

CSC 252: Computer Organization

Fall 2021: Lecture 21

Virtual Memory

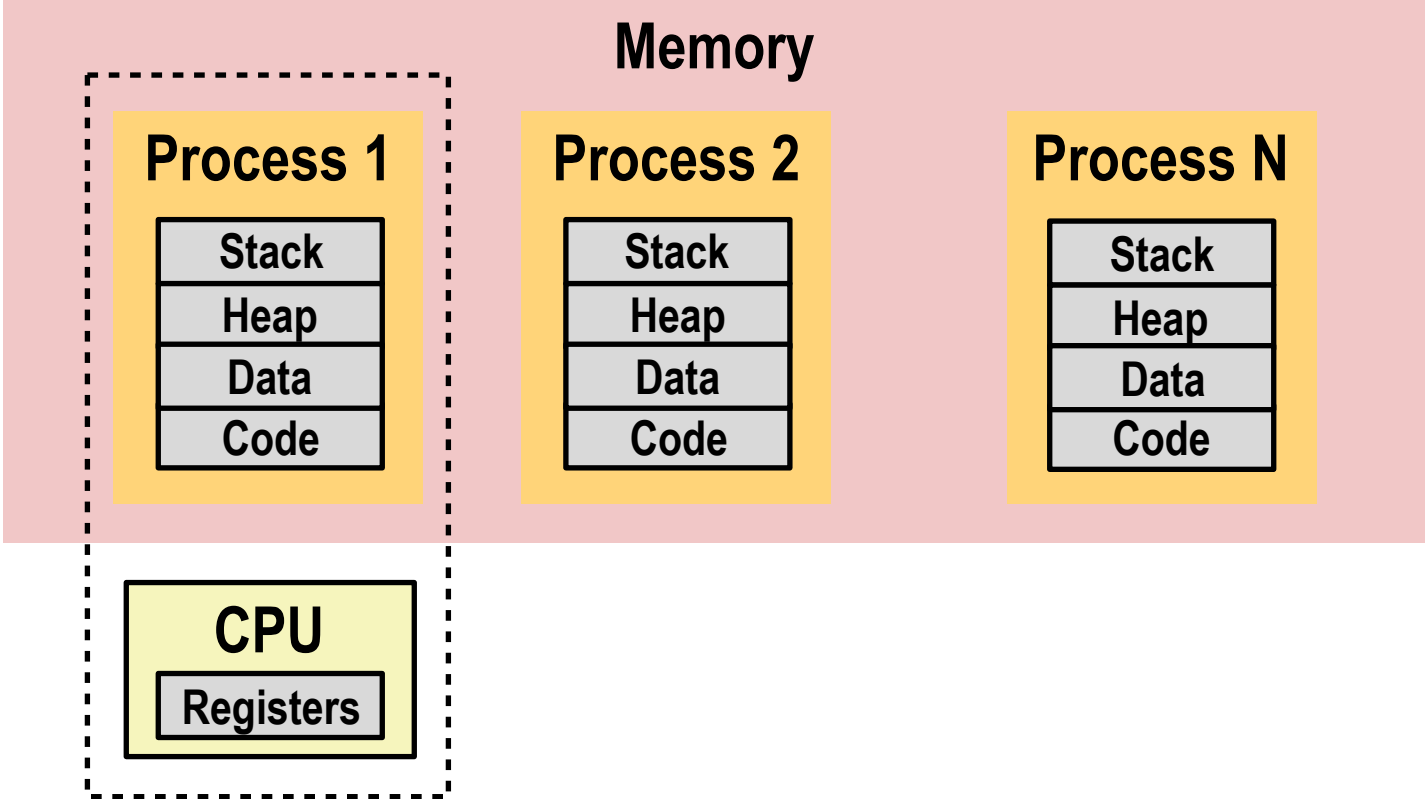
Instructor: Alan Beadle

Department of Computer Science
University of Rochester

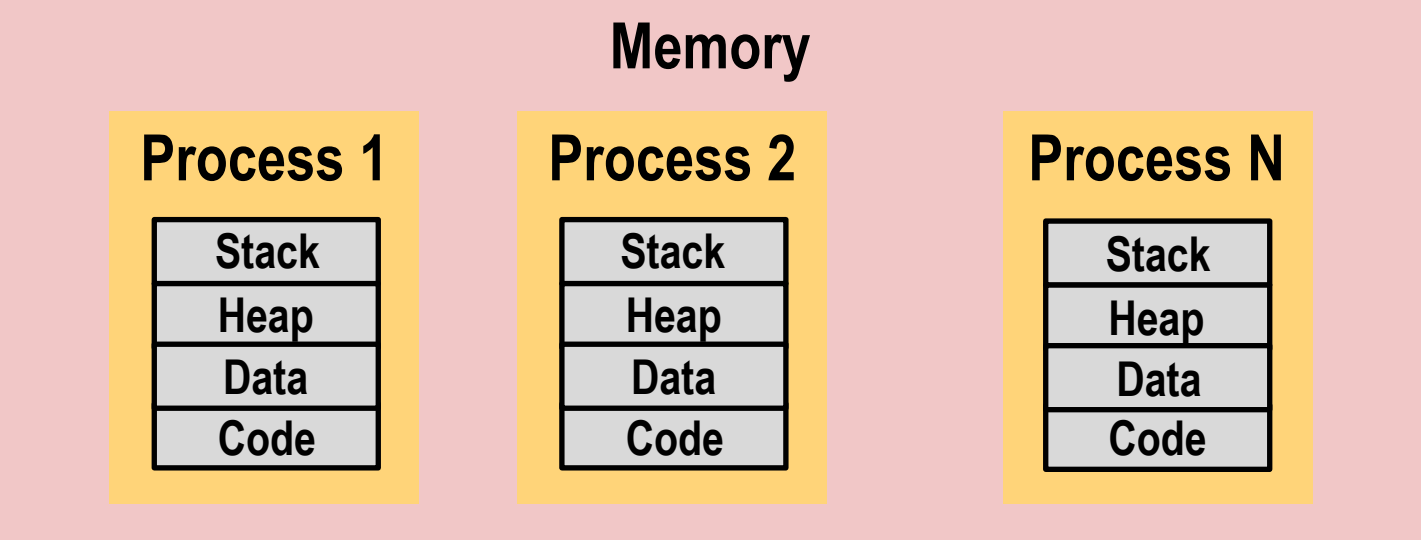
Announcements

- A4 is due 11:59pm, Thursday, November 18
- Remember to let us know about slip days
- Also remember to type the dot when running the turn-in script
- The first commercially produced microprocessor, the Intel 4004, was released 50 years ago today!

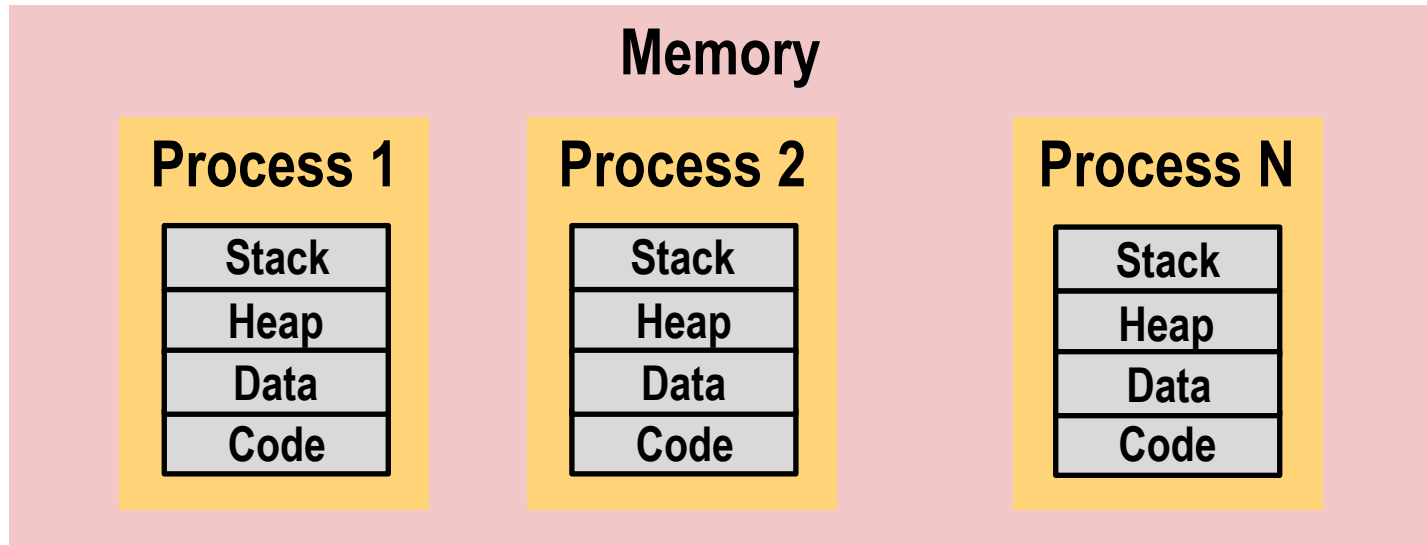
Multiprocessing Illustration



Problem 1: Space



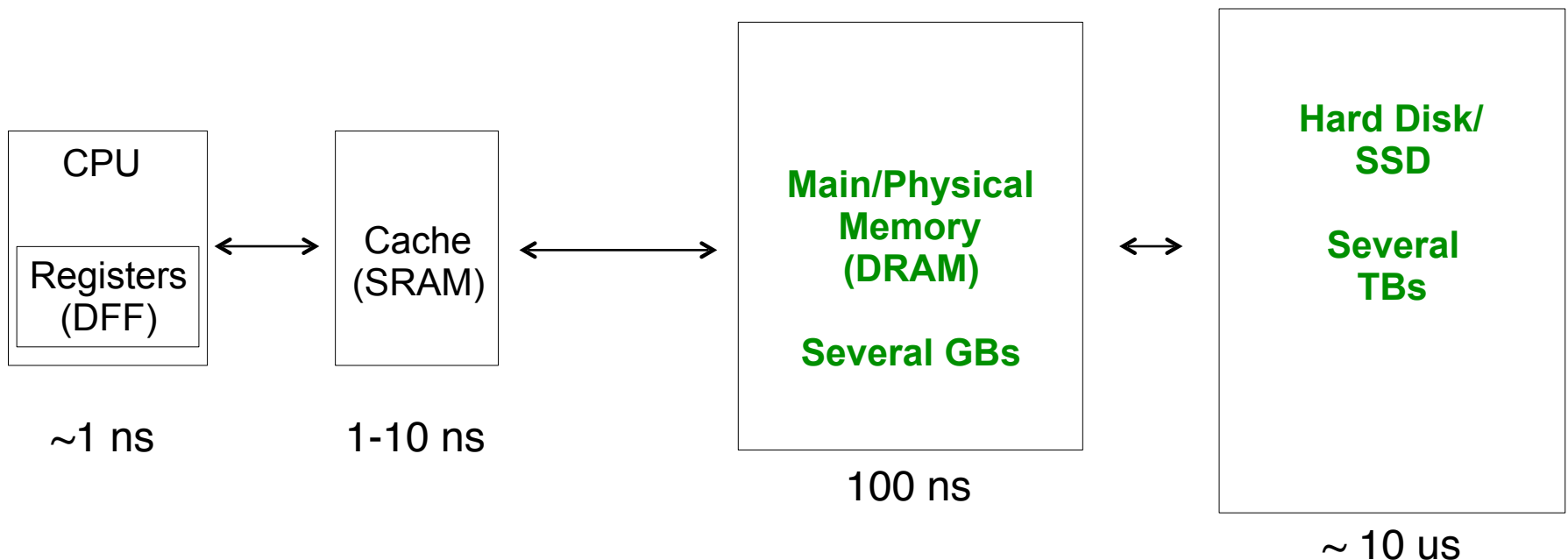
Problem 1: Space



- **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.

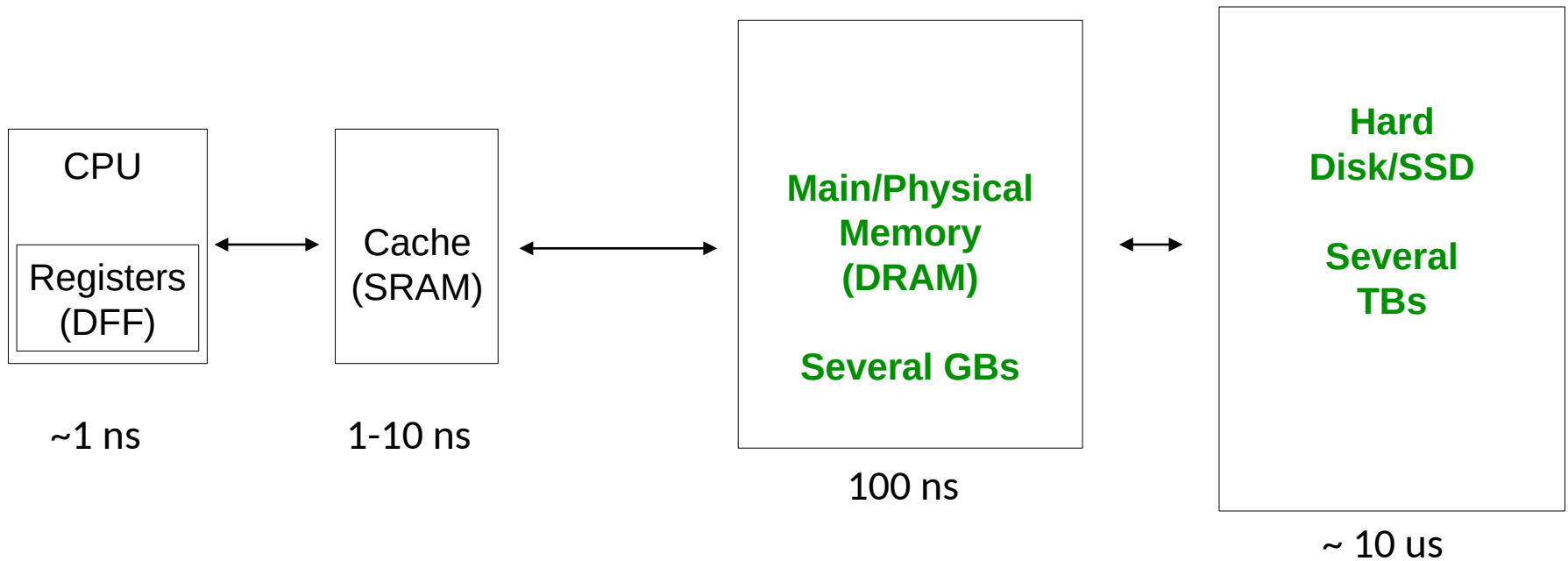


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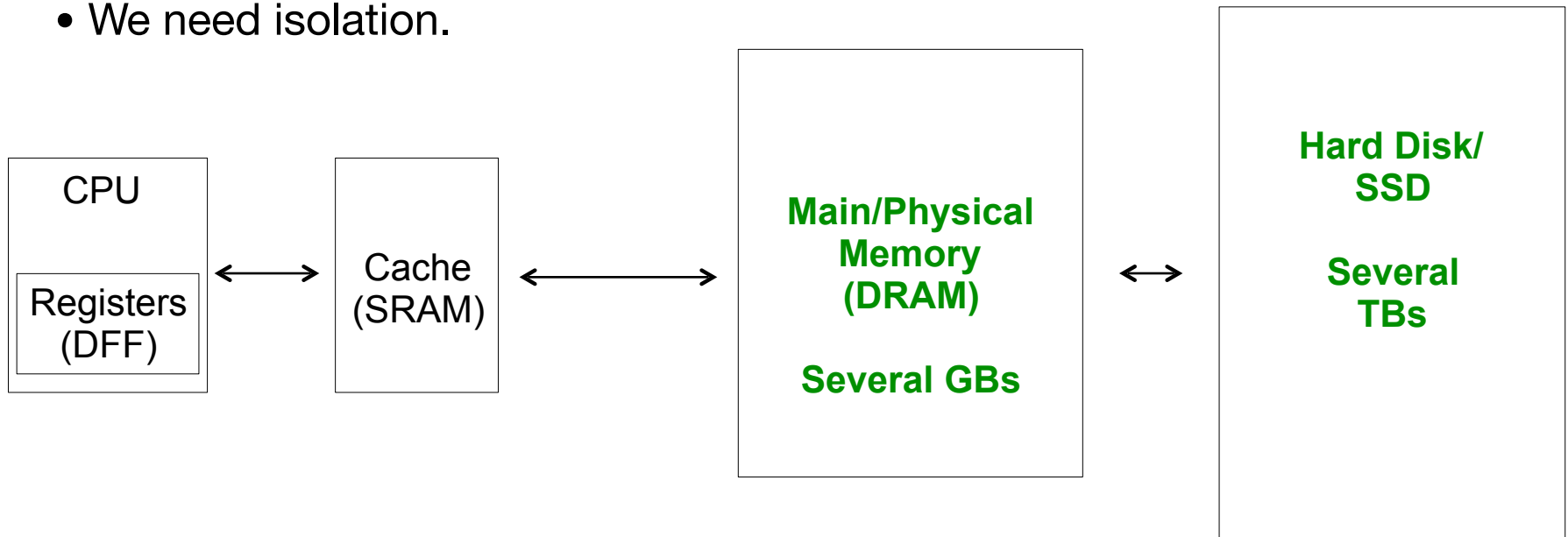
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Challenge: who is moving data back and forth between the DRAM/main memory/physical memory and the disk?



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.



