Roadmap

Data & addressing
Integers & floats
Machine code & C
x86 assembly programming
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

C:

```c
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```java
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Computer system:

Processes

- **Definition: A *process* is an instance of a running program**
  - One of the most important ideas in computer science
  - Not the same as “program” or “processor”

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  - Logical control flow
    - Each process seems to have exclusive use of the CPU
  - Private virtual address space
    - Each process seems to have exclusive use of main memory

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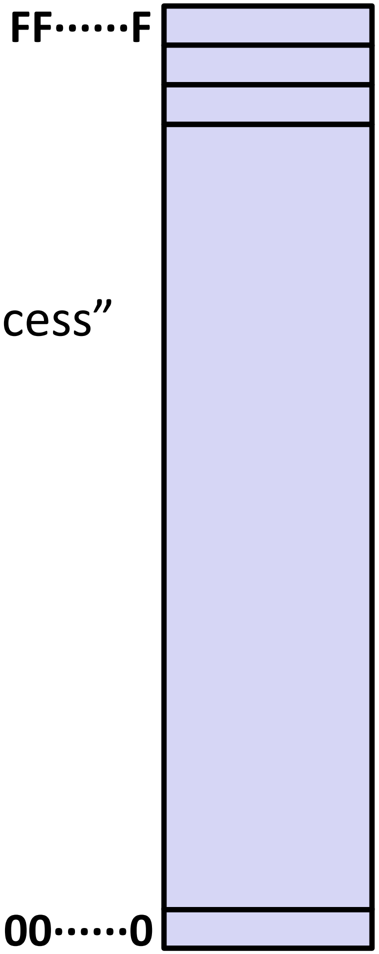
- **How are these illusions maintained?**
  - Process executions interleaved (multi-tasking) – last time
  - Address spaces managed by virtual memory system – today!

Virtual Memory (VM)

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

Virtual Memory (Previous Lectures)

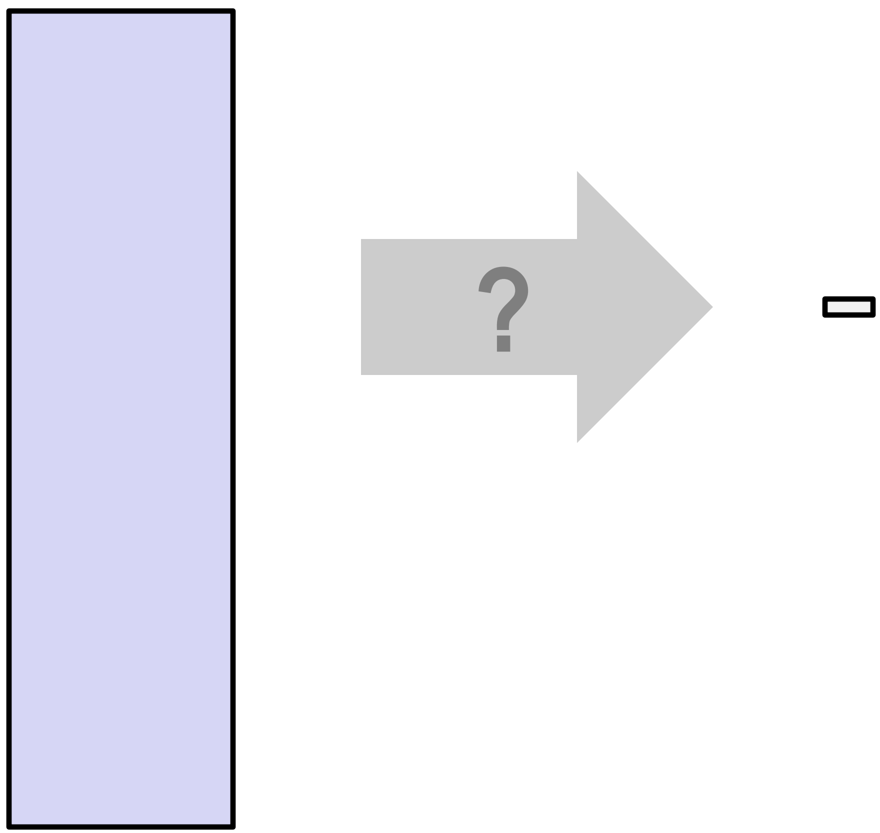
- **Programs refer to virtual memory addresses**
  - movl (%ecx),%eax
  - Conceptually memory is just a very large array of bytes
  - Each byte has its own address
  - System provides address space private to particular "process"
- **Allocation: Compiler and run-time system**
  - Where different program objects should be stored
  - All allocation within single virtual address space
- ***What problems does virtual memory solve?***



Problem 1: How Does Everything Fit?

64-bit addresses:
16 Exabyte

Physical main memory:
Few Gigabytes



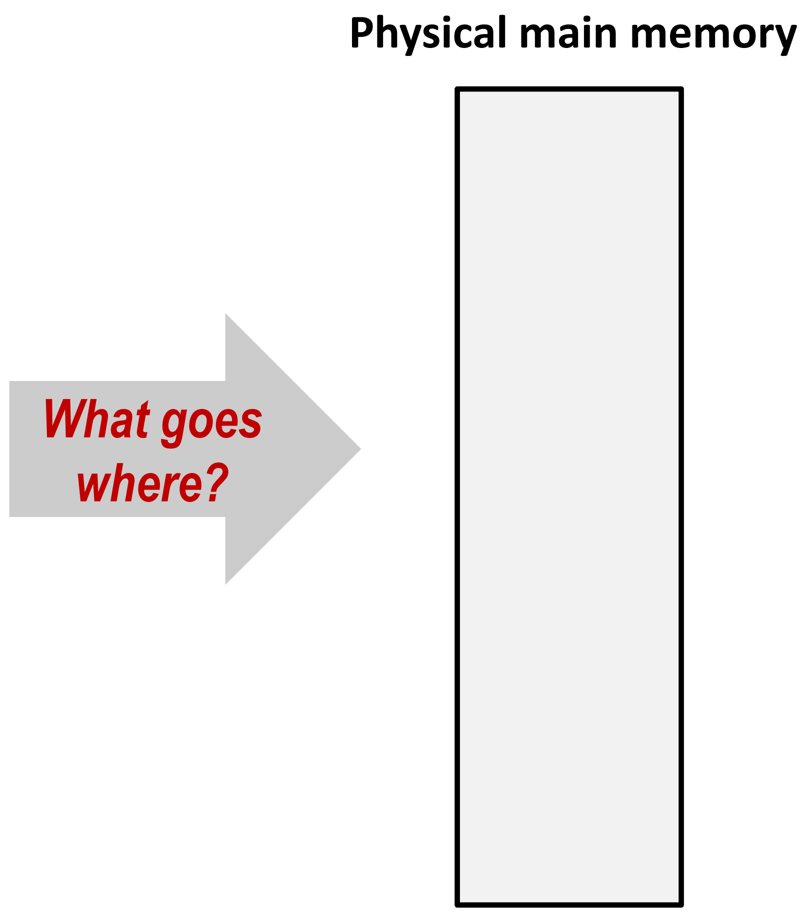
And there are many processes ….

Problem 2: Memory Management

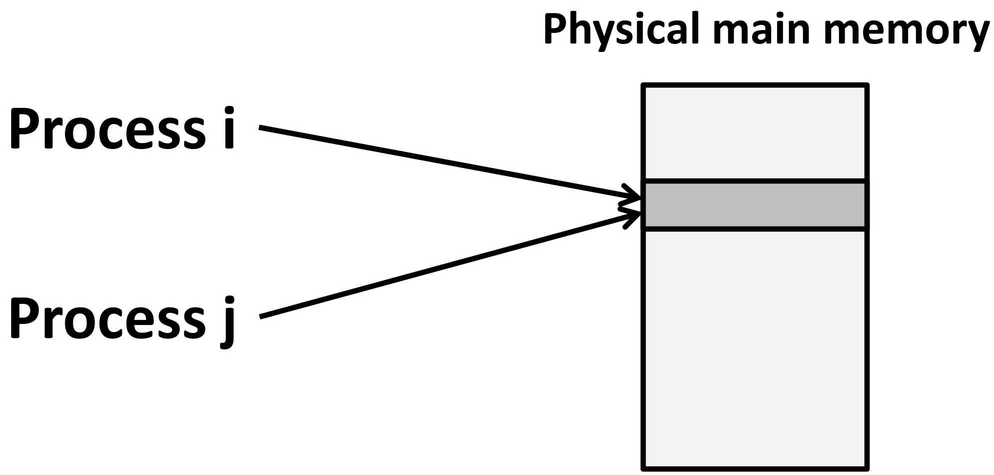
Process 1
Process 2
Process 3
…
Process n

X

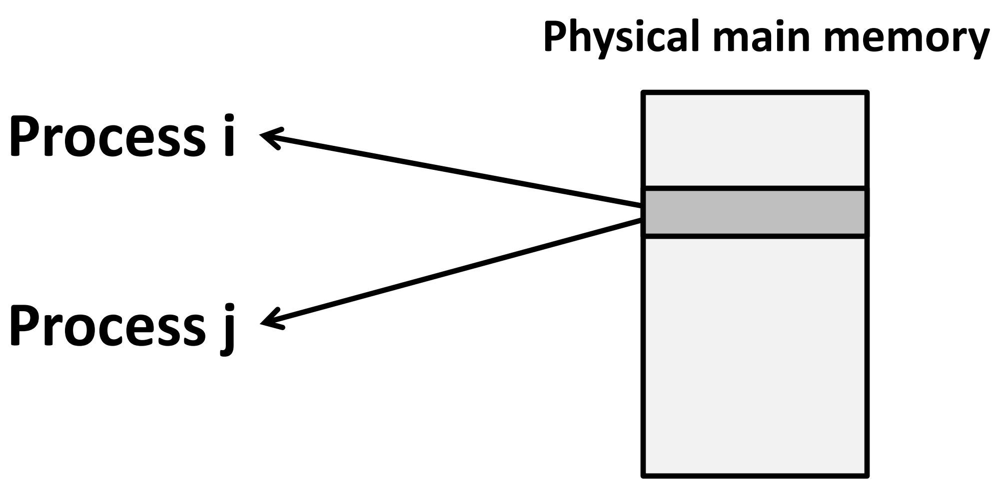
stack
heap
`.text`
`.data`
…



Problem 3: How To Protect



Problem 4: How To Share?



