Page Table Base Register). More on this later.

Today

- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

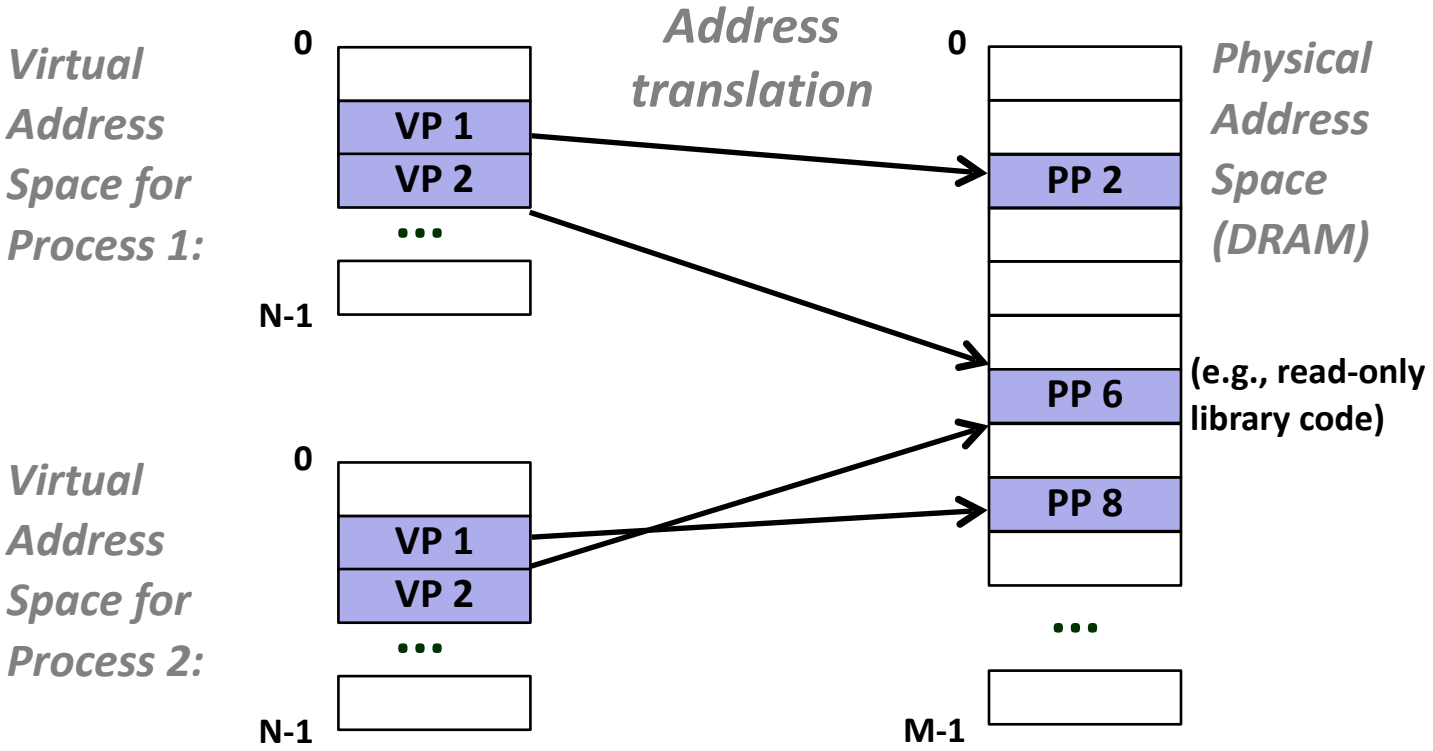
VM as a Tool for Memory Management

- 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



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 (read/write/executable/ accessible only in supervisor mode?)
- Remember buffer overflow attack?