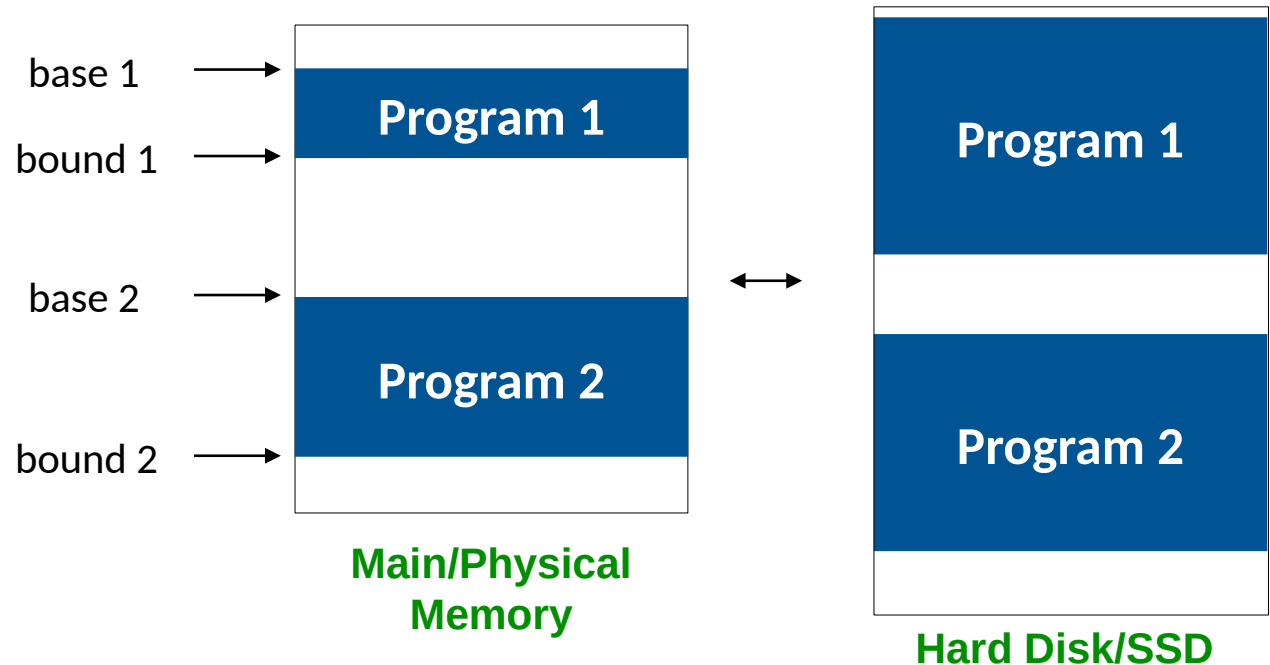
One Way to Isolate: Segments

Different processes will have exclusive access to just one part of the physical memory.

This is called **Segments**.

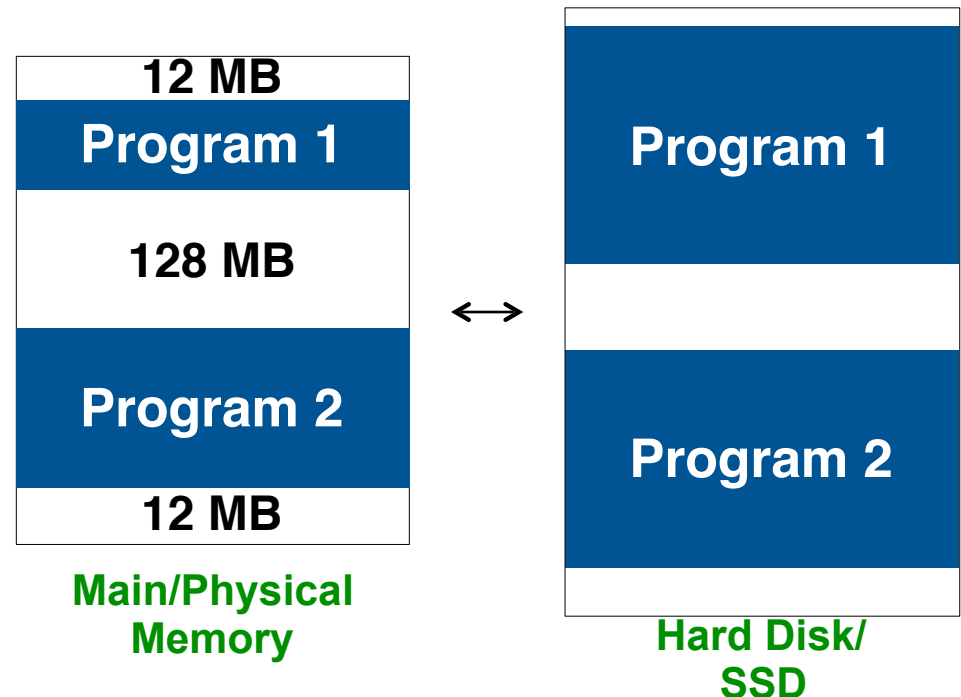
Need a base register and a bound register for each process. Not widely used today. x86 still supports it (backward compatibility!)

Fast but not flexible. Makes benign sharing hard.



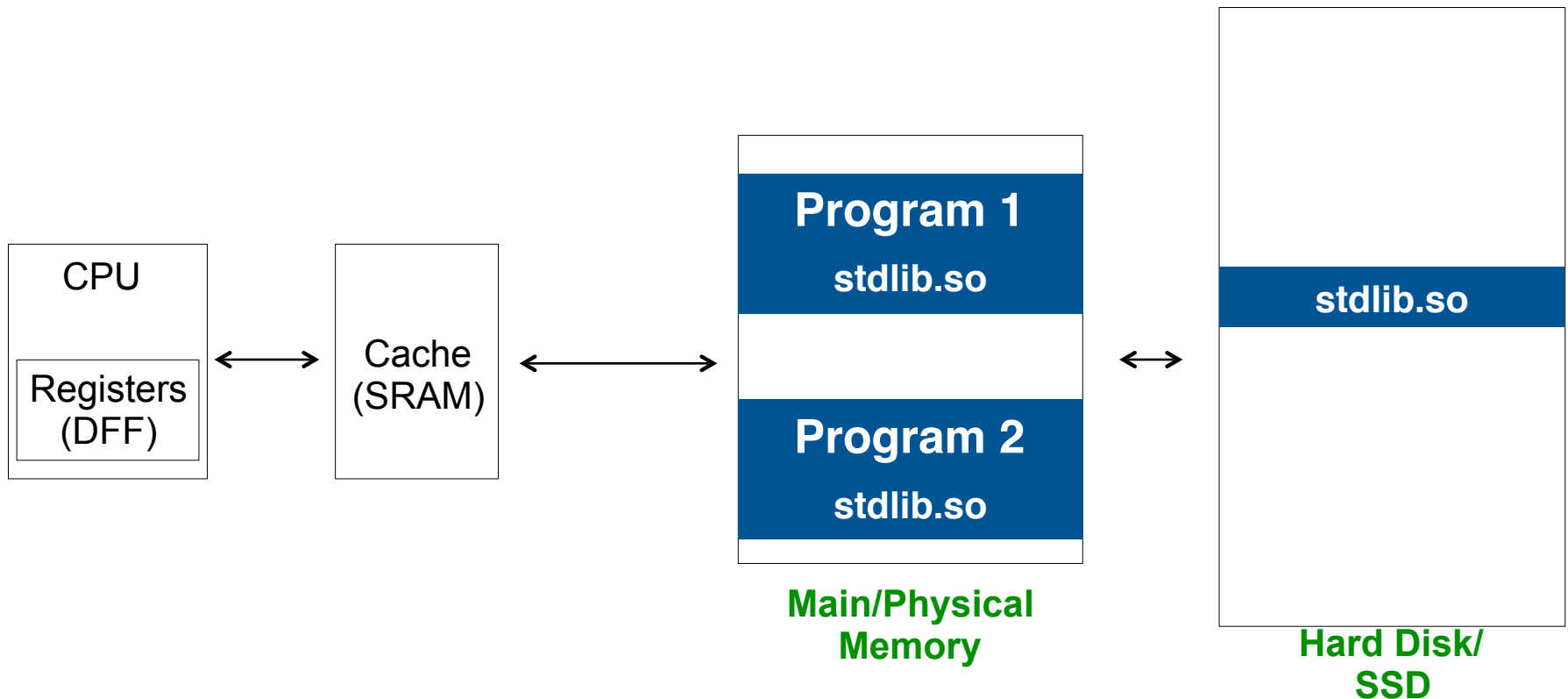
Problem 3: Fragmentation (with Segments)

- 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.

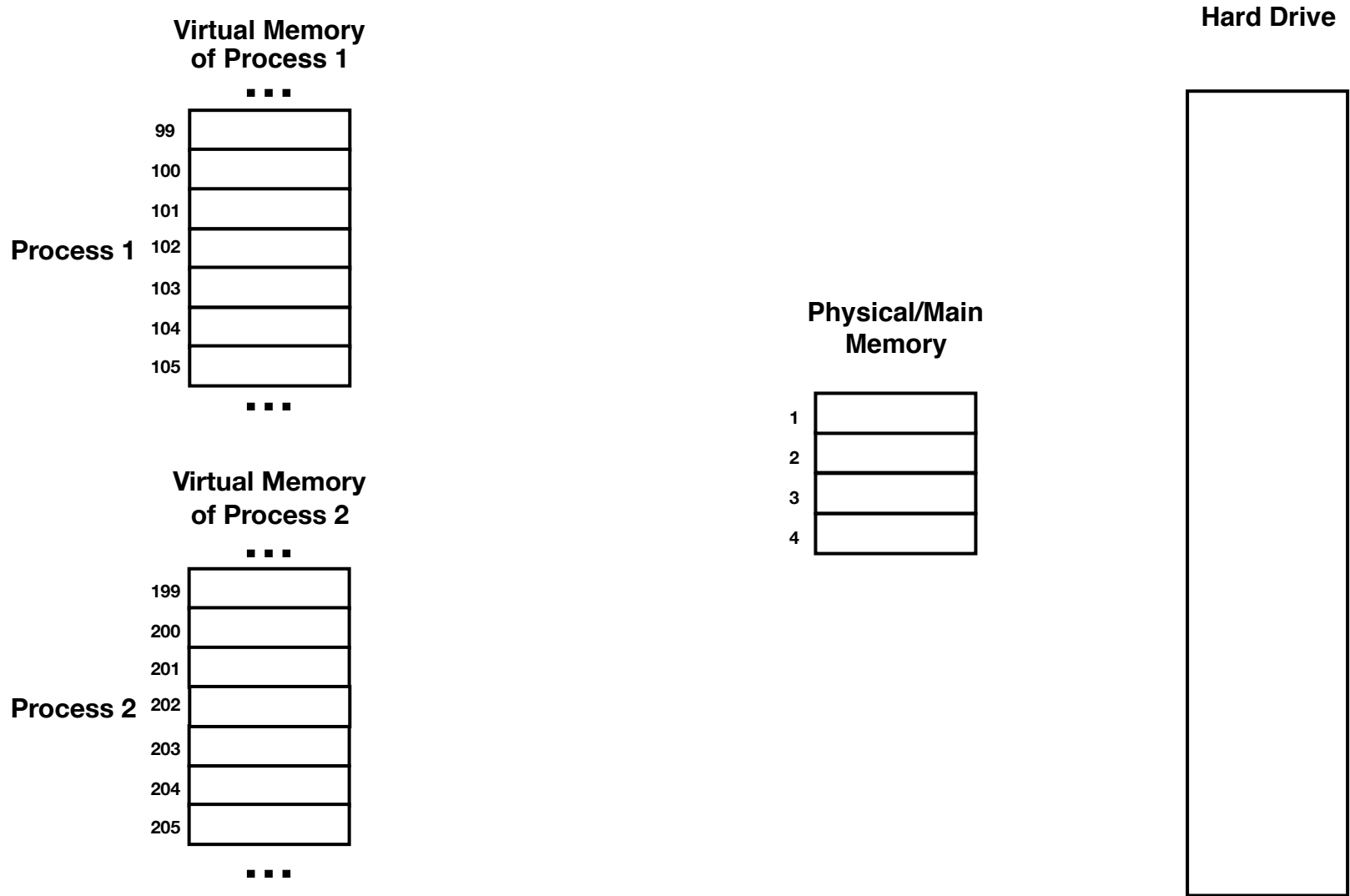


Problem 4: Benign Sharing (with Segments)

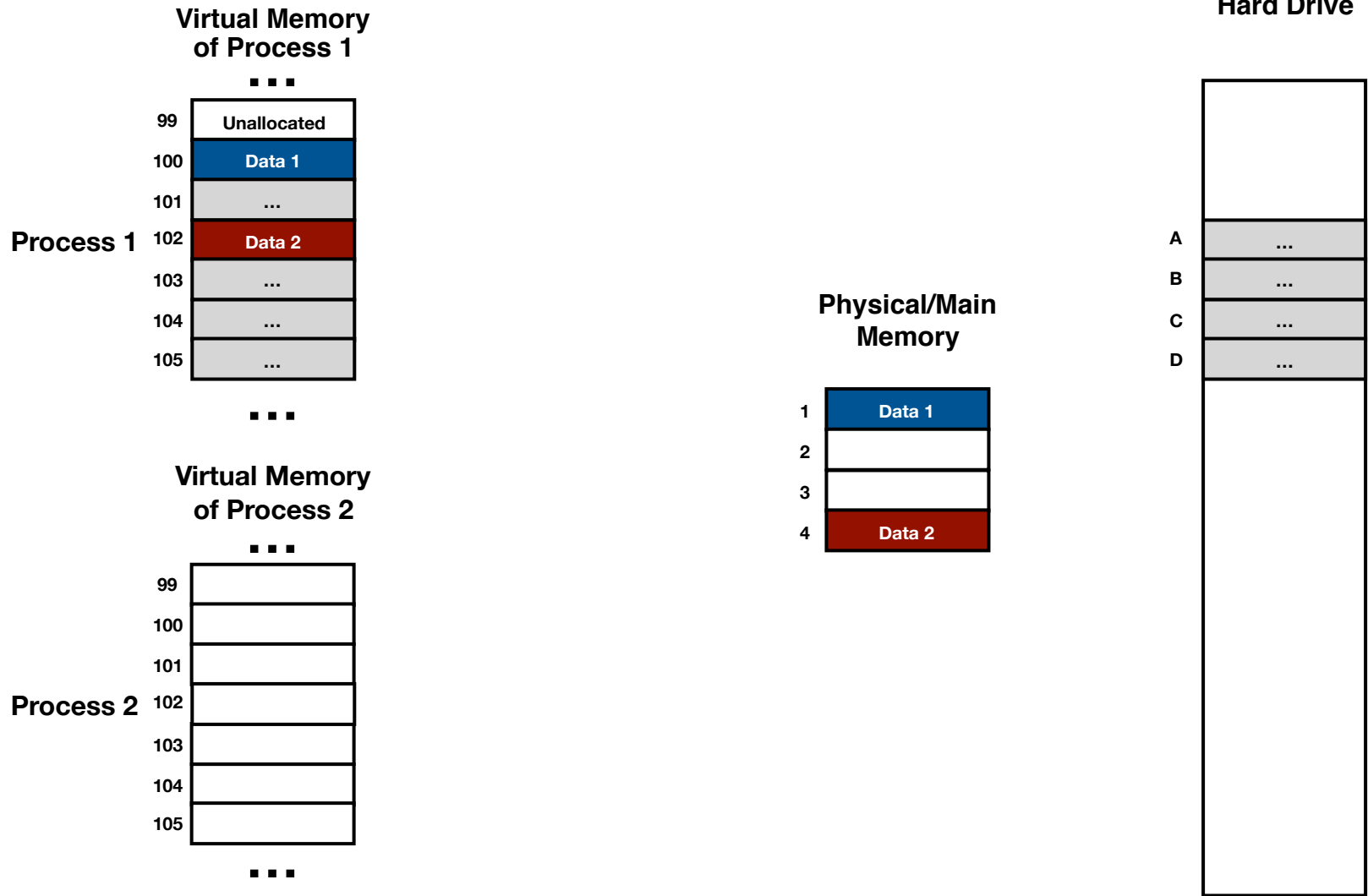
- Different programs/processes will share same data: files, libraries, etc.
- No need to have separate copies in the physical memory.
- Would be good to let other processes access part of the current's process' memory based on the "permission".