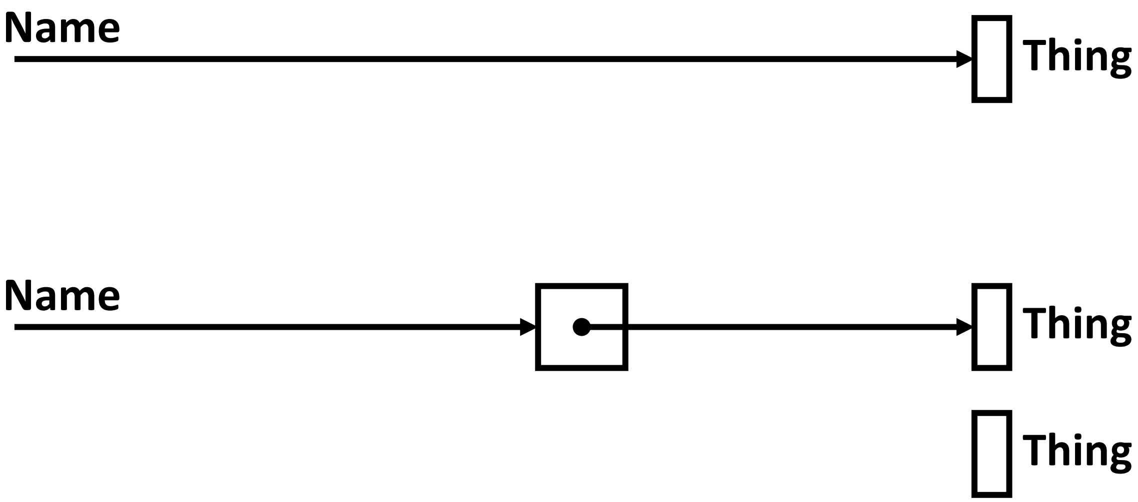
How would you solve those problems?

Indirection

- "Any problem in computer science can be solved by adding another level of indirection"

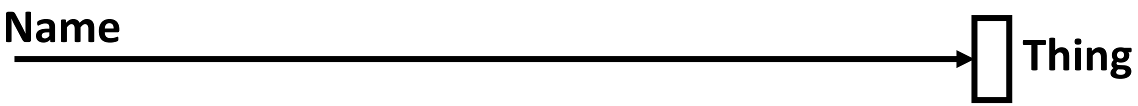
- Without Indirection

- With Indirection

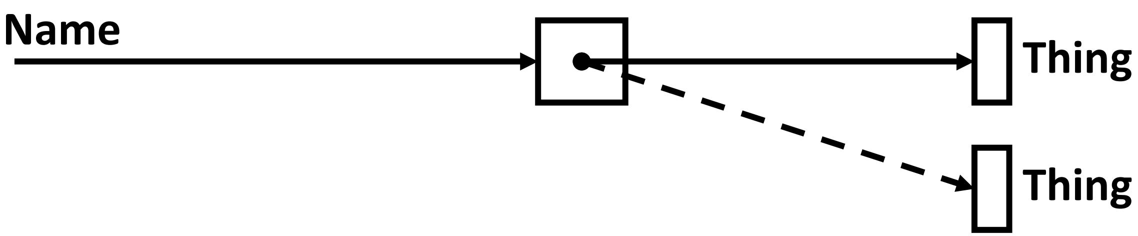


Indirection

- Indirection: the ability to reference something using a name, reference, or container instead the value itself. A flexible mapping between a name and a thing allows changing the thing without notifying holders of the name.



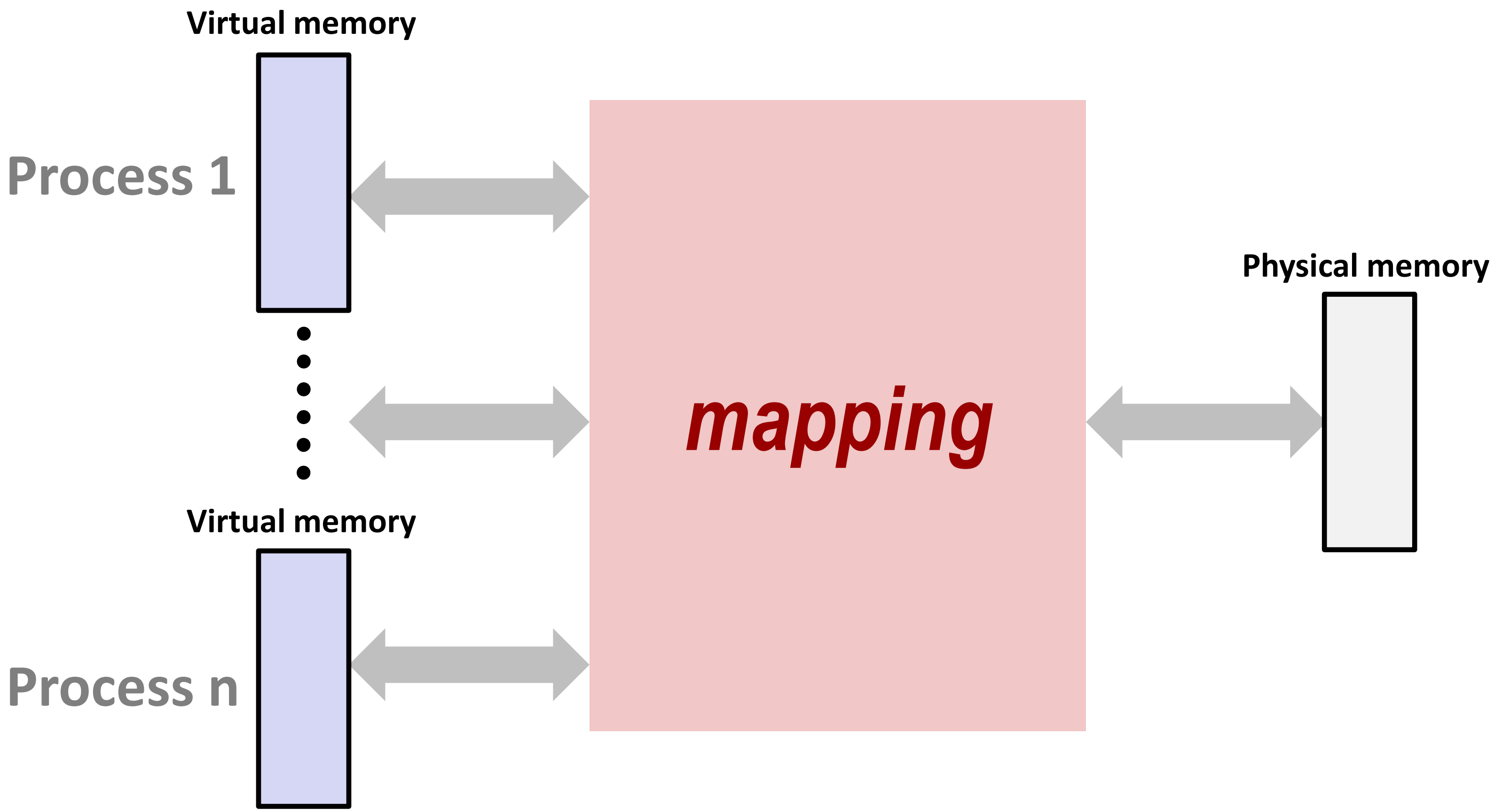
- Without Indirection



- With Indirection

- Examples:
  Domain Name Service (DNS) name->IP address, phone system (e.g., cell phone number portability), snail mail (e.g., mail forwarding), 911 (routed to local office), DHCP, call centers that route calls to available operators, etc.