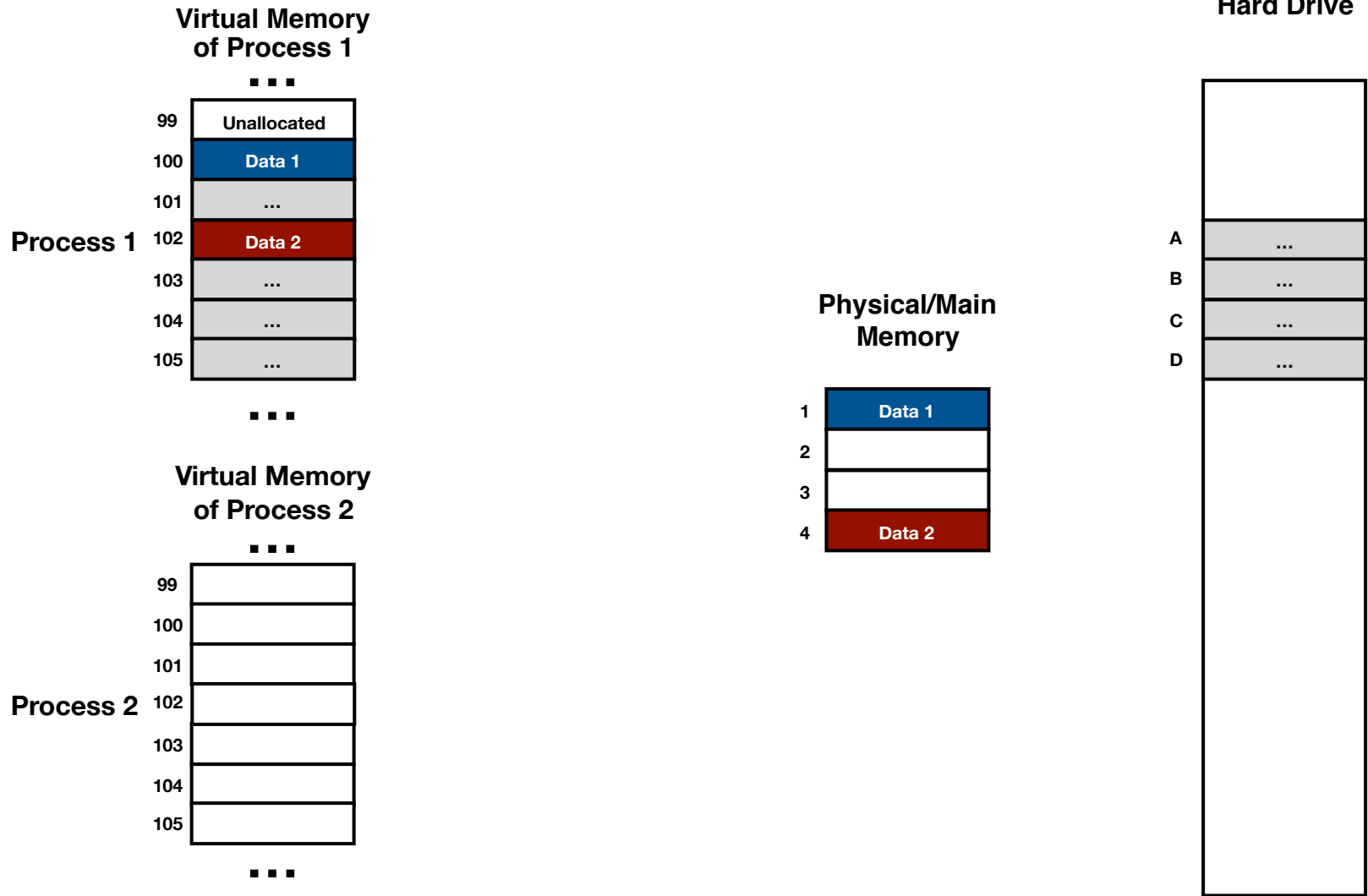
The Big Idea: Virtual Memory



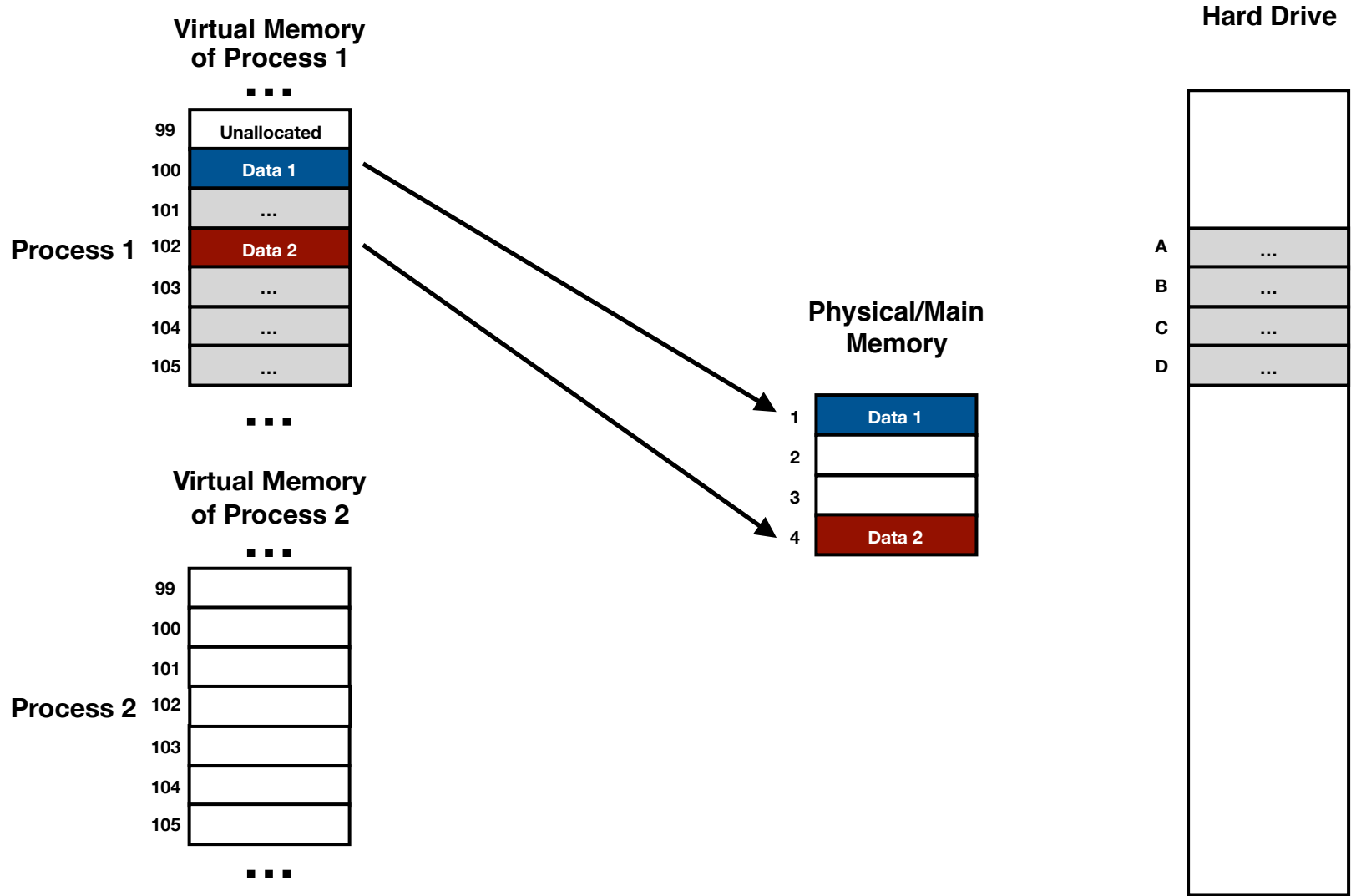
“Cache” Data in Physical Memory



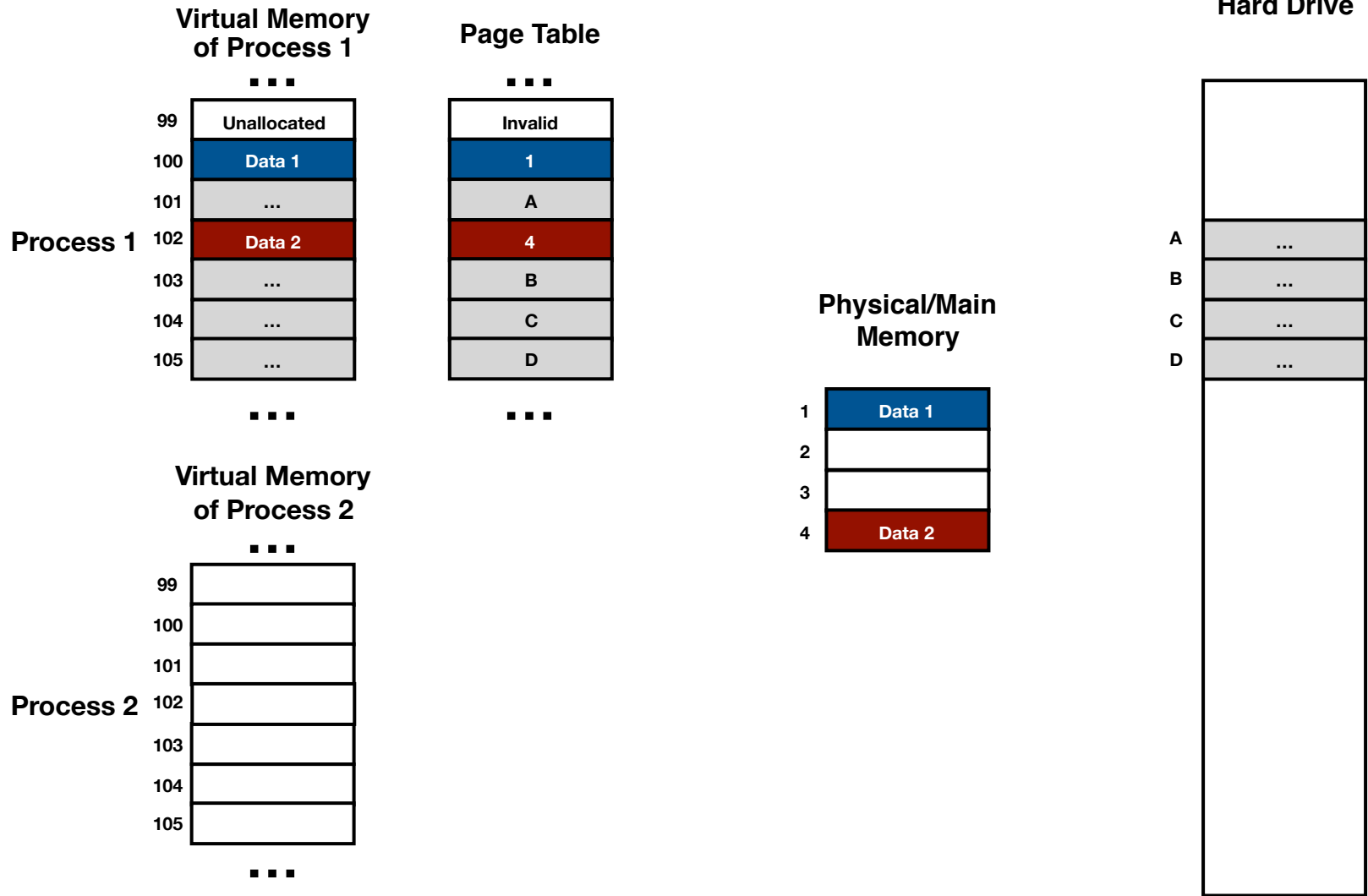
Allow Using Discontinuous Allocation



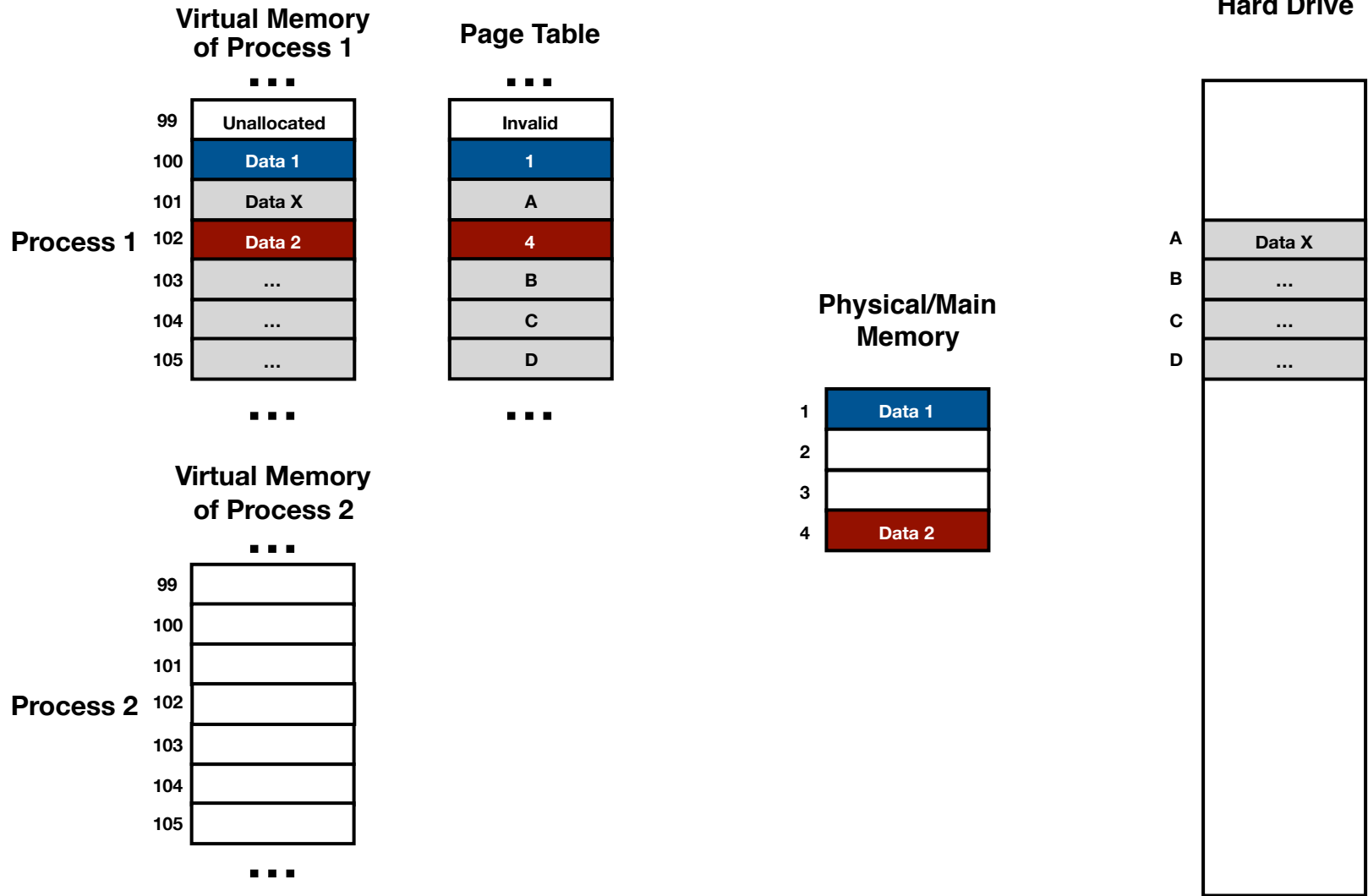
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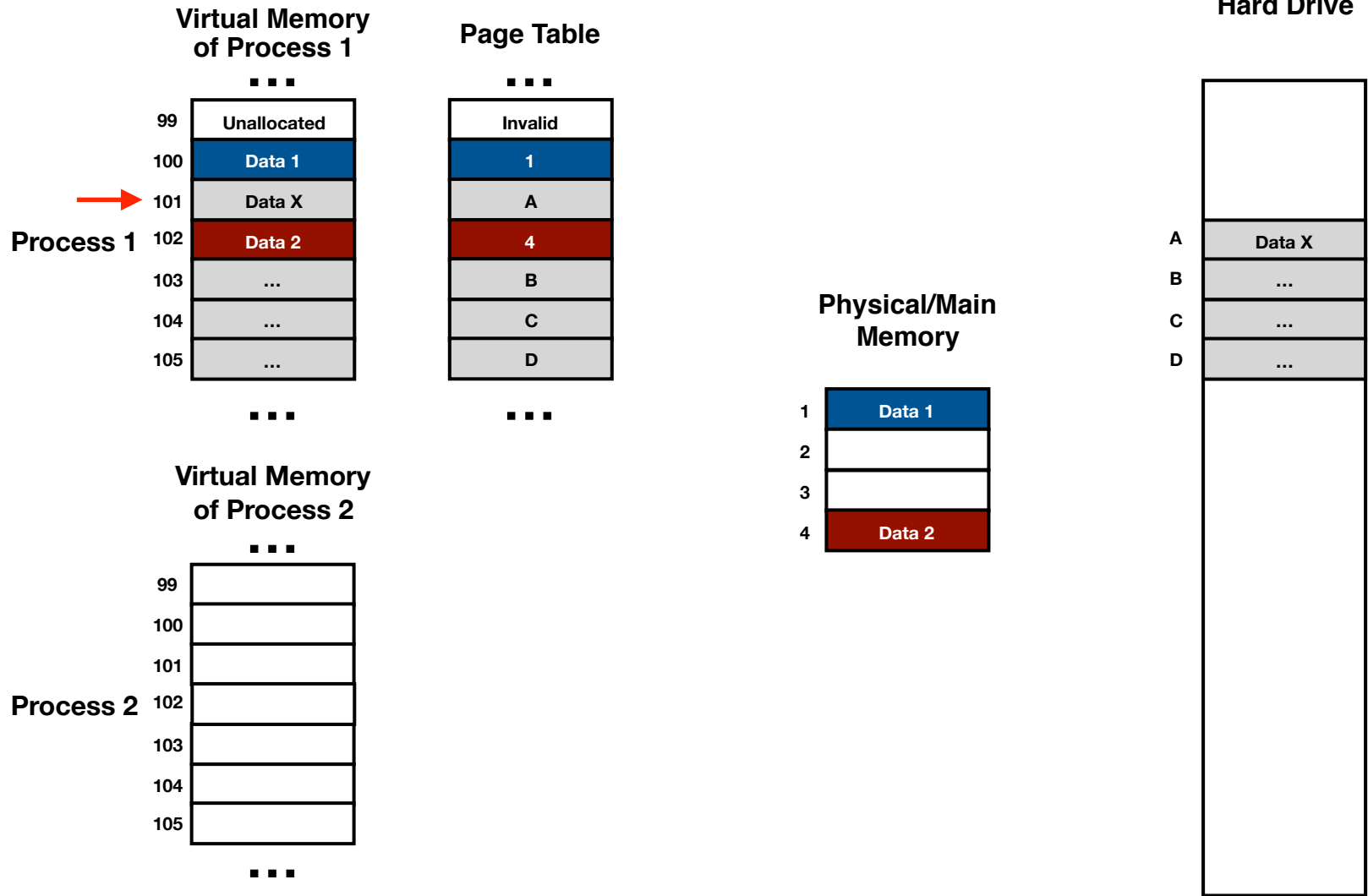
Page Table



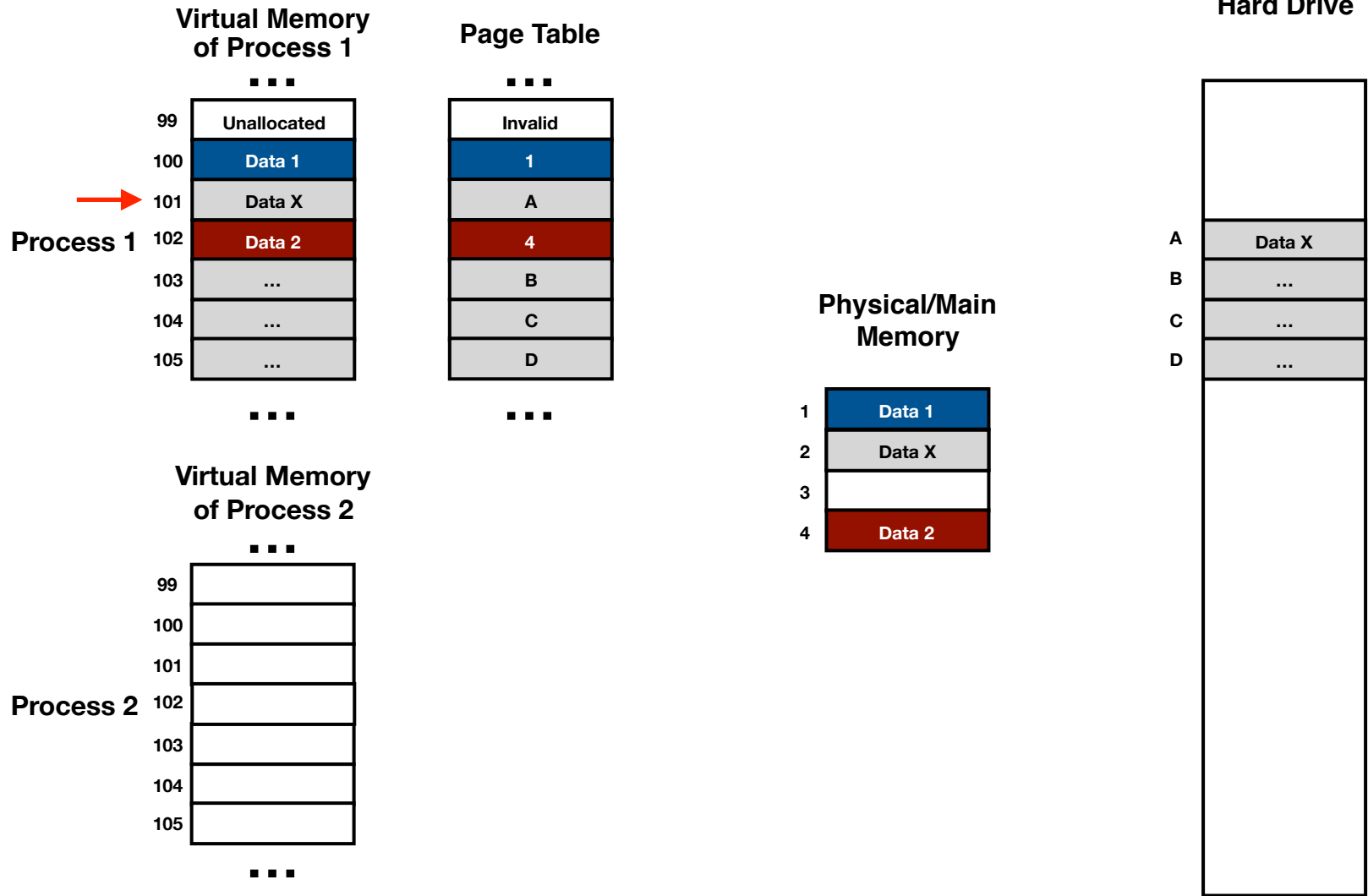
Demand Paging



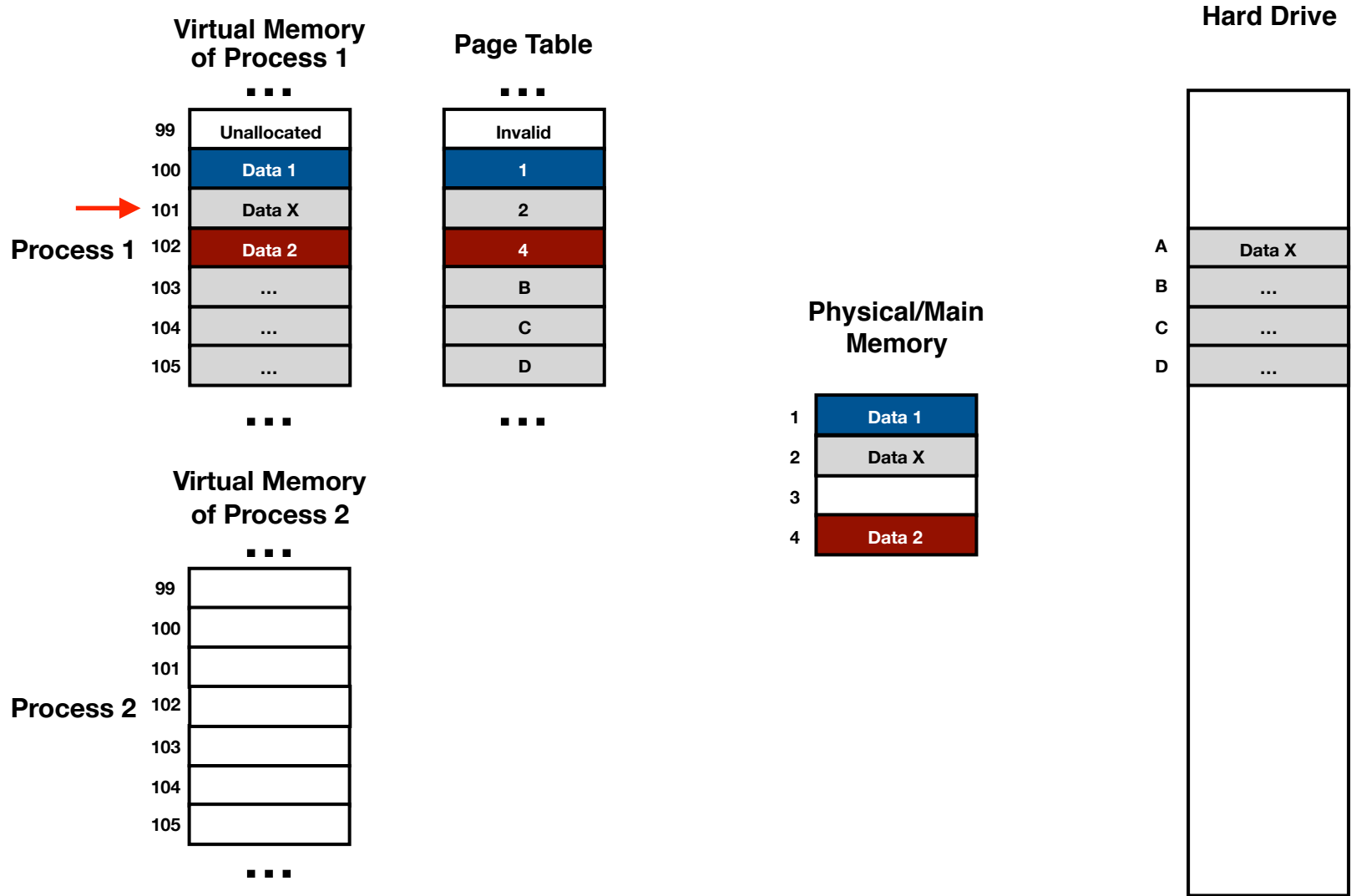
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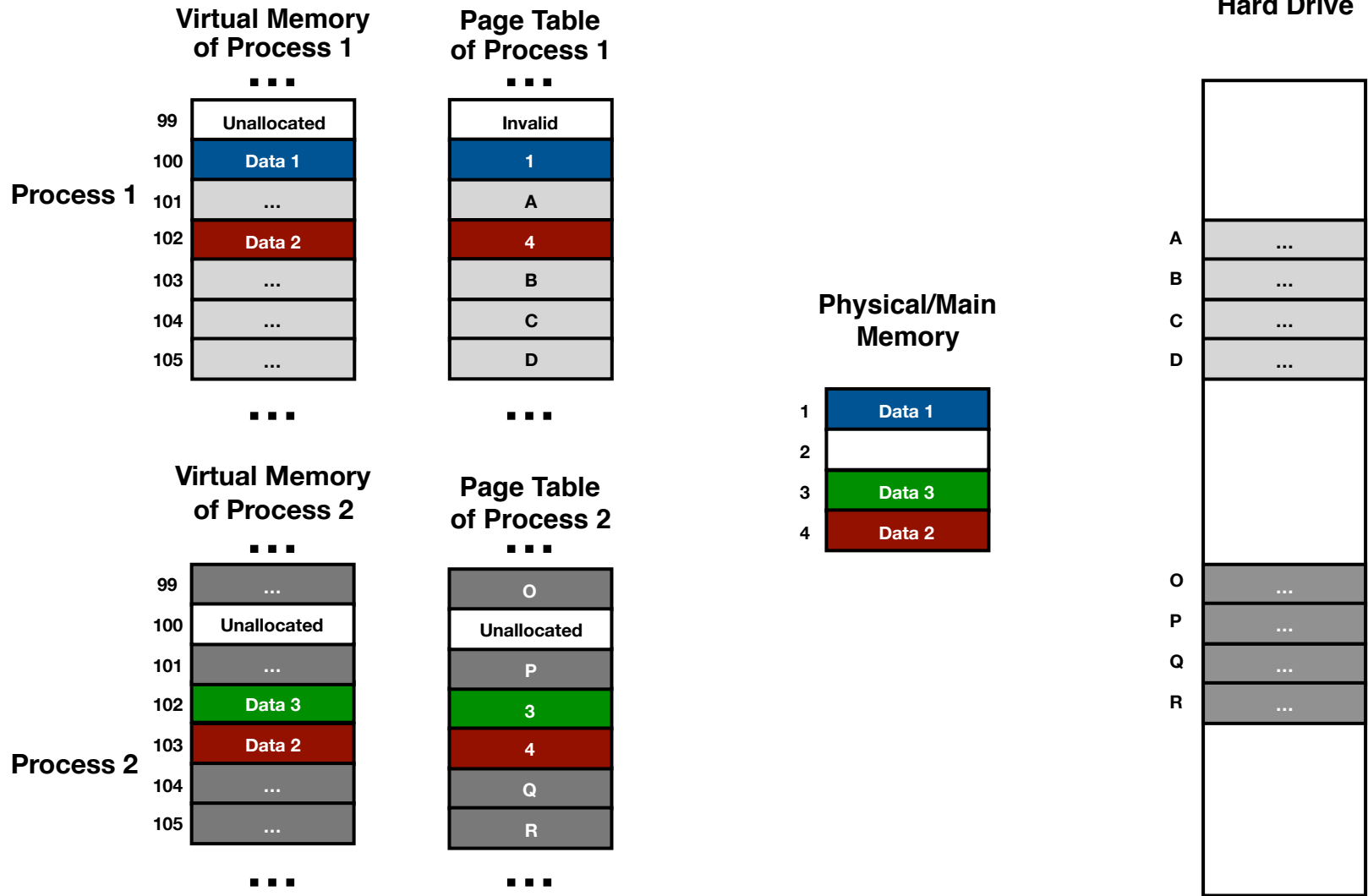
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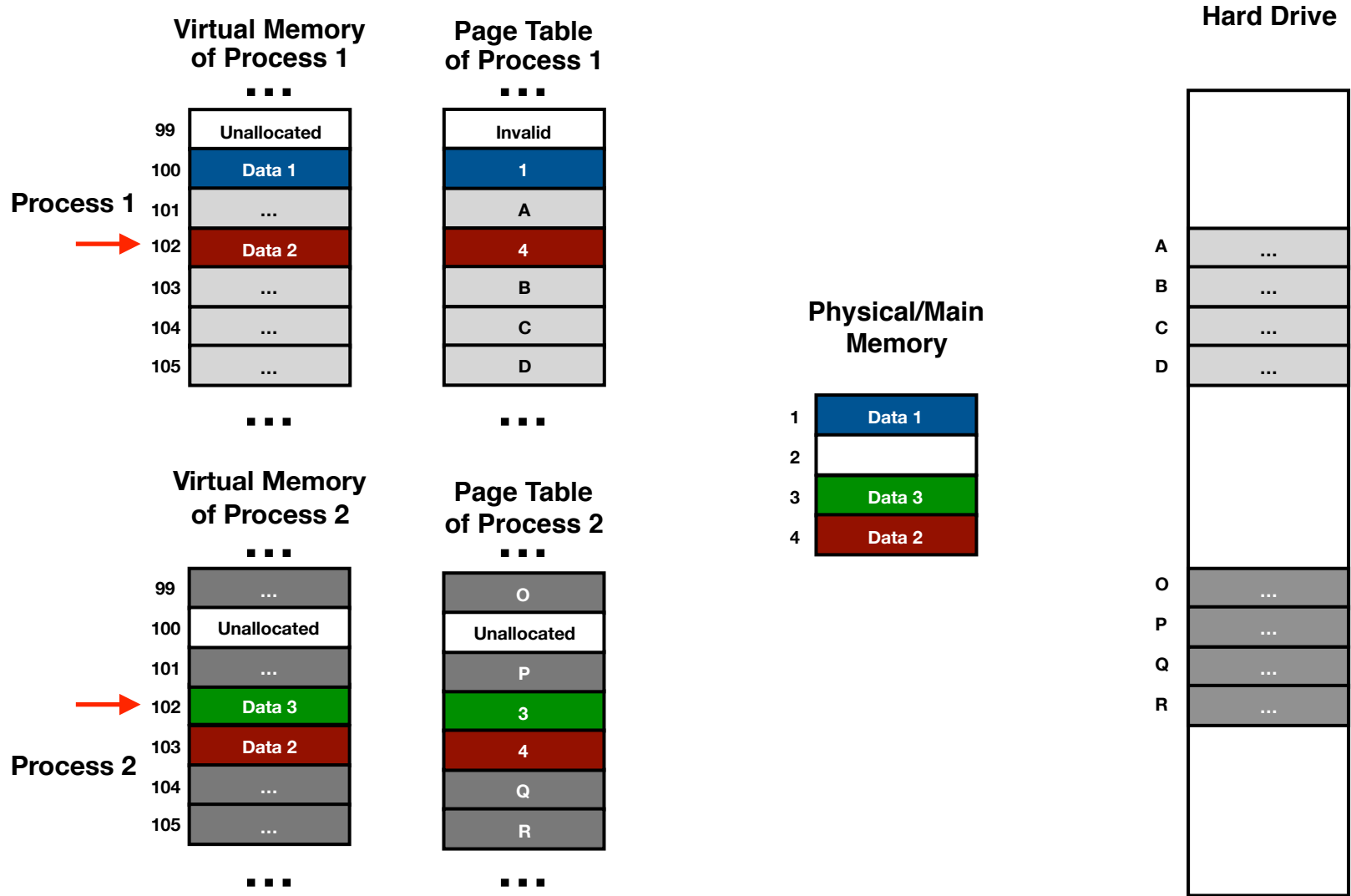
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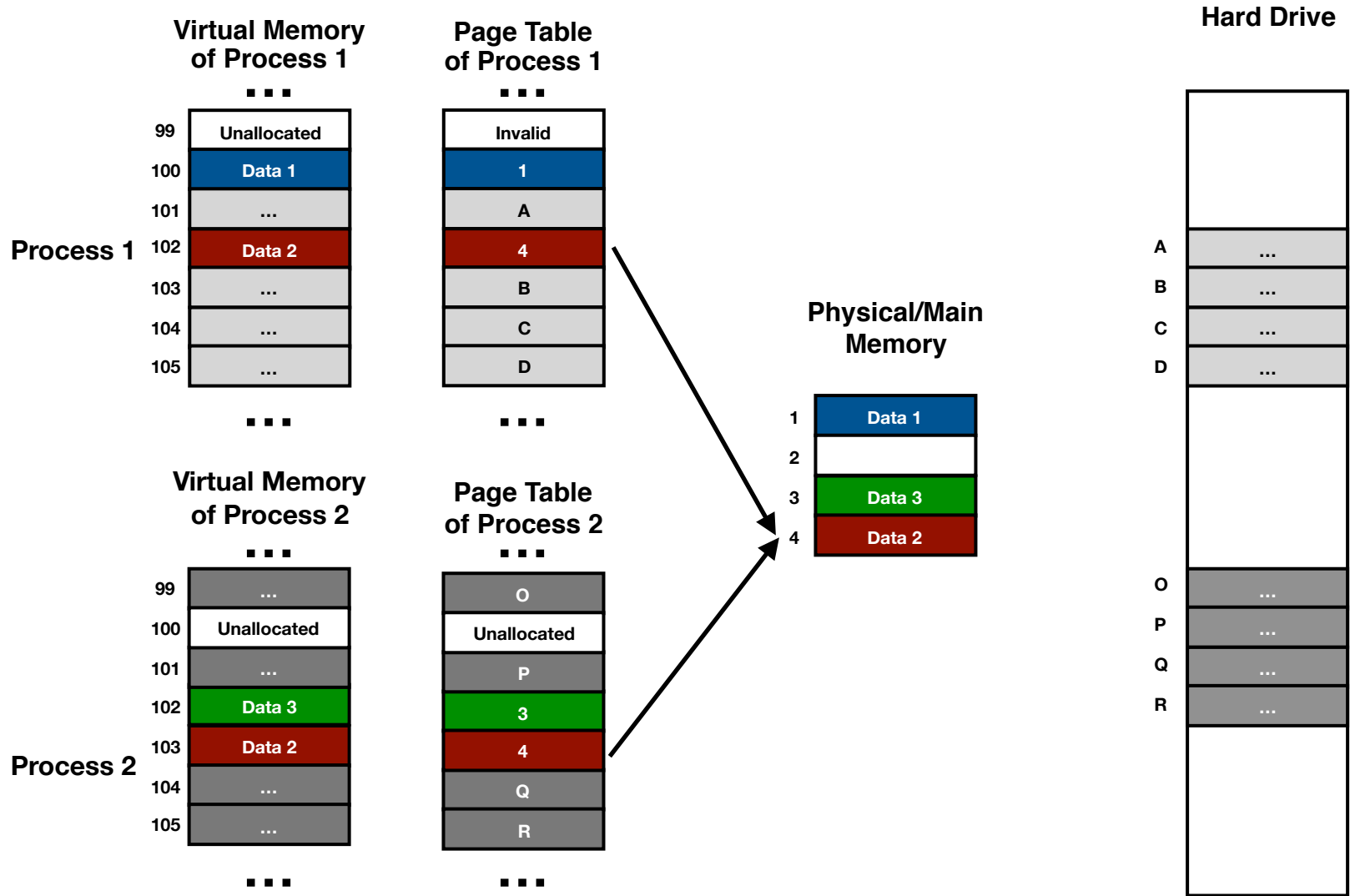
Prevent Unwanted Sharing



Prevent Unwanted Sharing



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!