Solution: Level Of Indirection

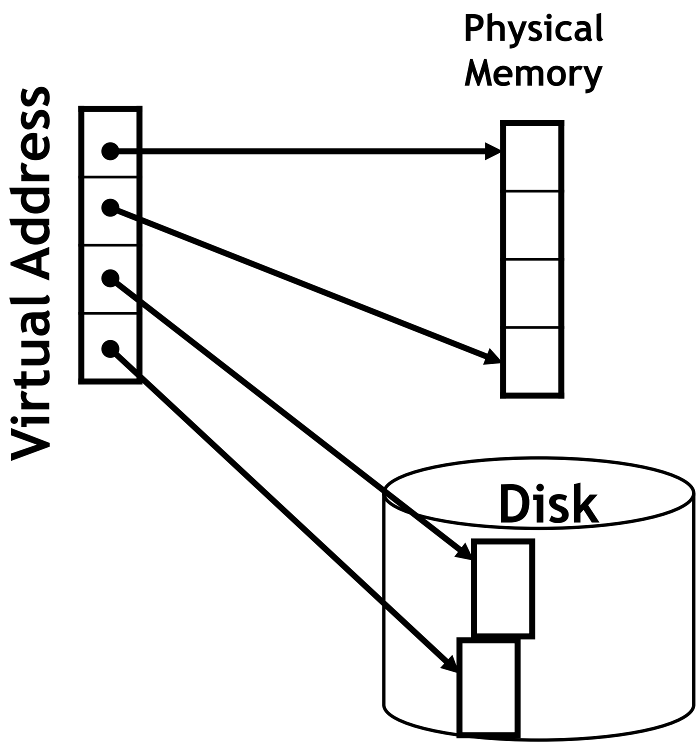


- Each process gets its own private virtual address space
- Solves the previous problems

Address Spaces

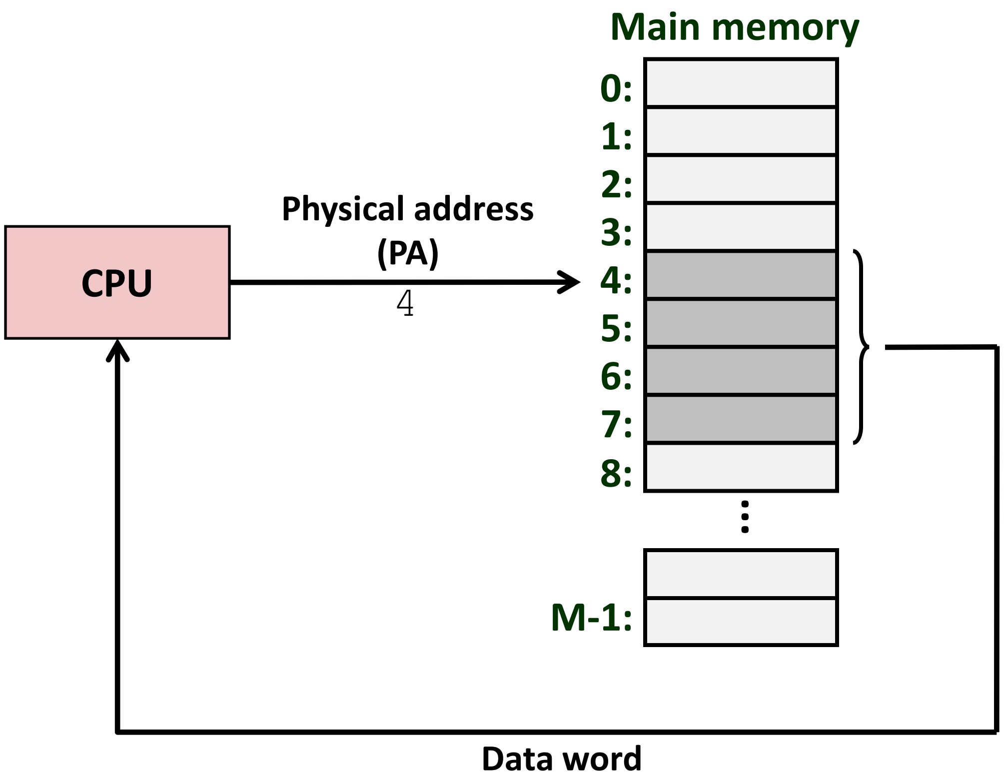
- **Virtual address space:** Set of $N = 2^n$ virtual addresses
  $\{0, 1, 2, 3, …, N-1\}$
- **Physical address space:** Set of $M = 2^m$ physical addresses $(n > m)$
  $\{0, 1, 2, 3, …, M-1\}$
- **Every byte in main memory:**
  one physical address; zero, one, or more virtual addresses

Mapping



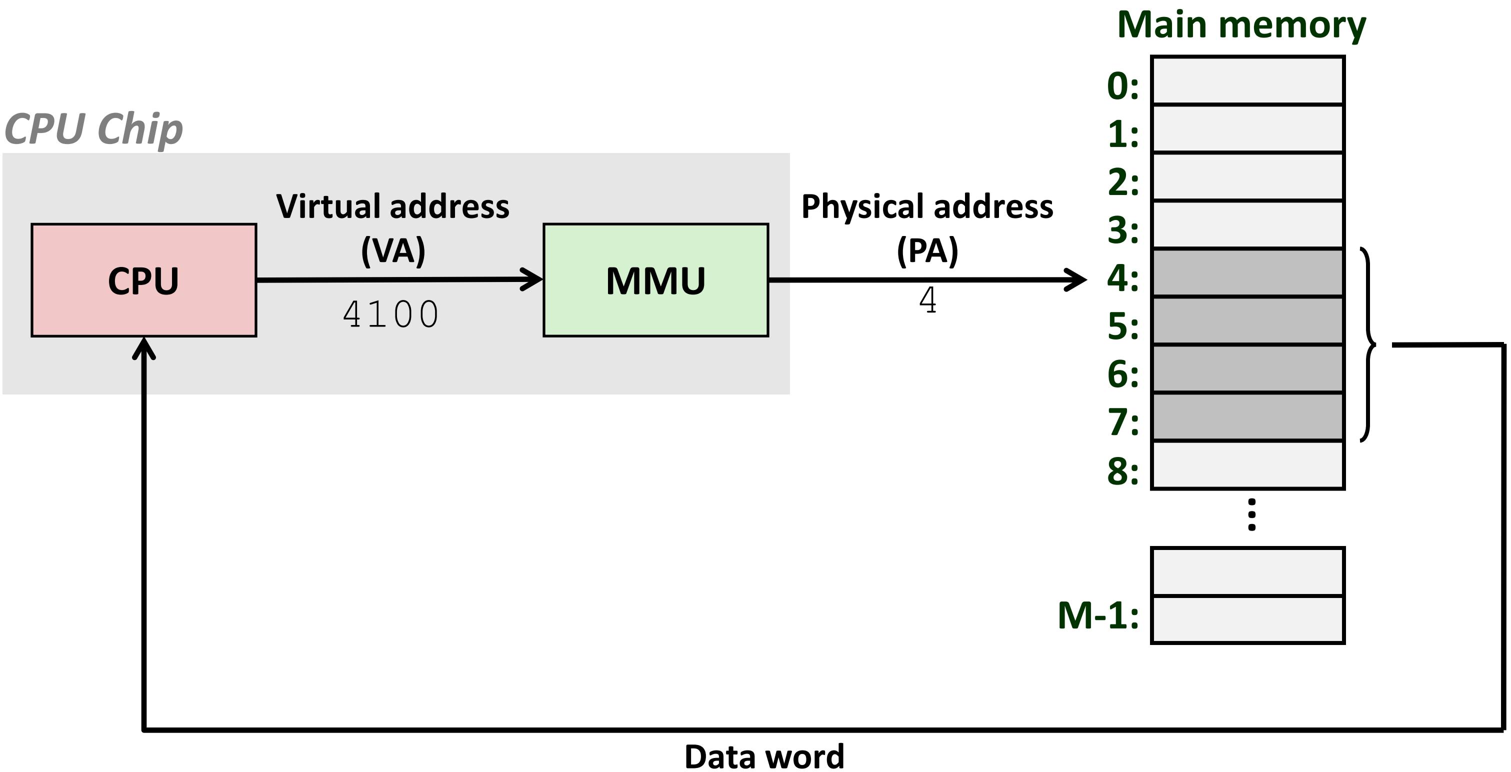
A virtual address can be mapped to either physical memory or disk.