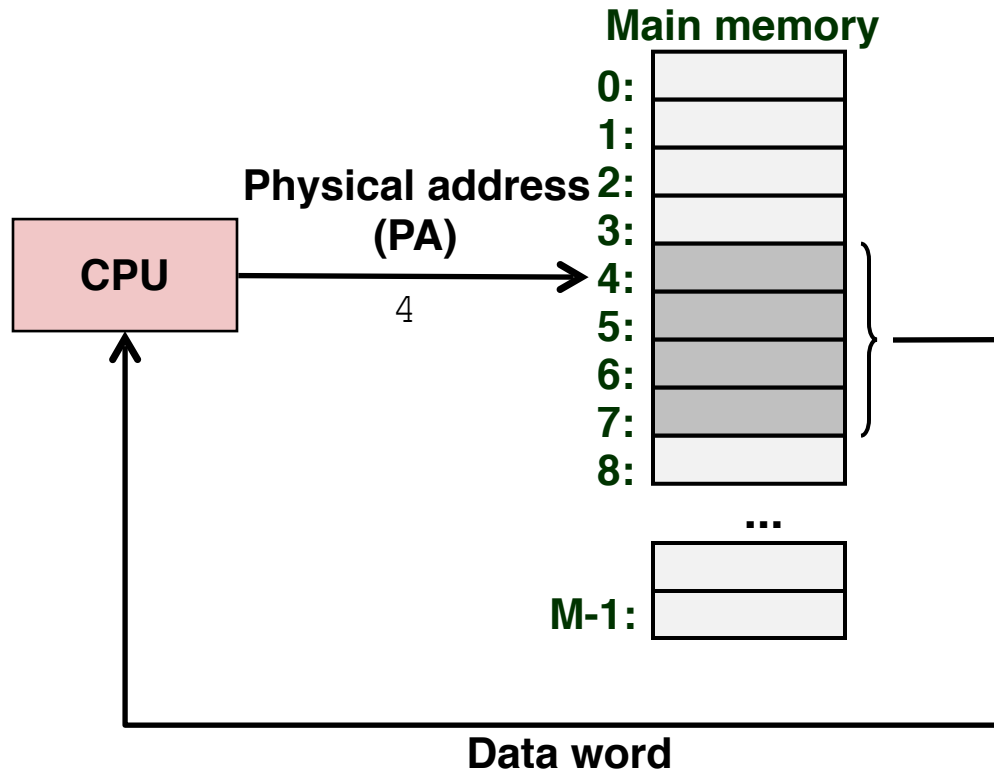


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- **Benefits**
 - **Ease of management:** Guest could change rooms (physical address). You can still find her without knowing it
 - **Protection:** Guest could have block on calls, block on calls from specific callers (permissions)
 - **Sharing:**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

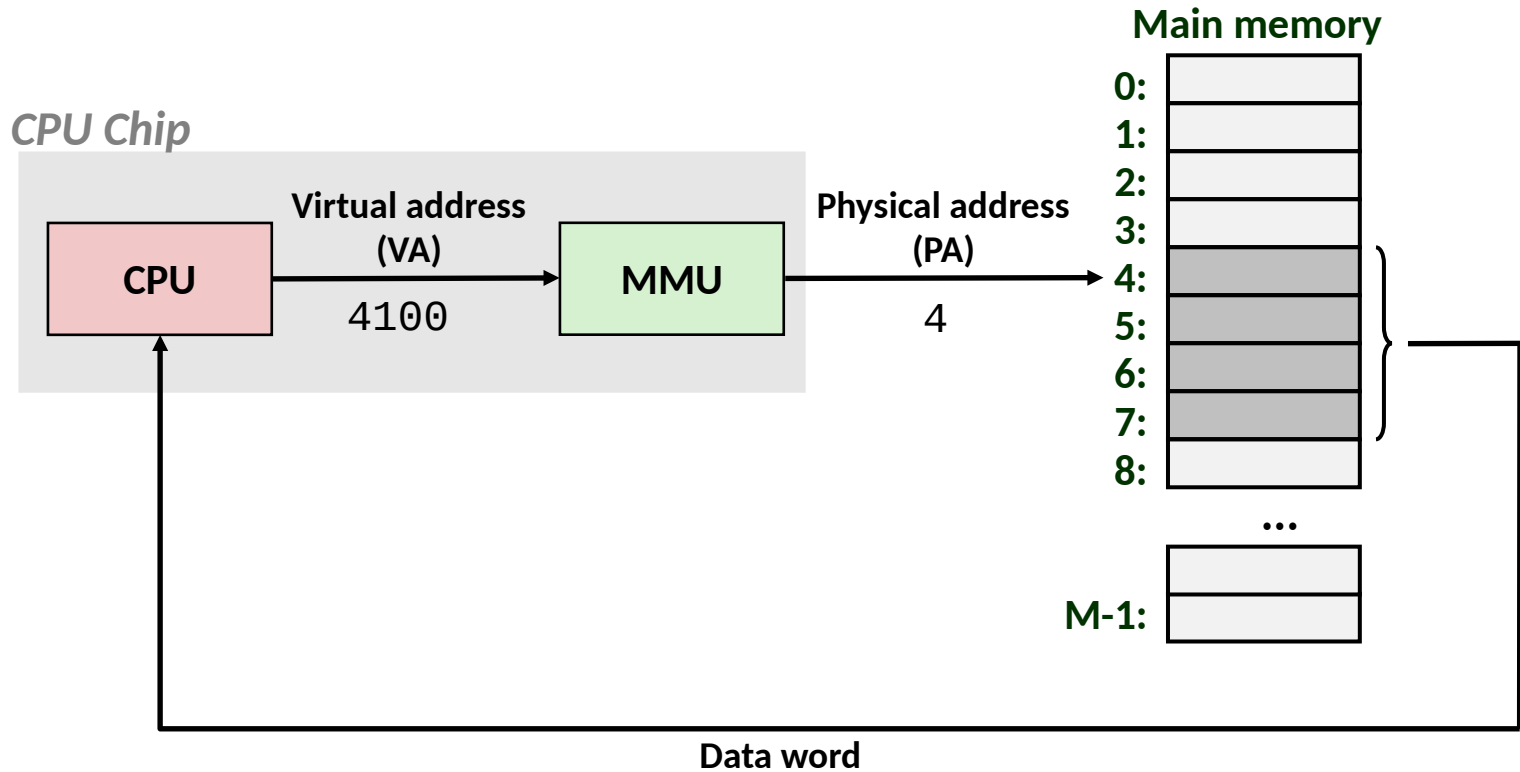


A System Using Physical Memory Only



- 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)

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- What Does a Programmer Want?
 - Infinitely large, infinitely fast memory
 - Strong isolation between processes to prevent unwanted sharing
 - Enable wanted sharing

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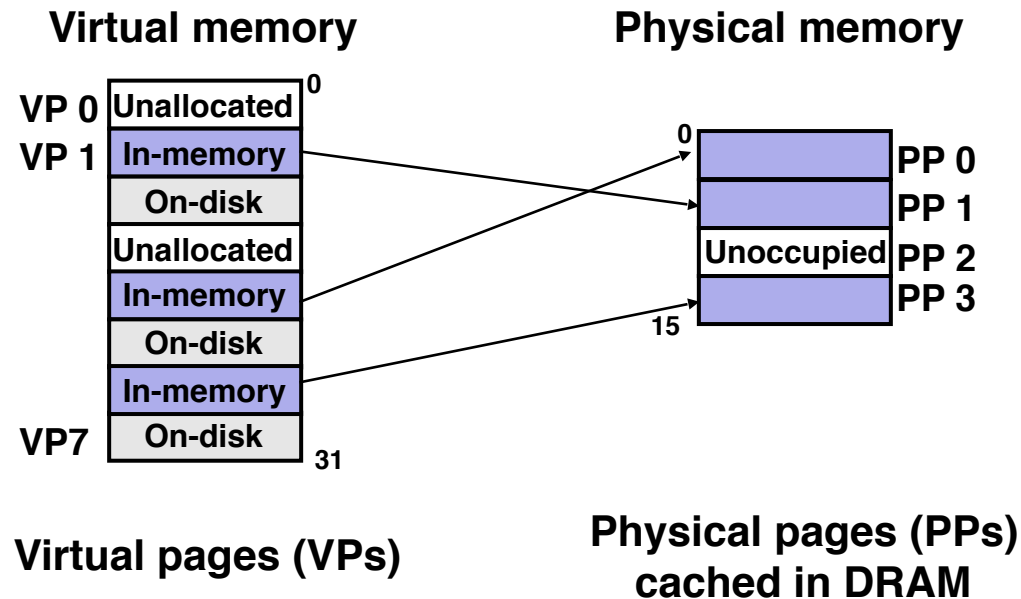
- What Does a Programmer Want?
 - Infinitely large, infinitely fast memory
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 - Enable wanted sharing
- Virtual memory to the rescue
 - Present a large, uniform memory to programmers
 - Data in virtual memory by default stays in disk
 - Data moves to 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

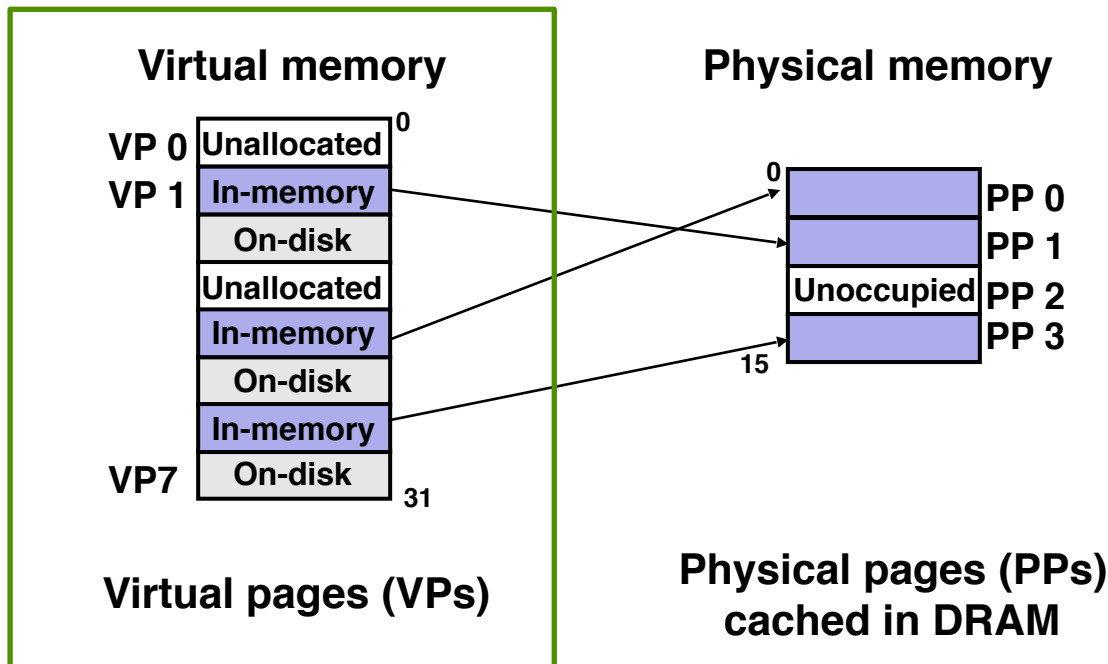
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- Physical memory is also divided into pages. Each physical page (sometimes called *frames*) has the same size as a virtual page. Physical memory has way fewer pages.
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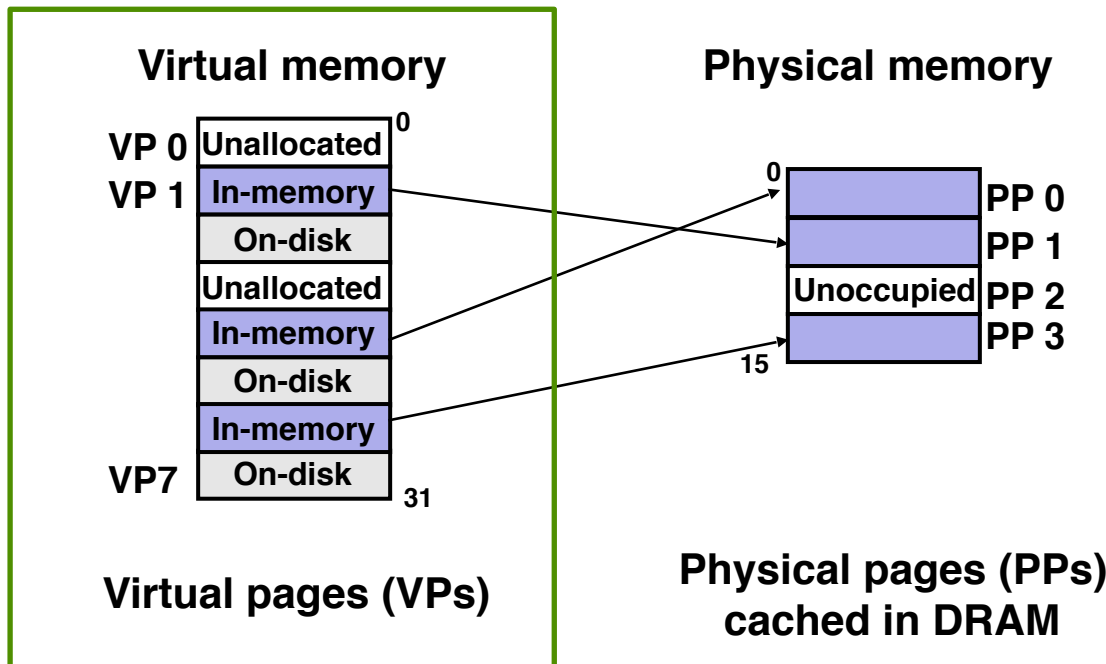
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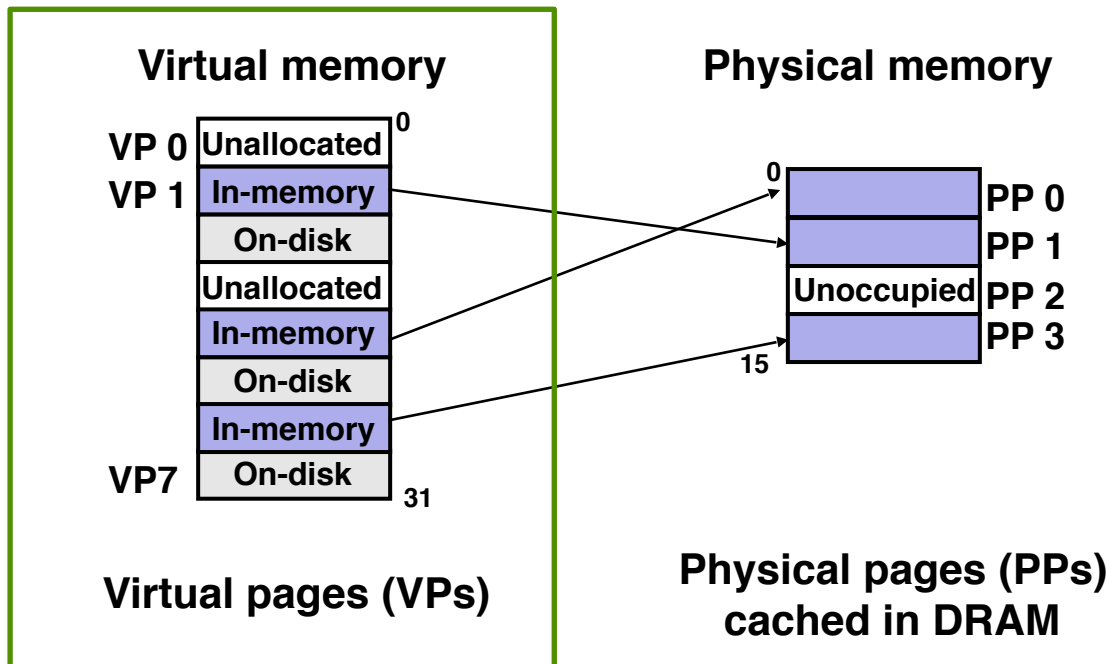


Assuming page size is 4B
Virtual memory size is 32B
Physical memory size is 16B

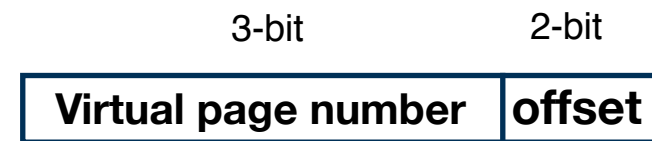
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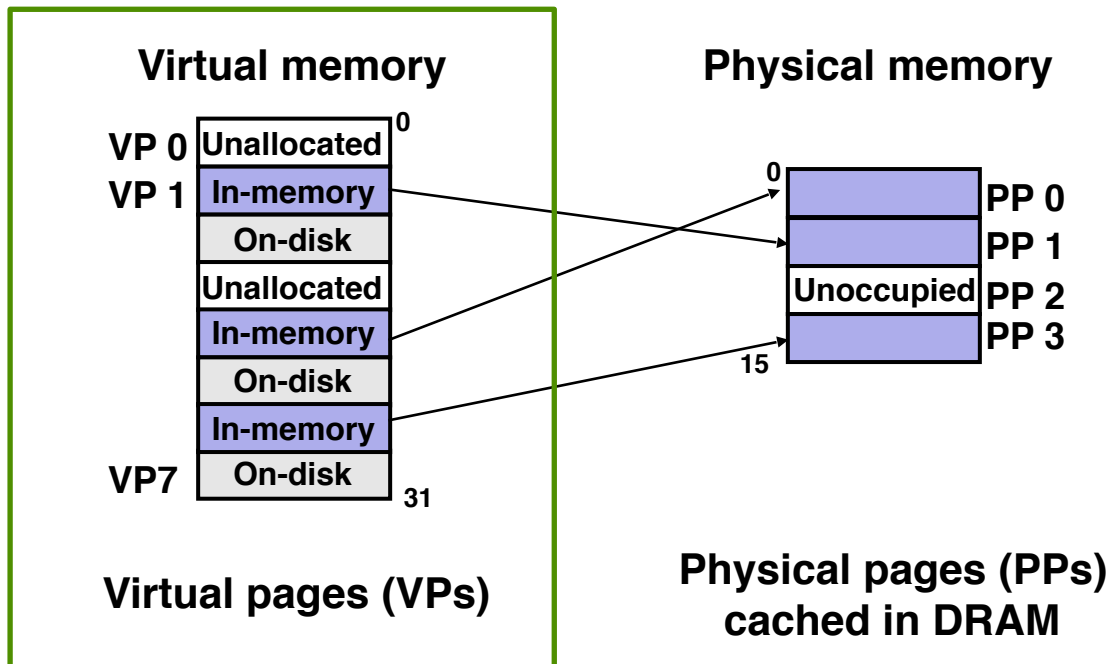
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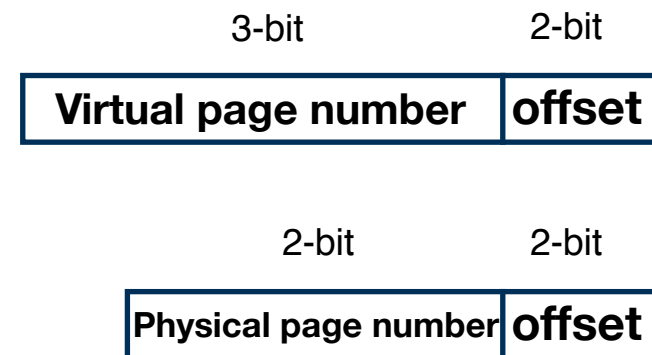
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 - Per-process data structure; managed by the OS kernel

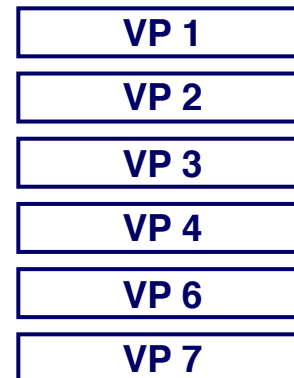
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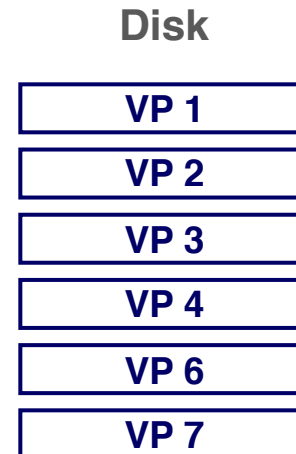
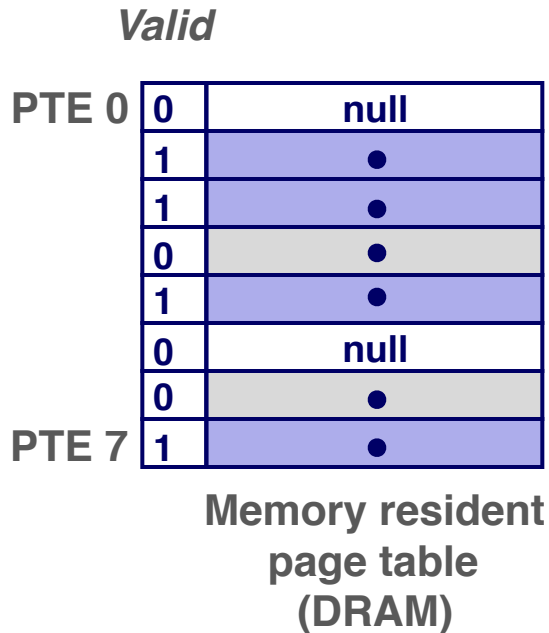
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Disk



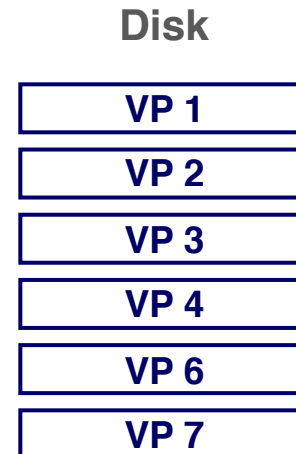
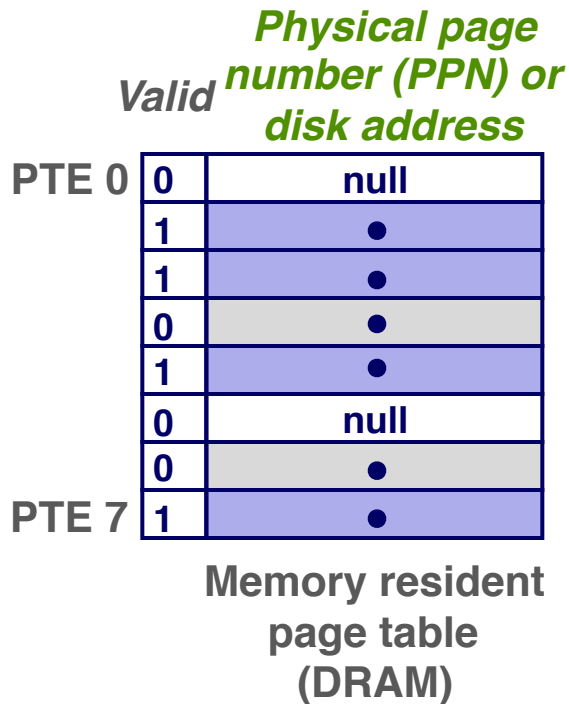
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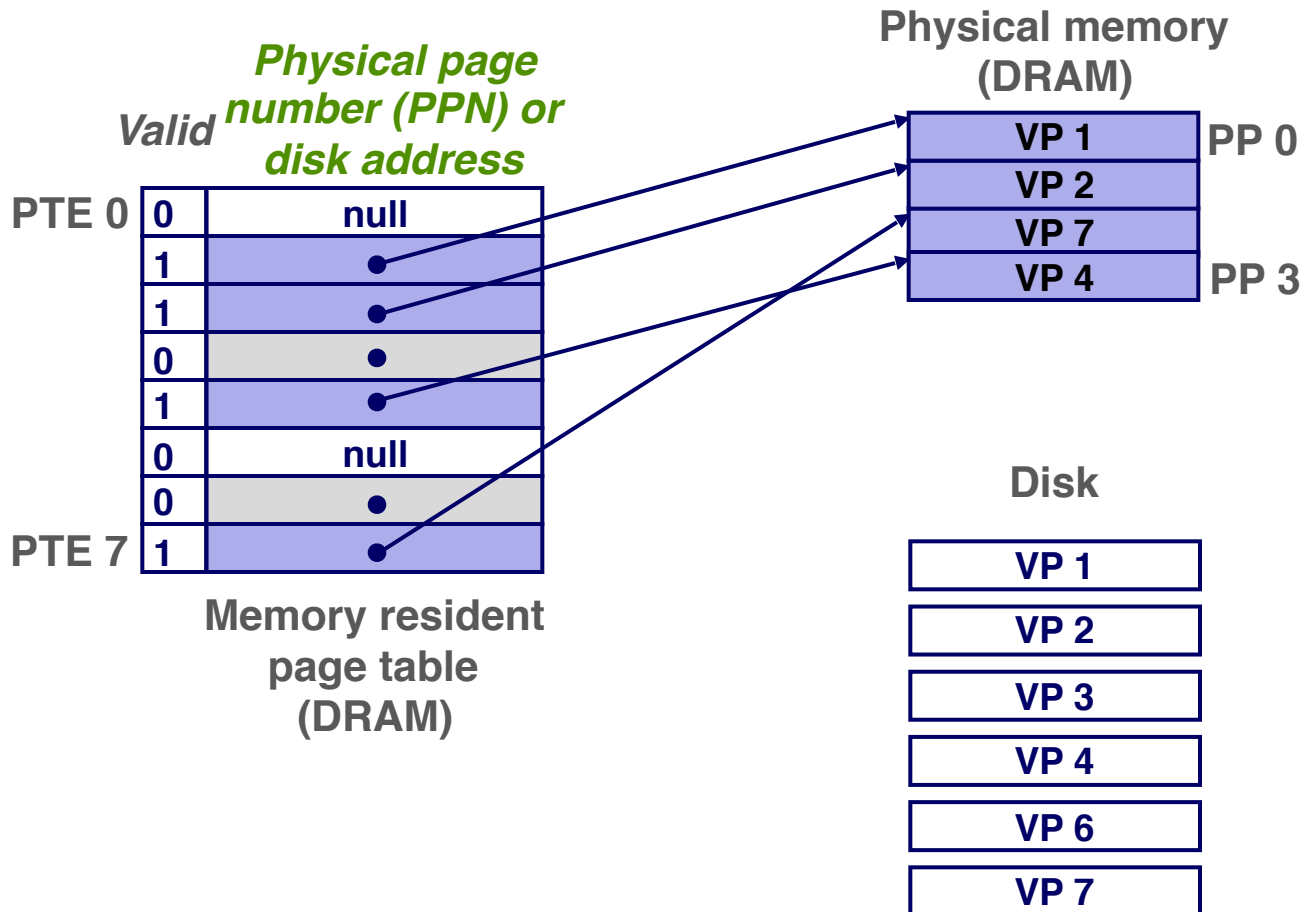
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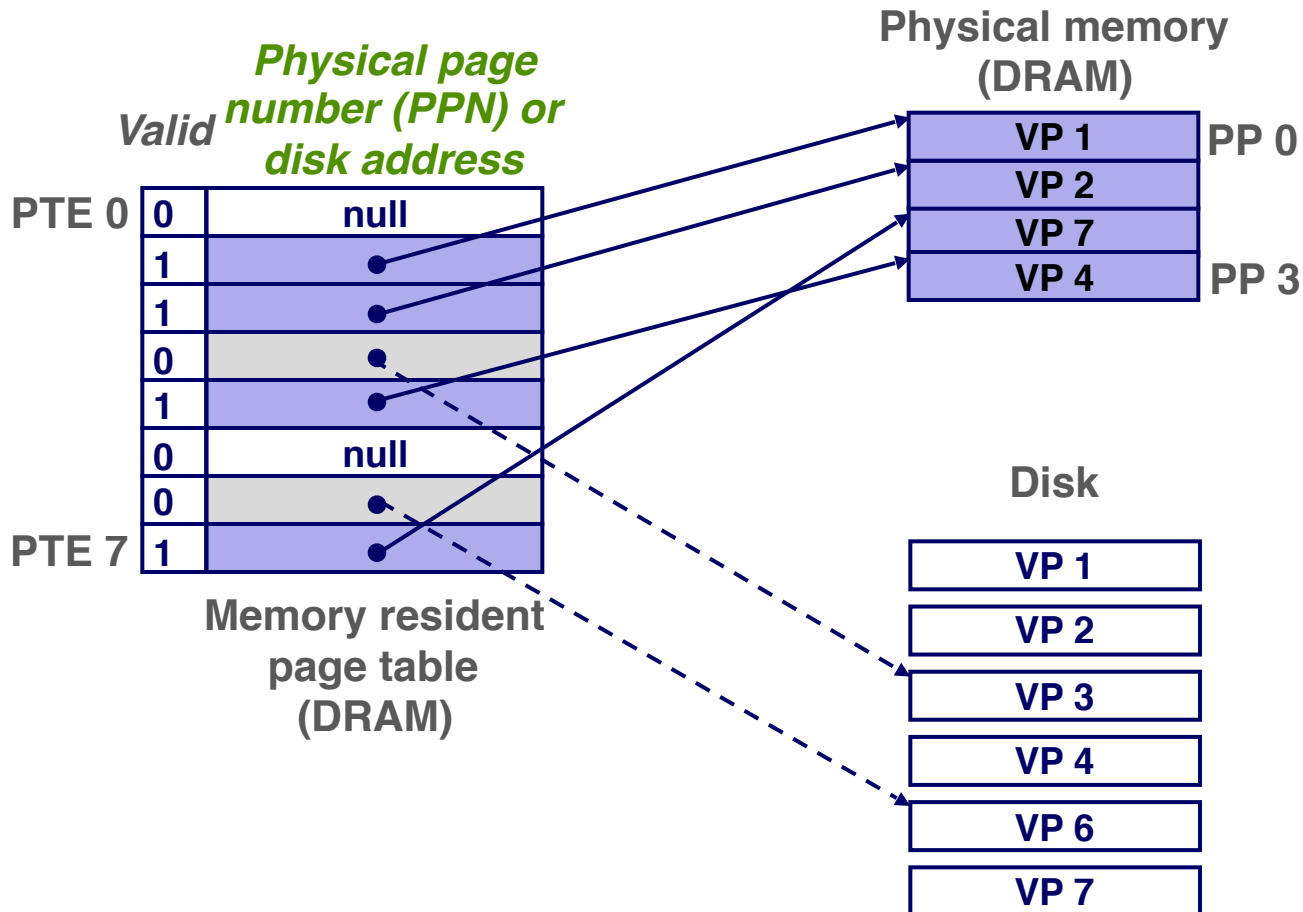
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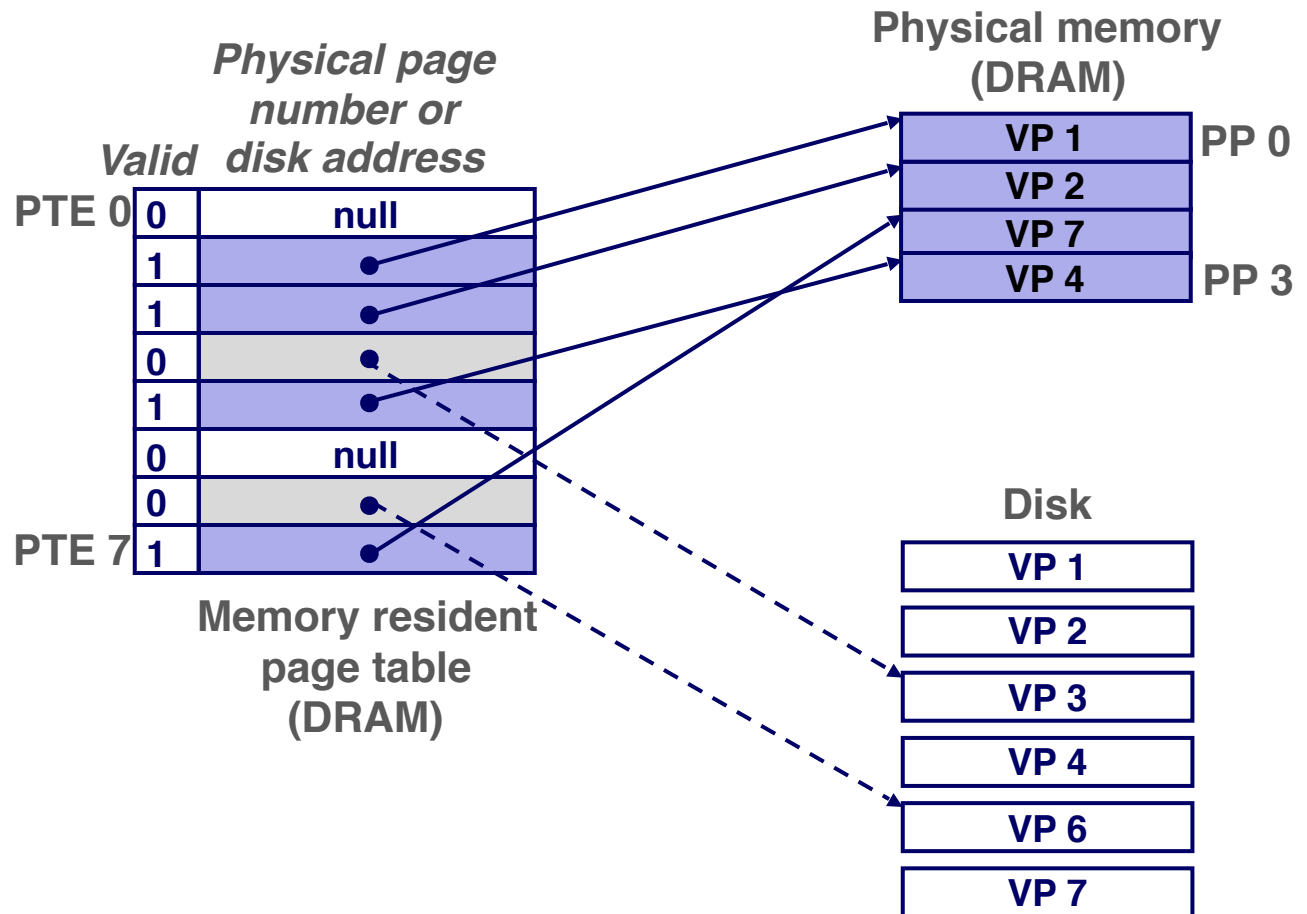
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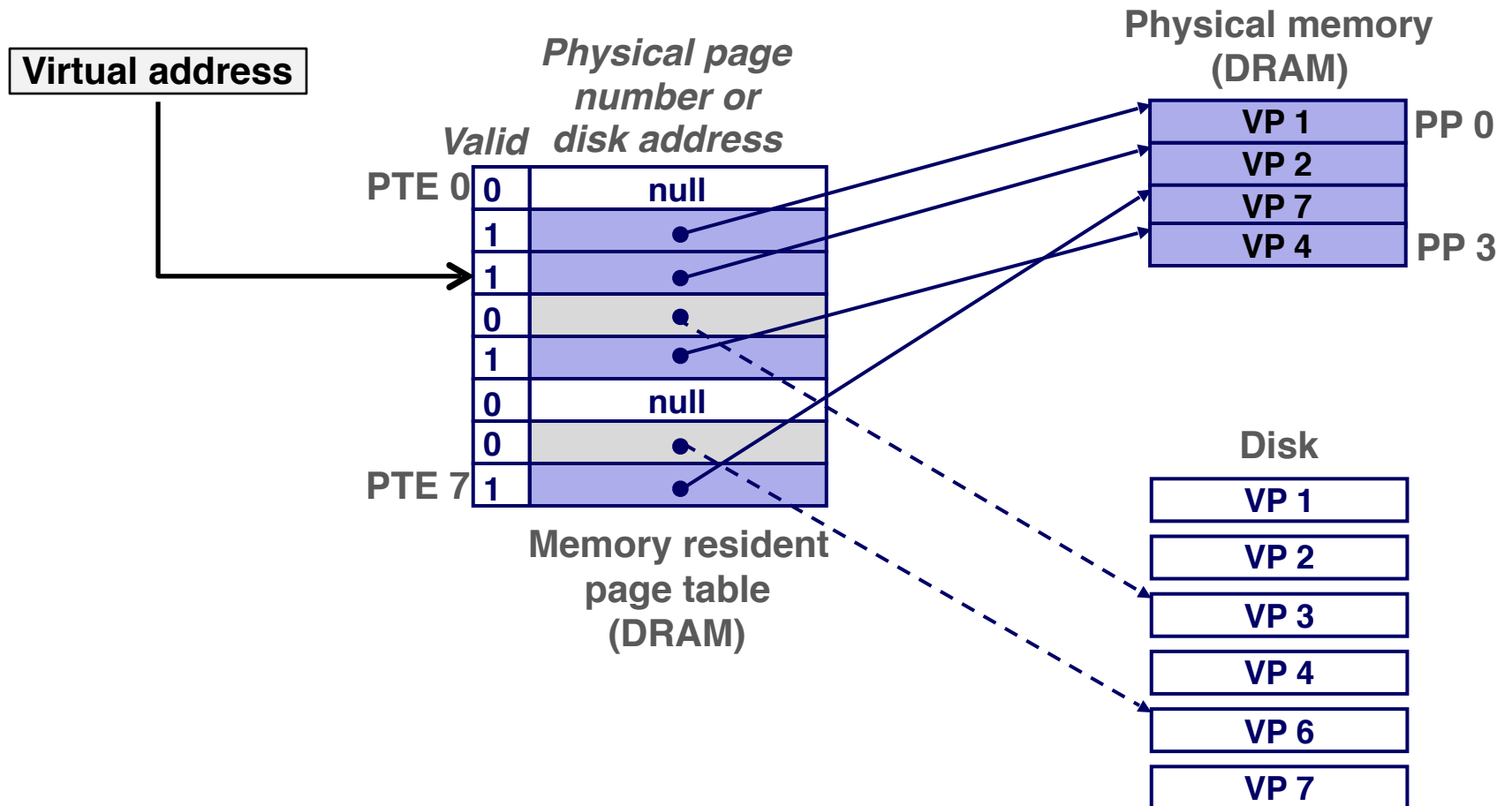
Page Hit