A System Using Physical Addressing



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

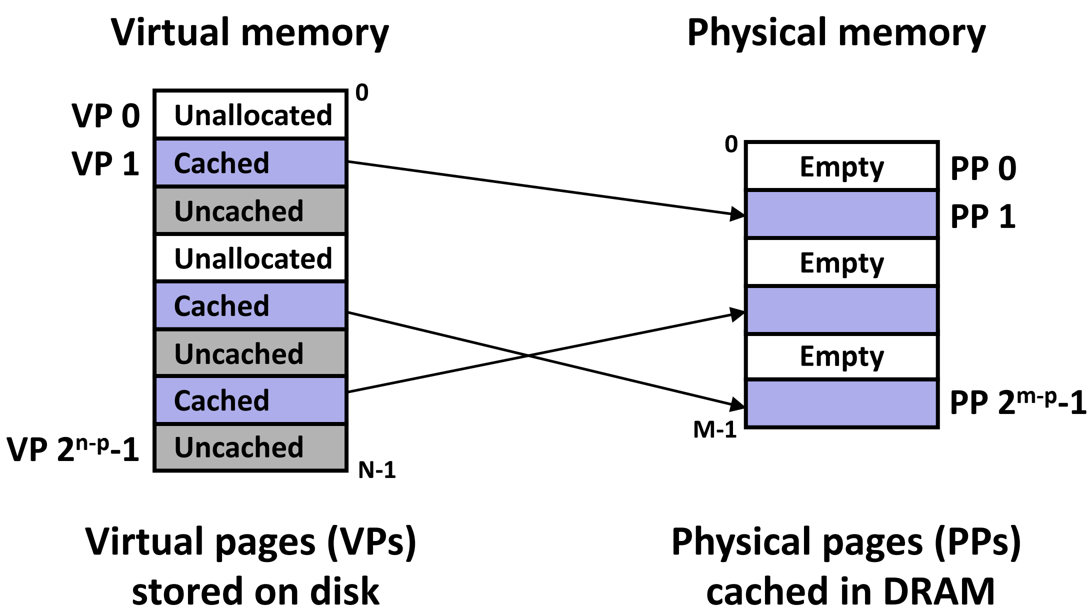
A System Using Virtual Addressing



- Used in all modern desktops, laptops, servers
- One of the great ideas in computer science

VM and the Memory Hierarchy

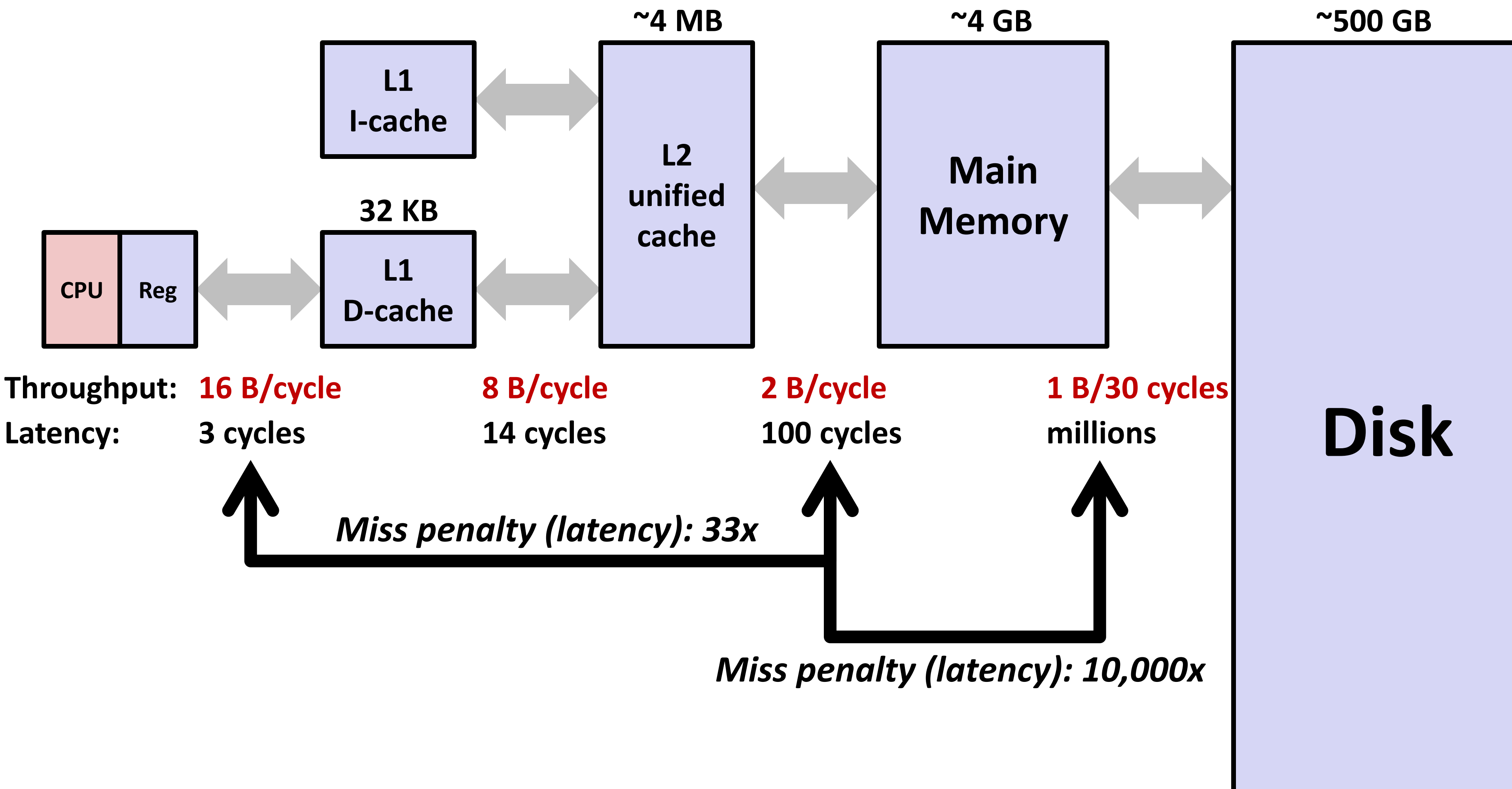
- Think of virtual memory as an array of $N = 2^n$ contiguous bytes stored *on a disk*
- Then physical main memory (DRAM) is used as a *cache* for the virtual memory array
  - The cache blocks are called *pages* (size is $P = 2^p$ bytes)



Memory Hierarchy: Core 2 Duo

Not drawn to scale

L1/L2 cache: 64 B blocks



DRAM Cache Organization

- **DRAM cache organization driven by the enormous miss penalty**
  - DRAM is about 10x slower than SRAM
  - Disk is about 10,000x slower than DRAM
    - (for first byte; faster for next byte)

- **Consequences?**
  - Block size?
  - Associativity?
  - Write-through or write-back?

DRAM Cache Organization

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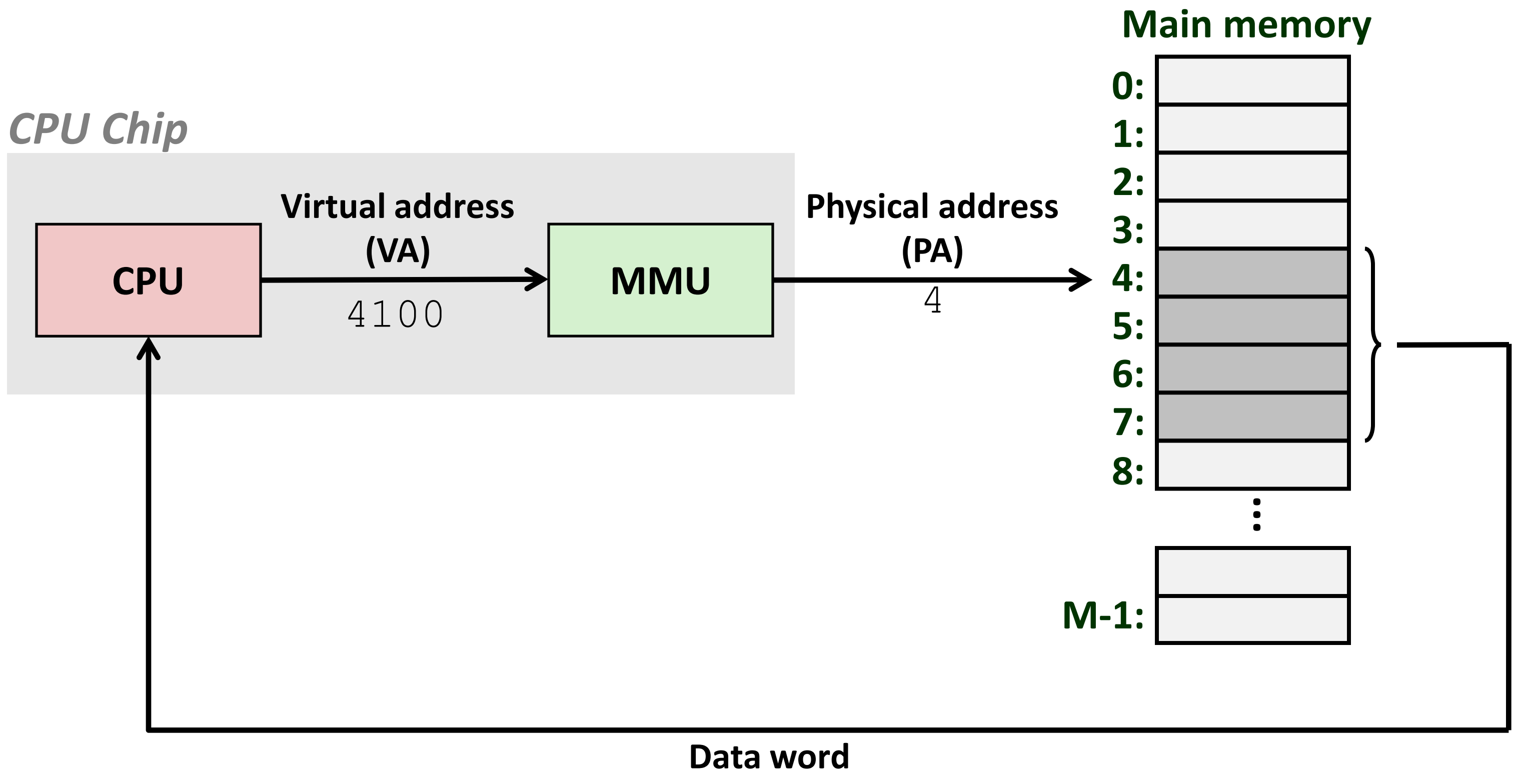
- **Consequences**
  - Large page (block) size: typically 4-8 KB, sometimes 4 MB
  - Fully associative
    - Any VP can be placed in any PP
    - Requires a “large” mapping function – different from CPU caches
  - Highly sophisticated, expensive replacement algorithms
    - Too complicated and open-ended to be implemented in hardware
  - Write-back rather than write-through

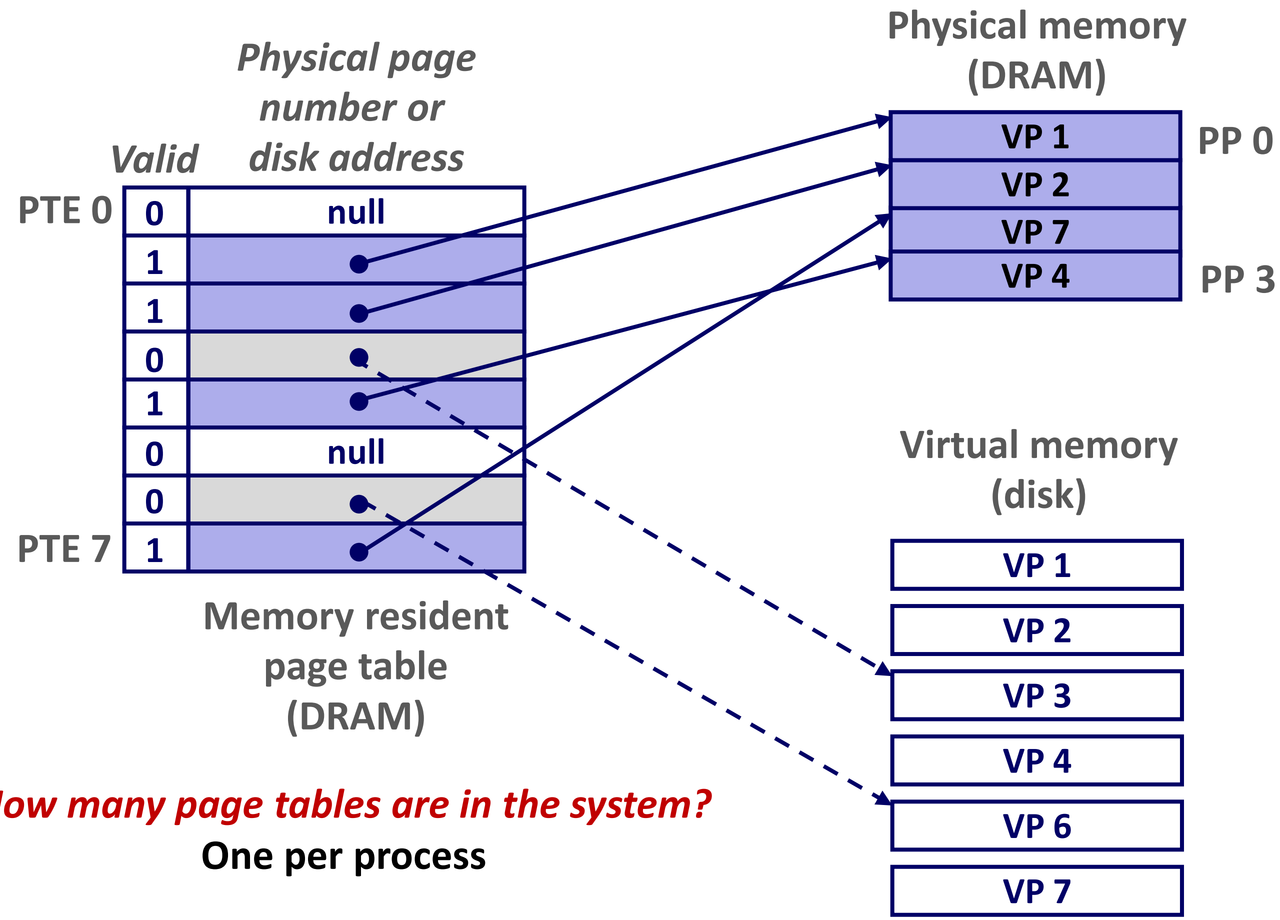
Indexing into the "DRAM Cache"



How do we perform the VA -> PA translation?

Address Translation: Page Tables

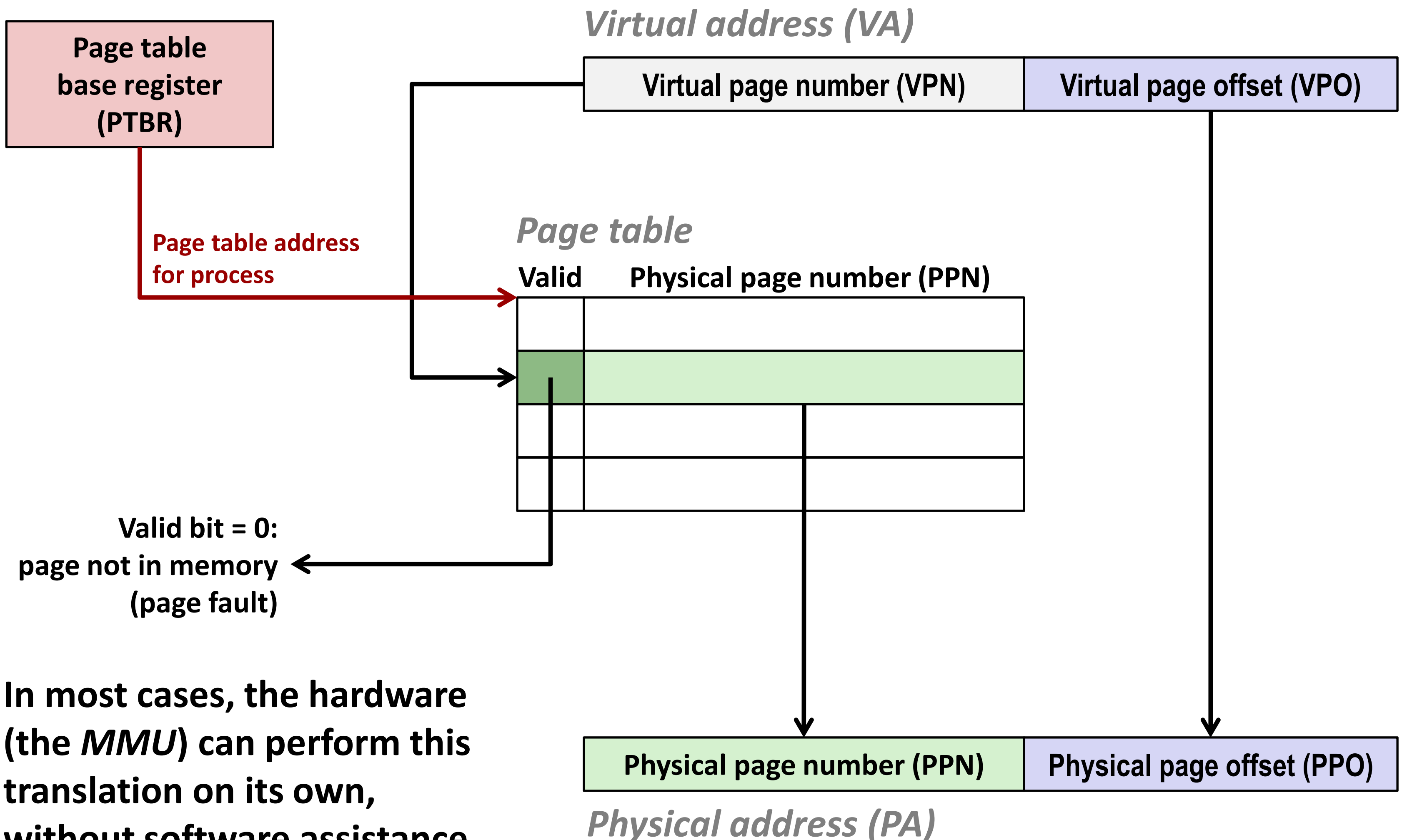
- A ***page table*** (PT) is an array of ***page table entries*** (PTEs) that maps virtual pages to physical pages.