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



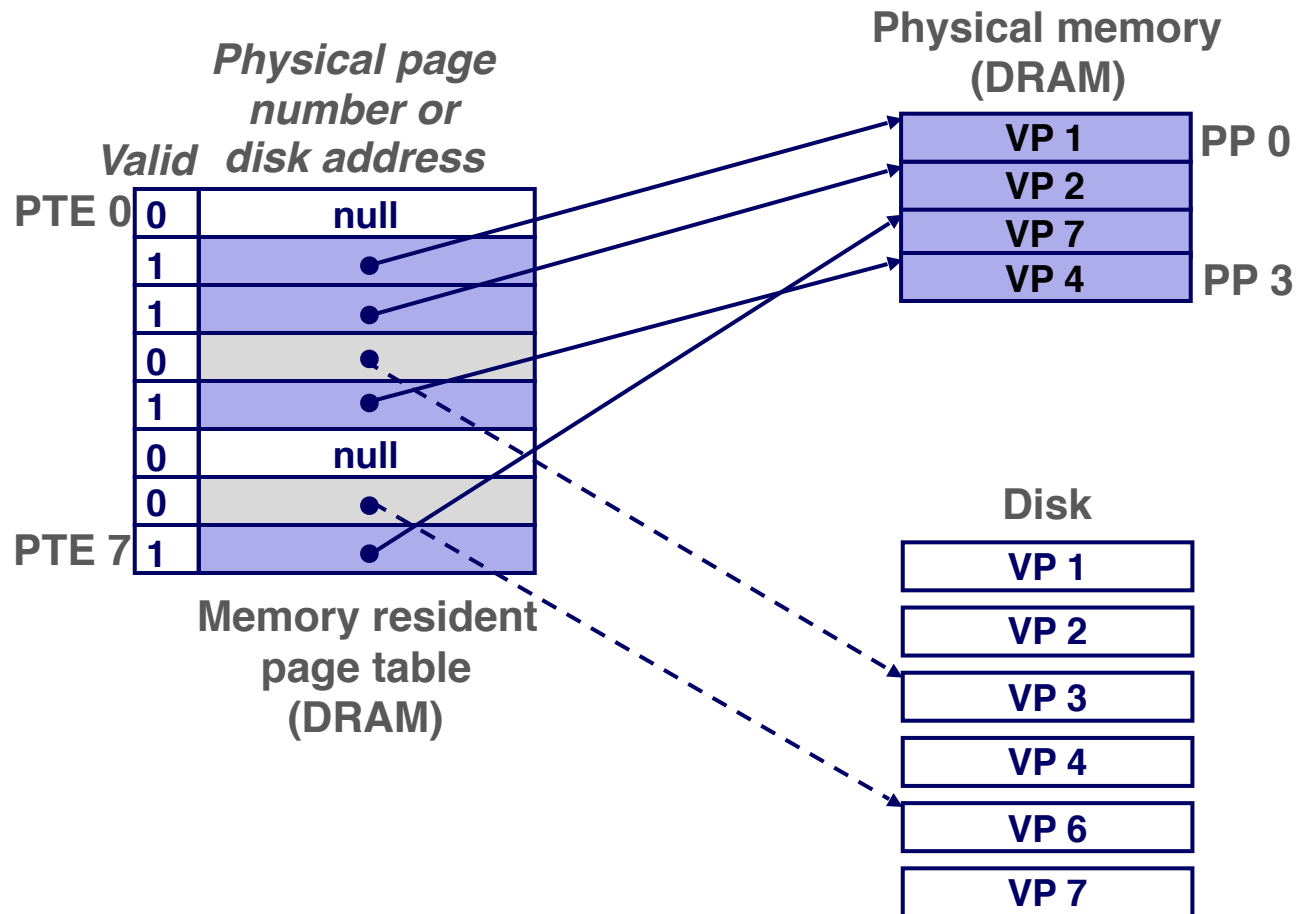
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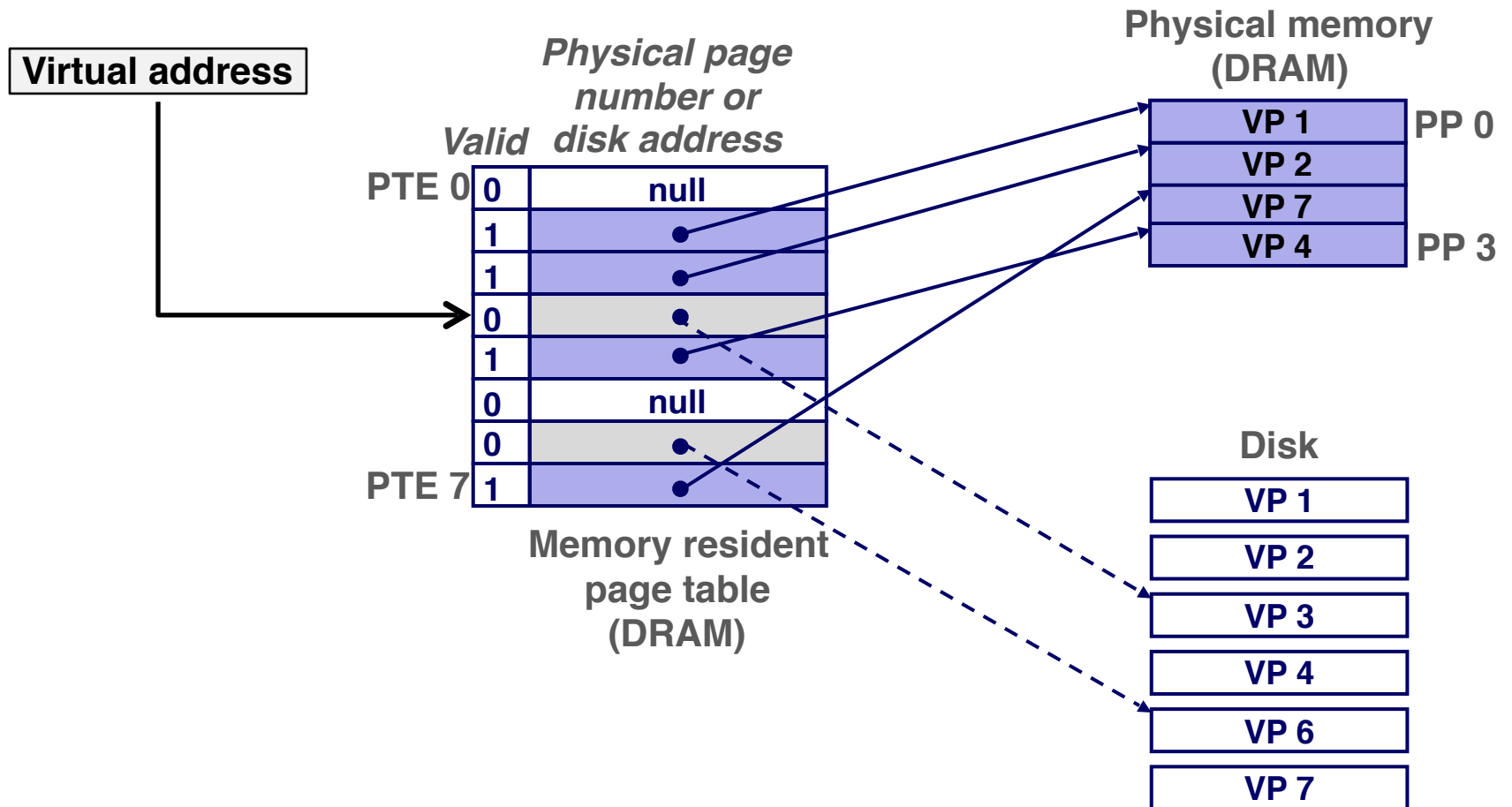
Page Fault

- *Page fault*: reference to VM word that is not in physical memory



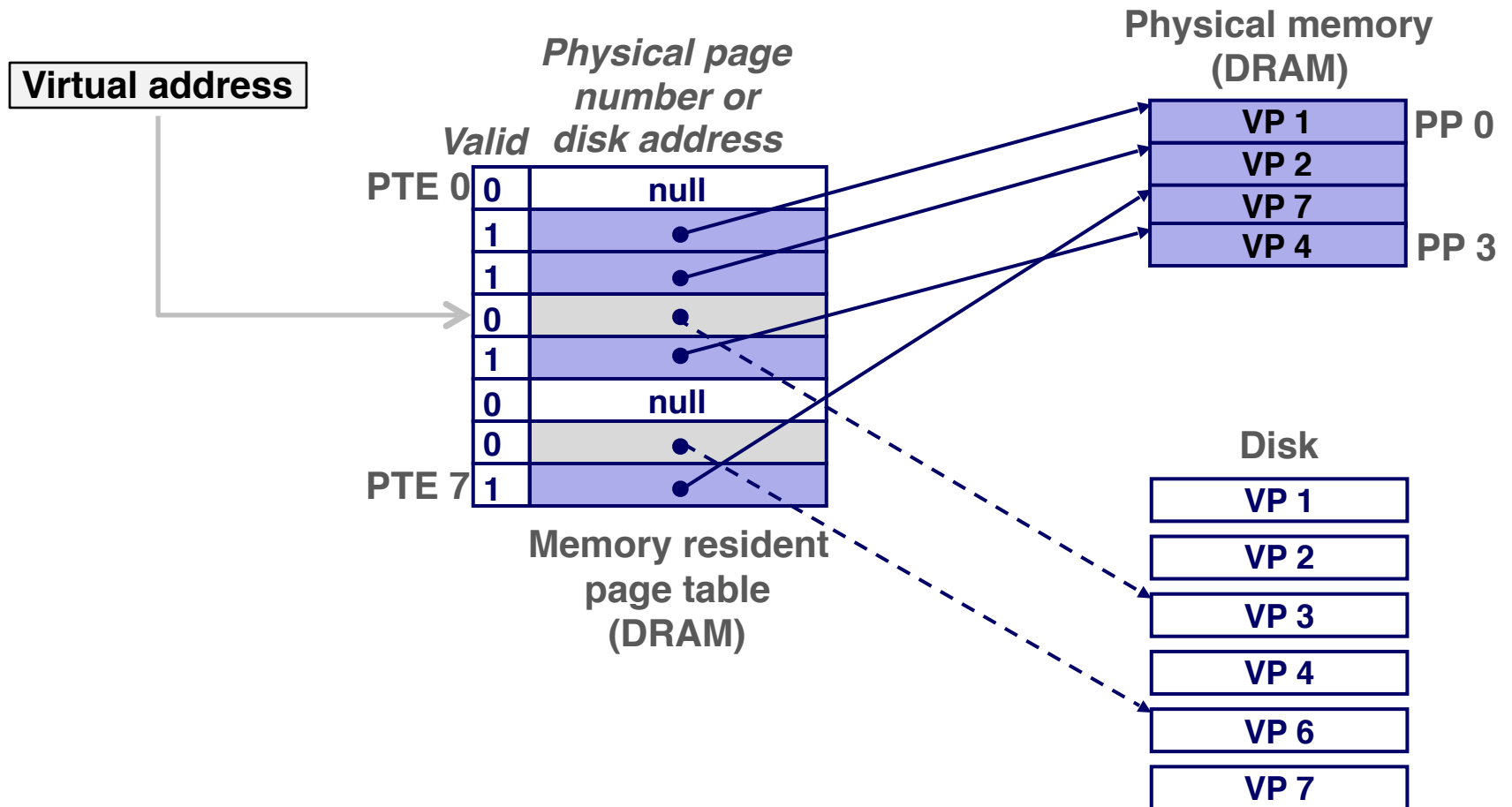
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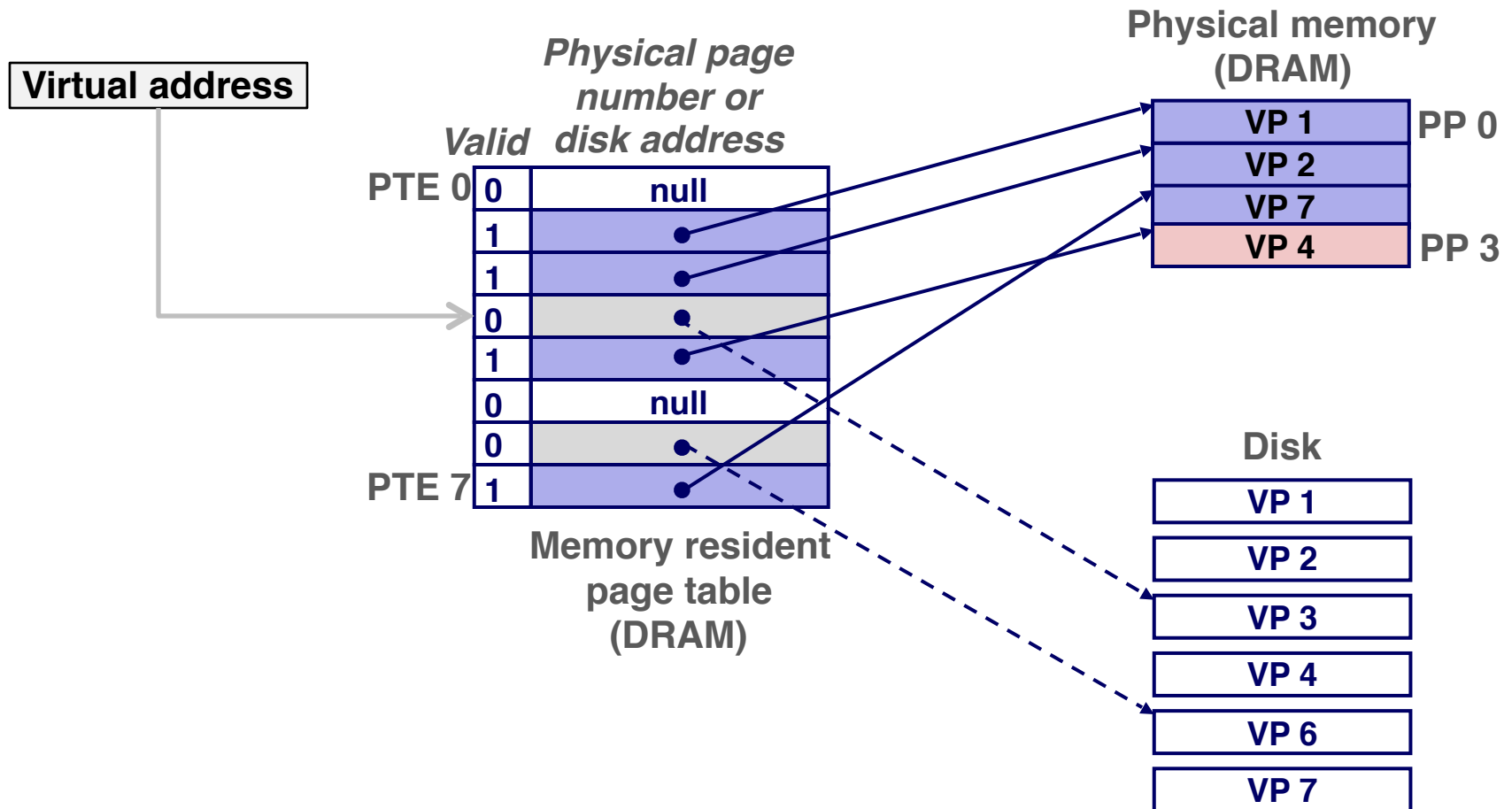
Handling Page Fault