How many page tables are in the system?

One per process

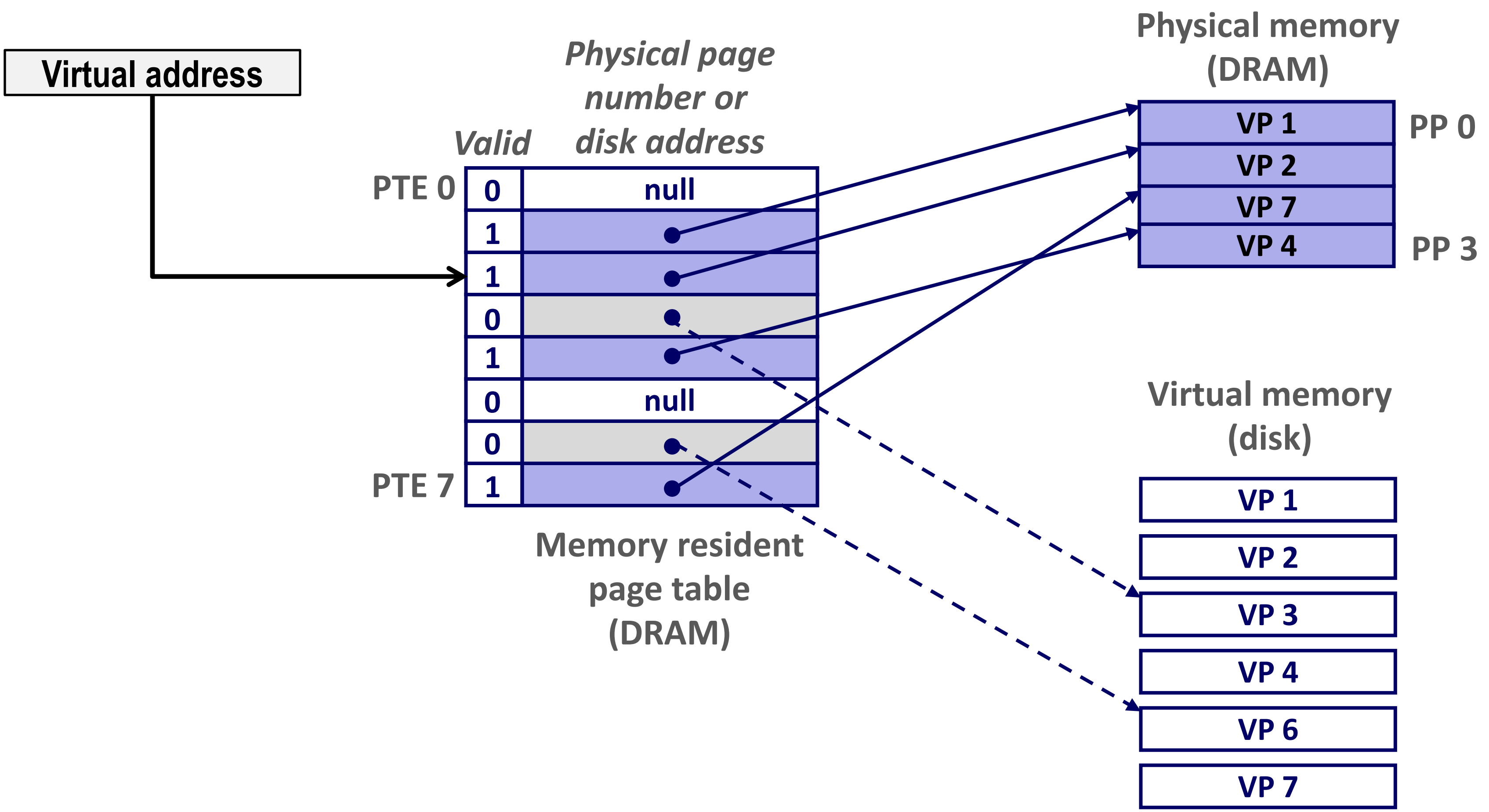
Address Translation With a Page Table



In most cases, the hardware (the *MMU*) can perform this translation on its own, without software assistance

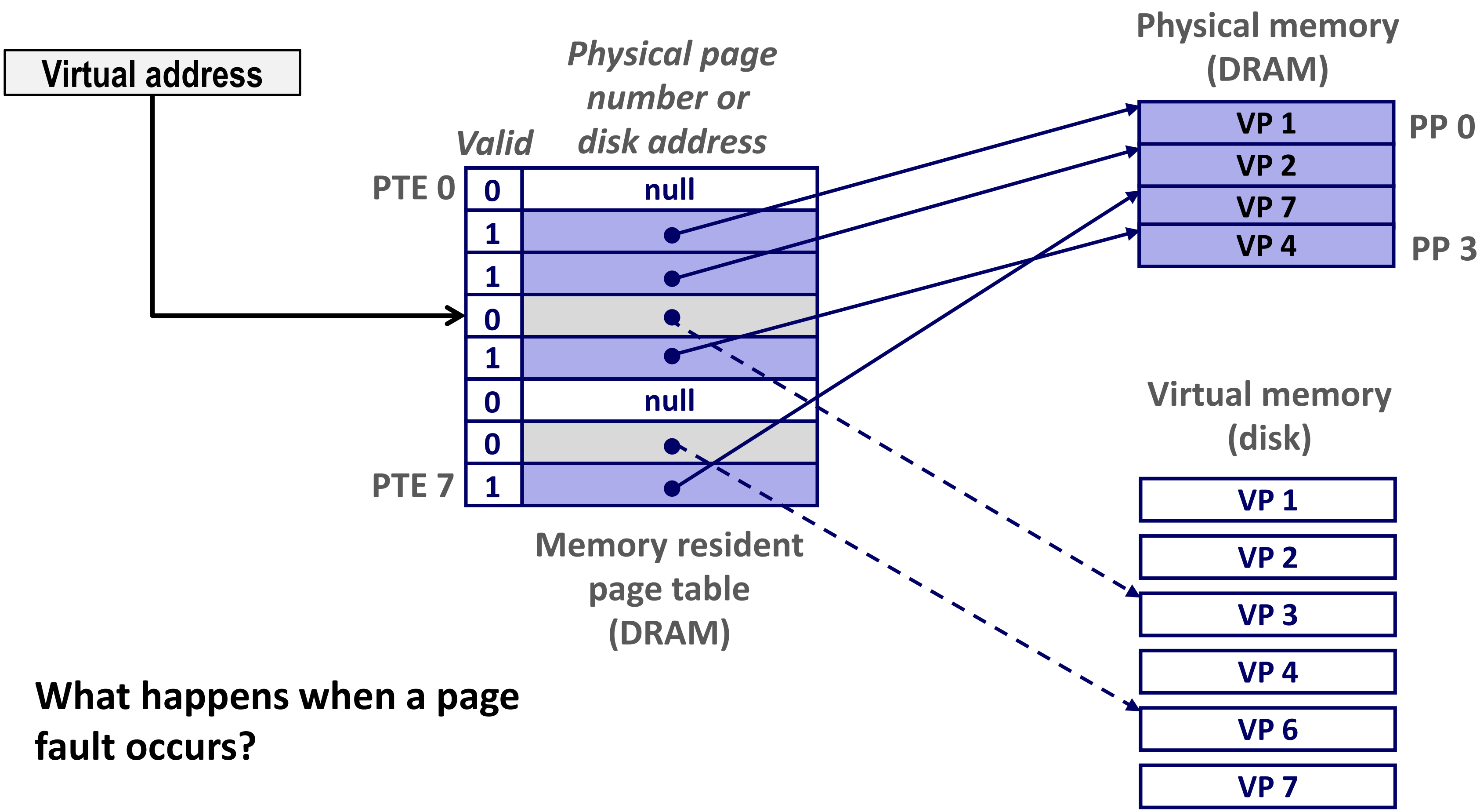
Page Hit

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



Page Fault

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



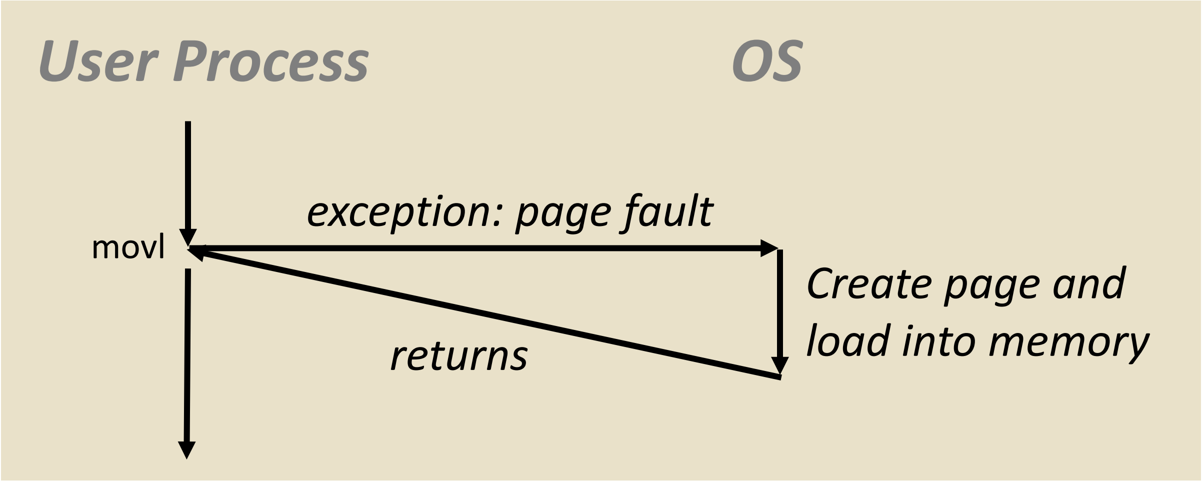
What happens when a page fault occurs?

Fault Example: Page Fault

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

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

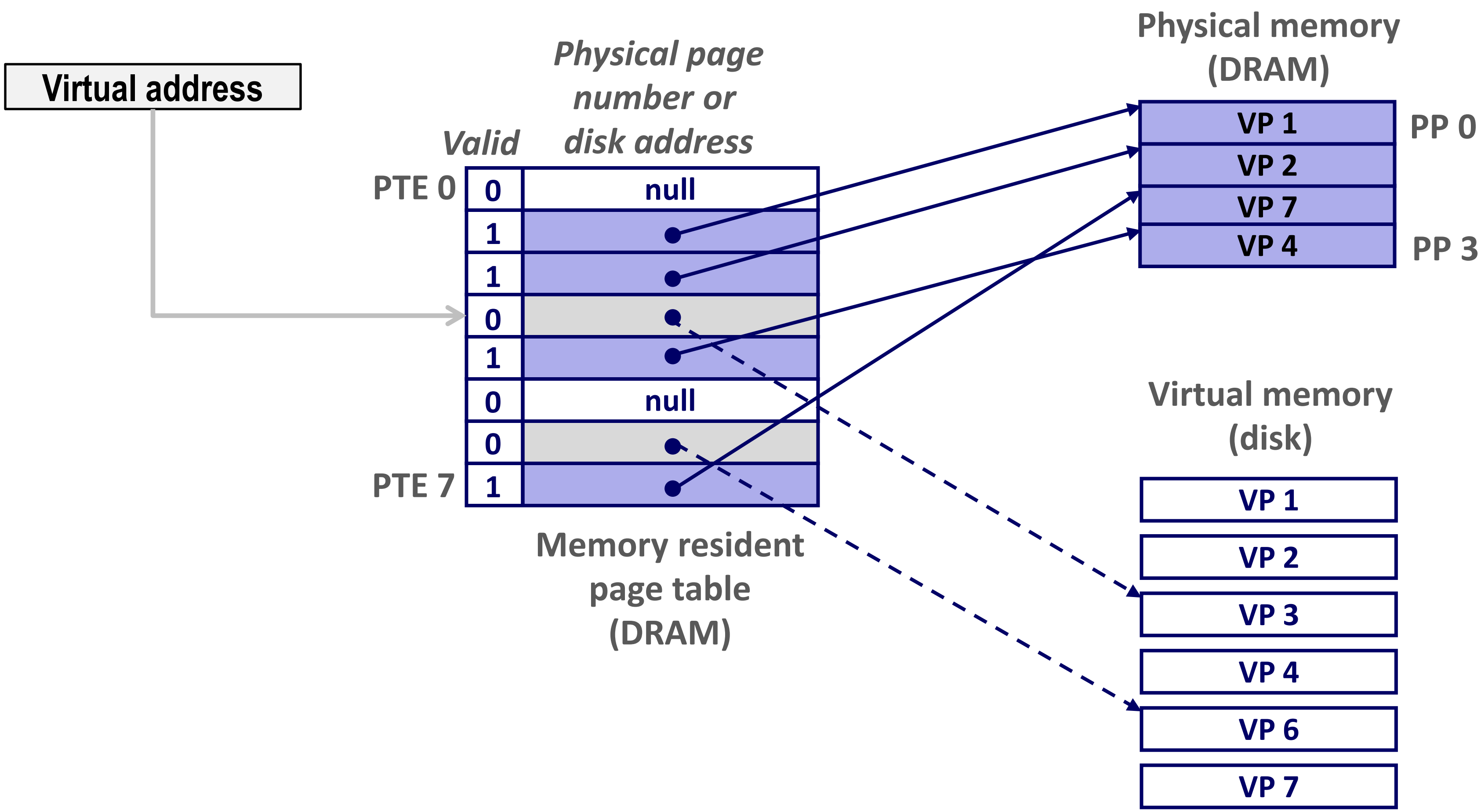
```
80483b7:        c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



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

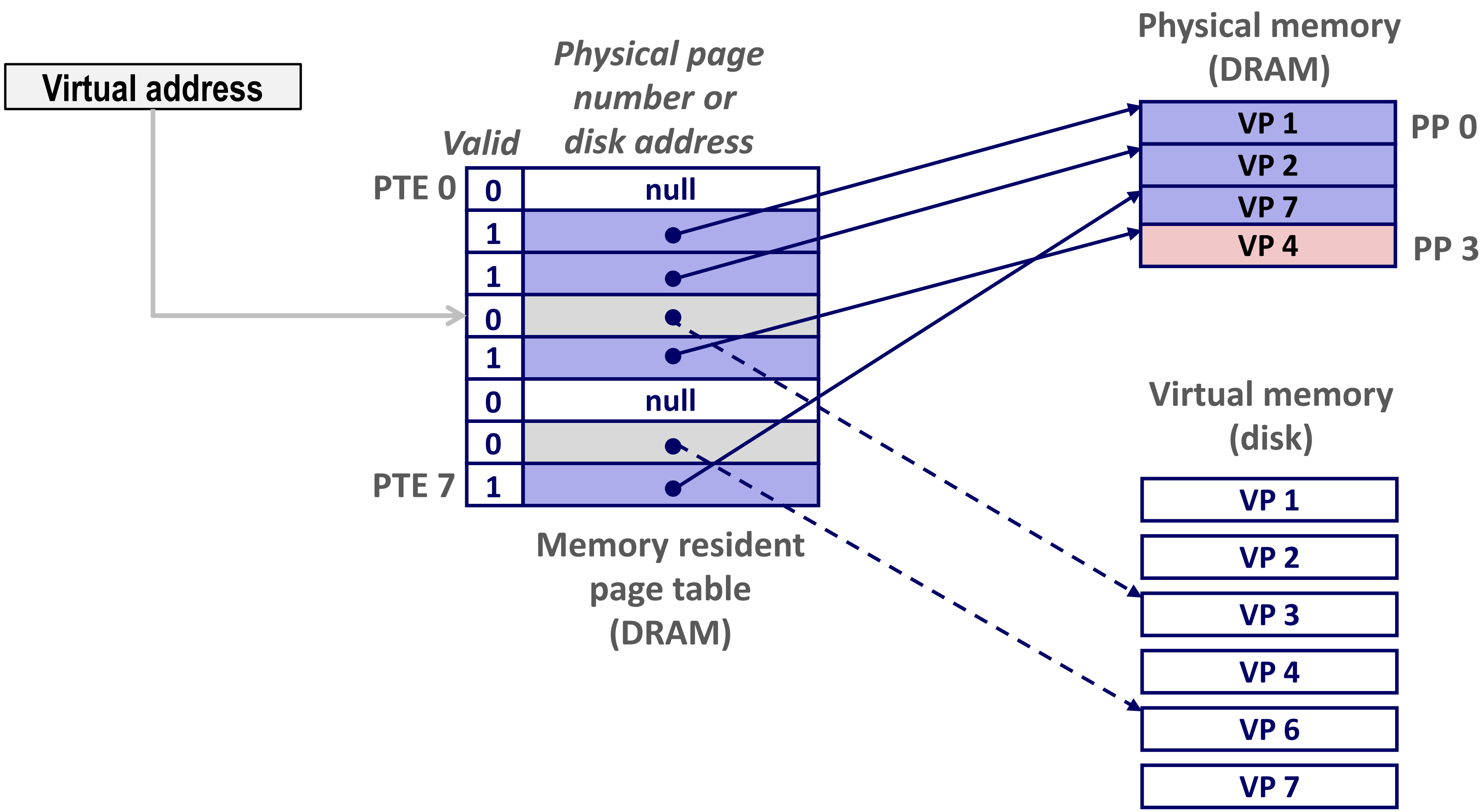
Handling Page Fault

- Page miss causes page fault (an exception)



Handling 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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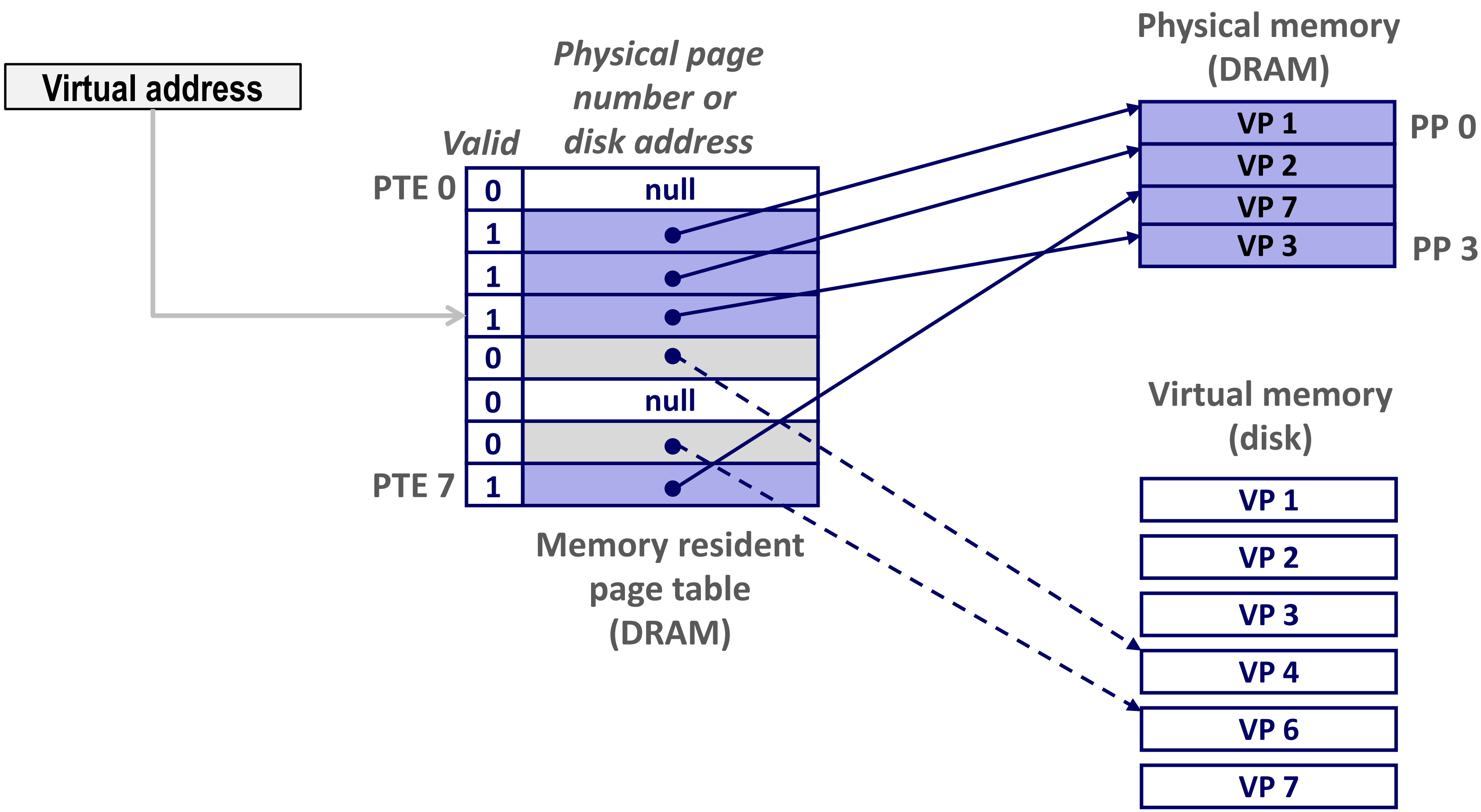