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



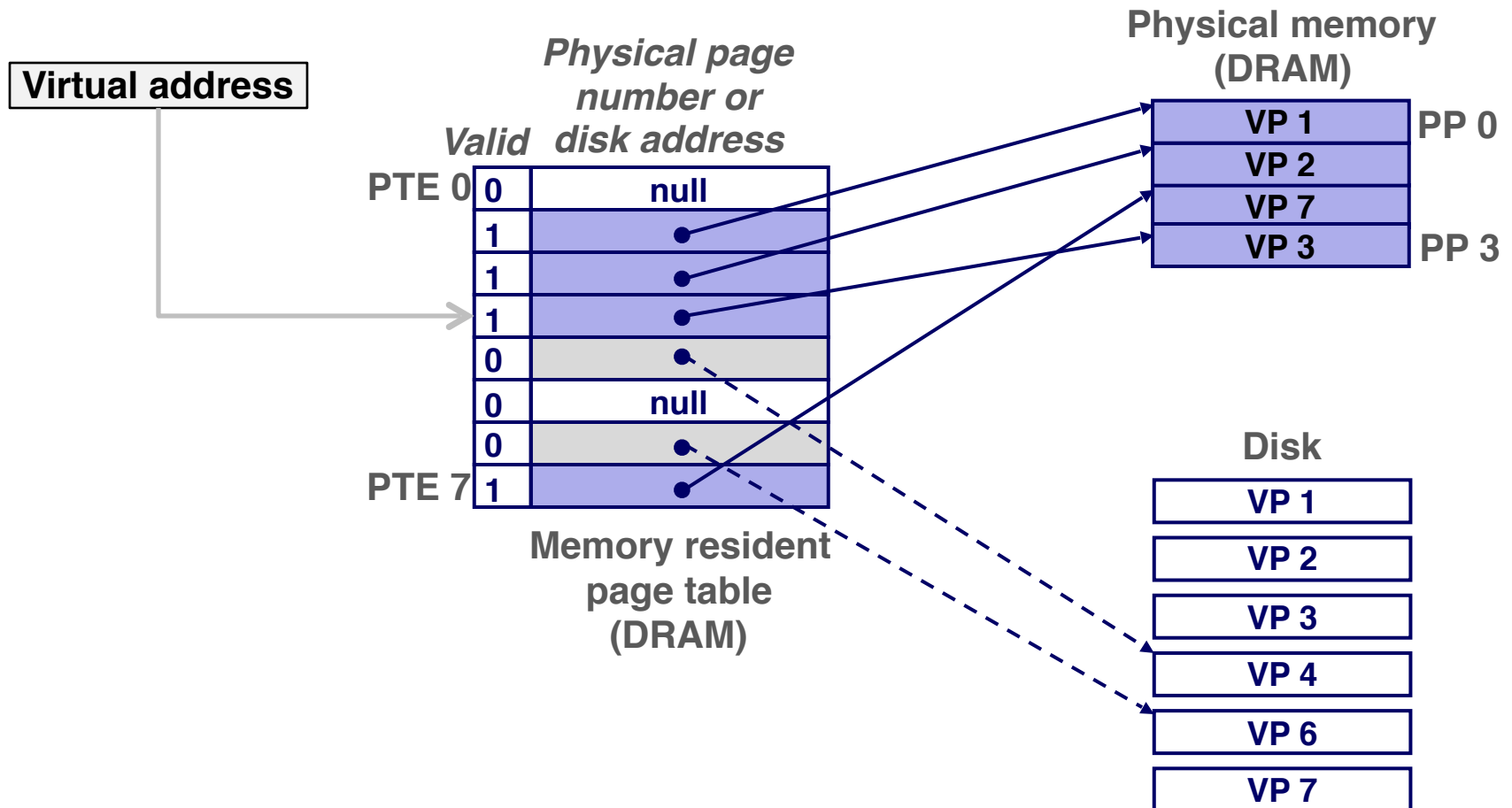
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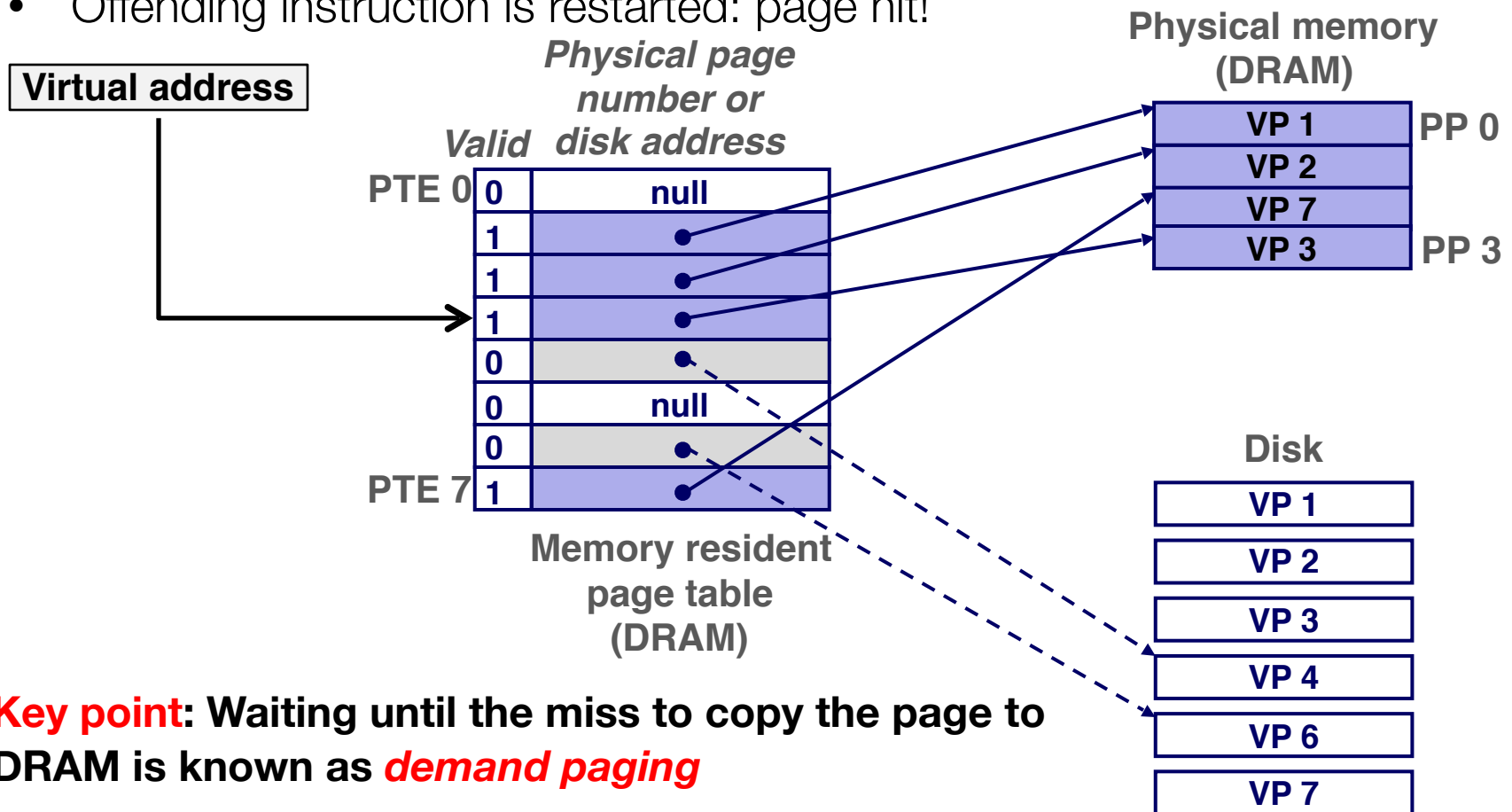
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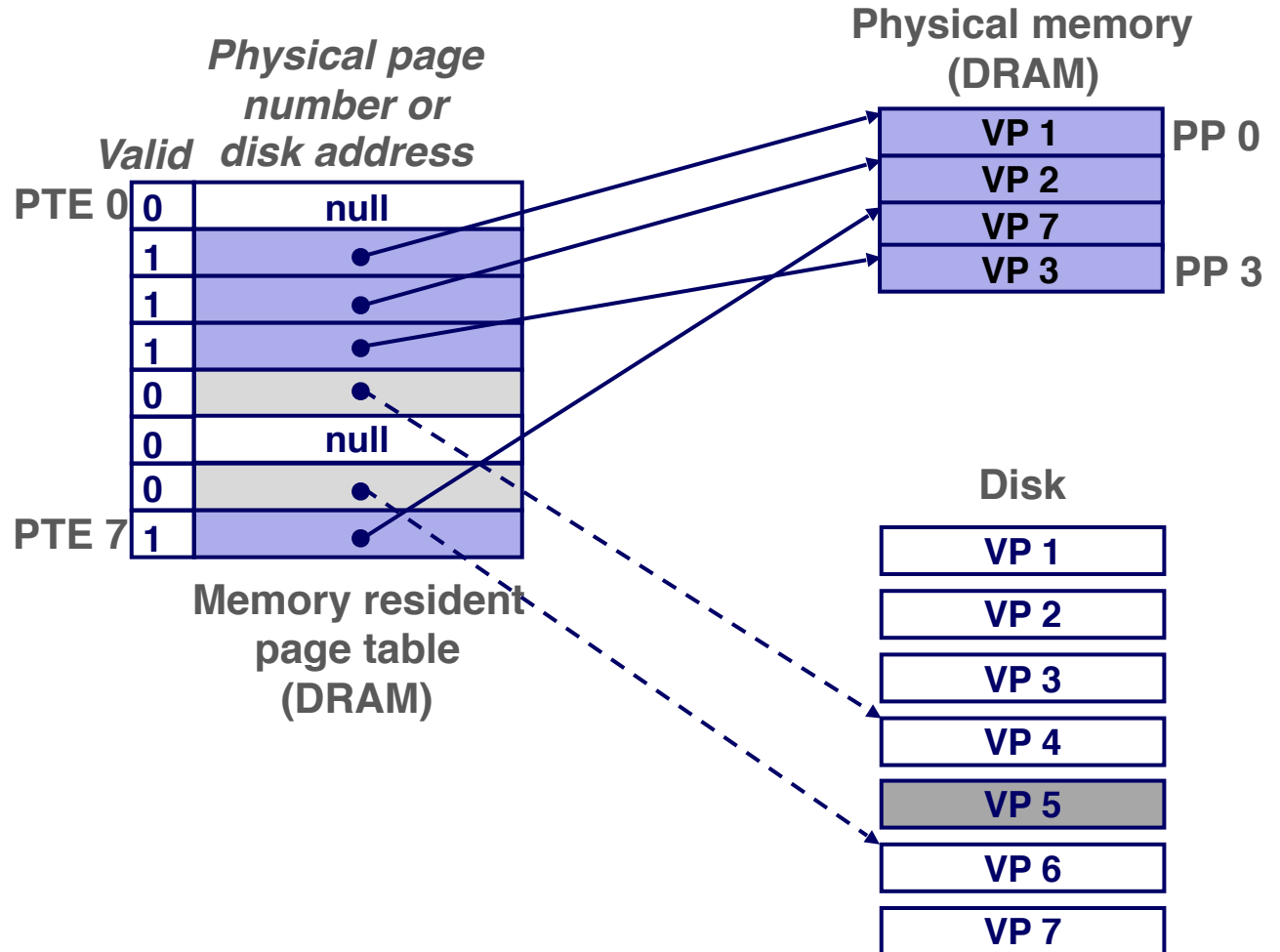
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- Offending instruction is restarted: page hit!



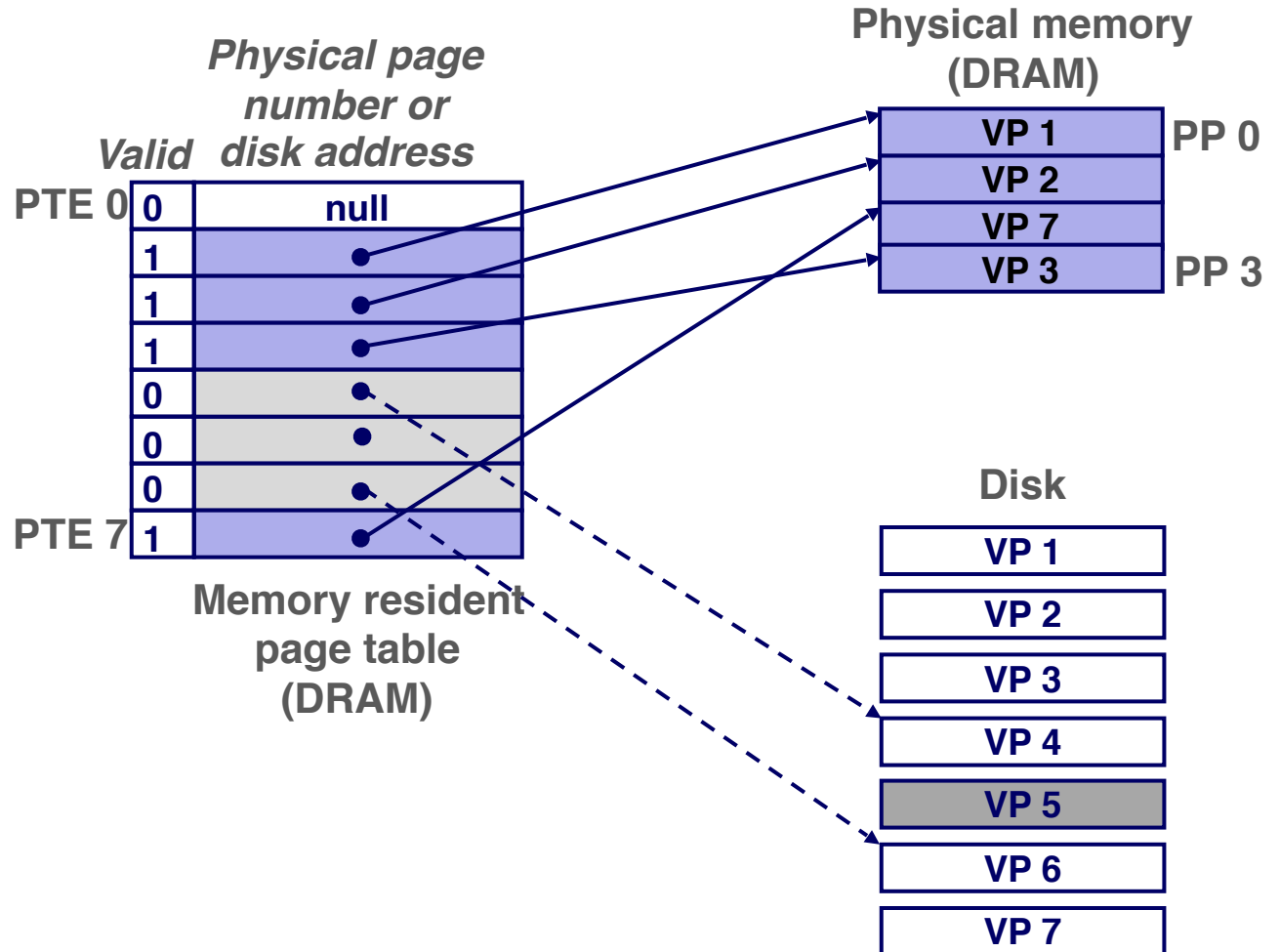
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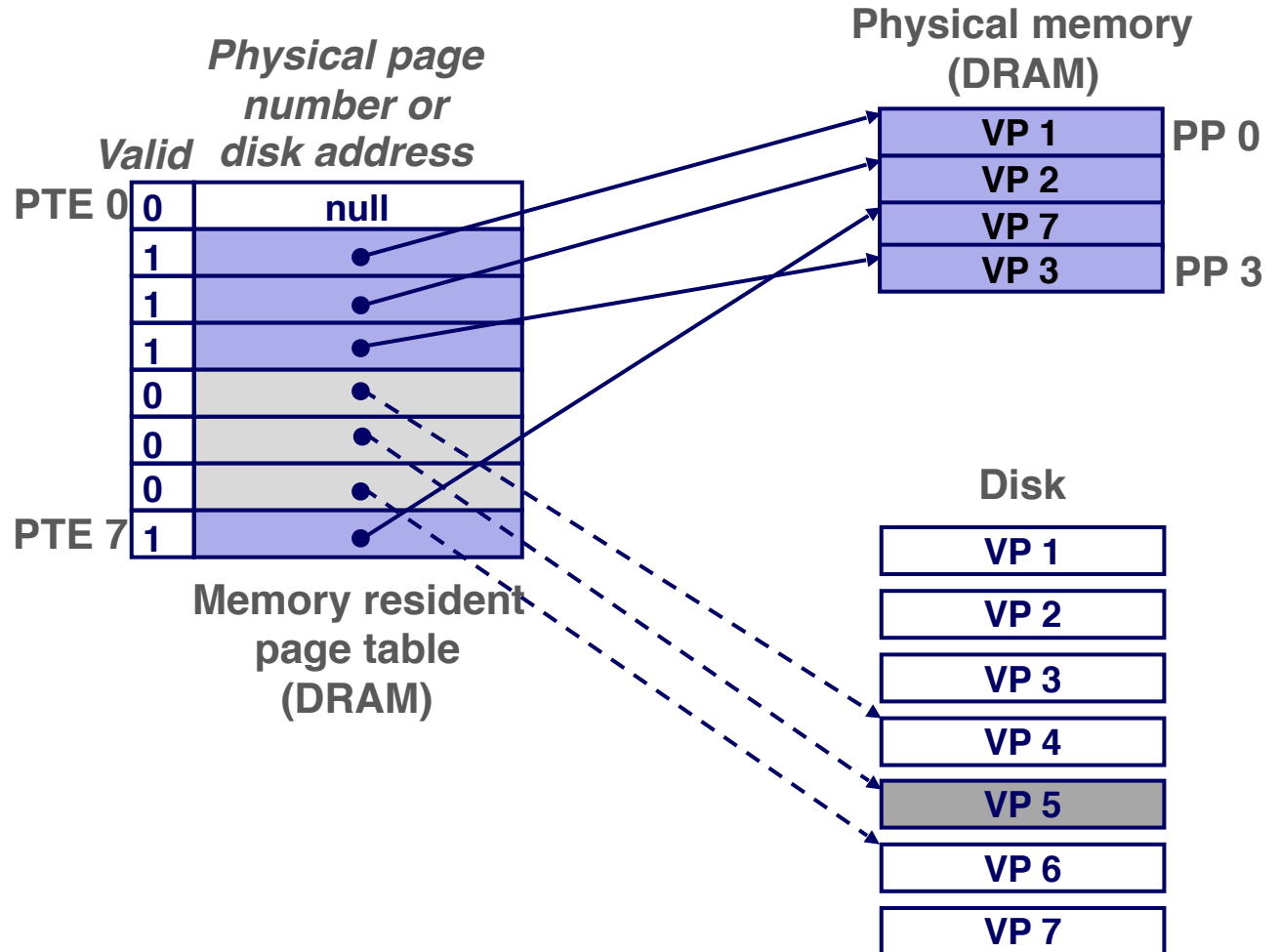
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Virtual Memory Exploits Locality (Again!)

- 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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- Physical memory size is much much smaller:
 - iPhone 8: 2 GB (2^{31})
 - 15-inch Macbook Pro 2017: 16 GB (2^{34})

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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.