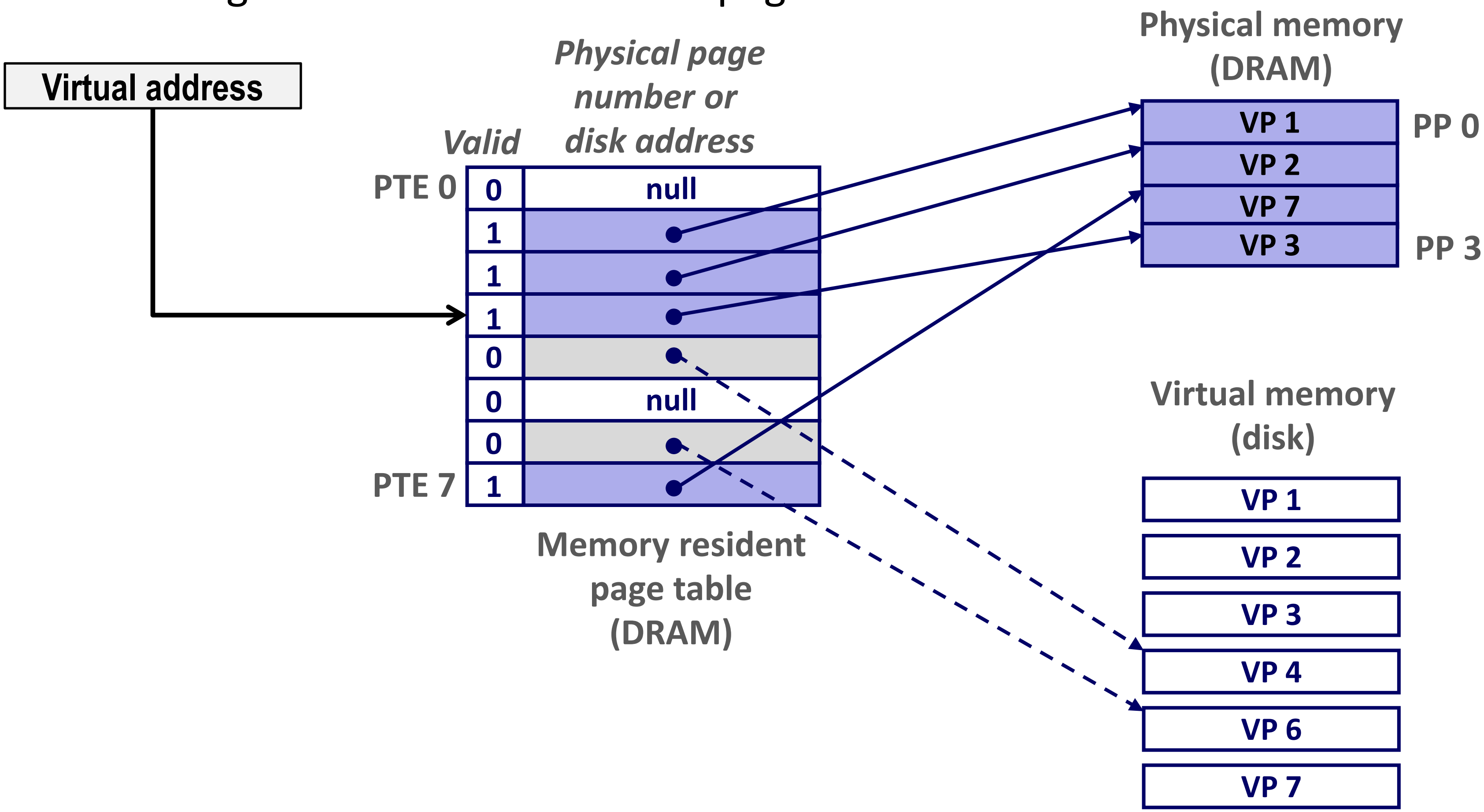


Handling Page Fault

- 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!



Why does it work?

Why does it work? Locality

- **Virtual memory works well 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***
  - Programs with better temporal locality will have smaller working sets
- **If (working set size < main memory size):**
  - Good performance for one process after compulsory misses
- **If (SUM(working set sizes) > main memory size):**
  - *Thrashing:* Performance meltdown where pages are swapped (copied) in and out continuously