Virtual Memory

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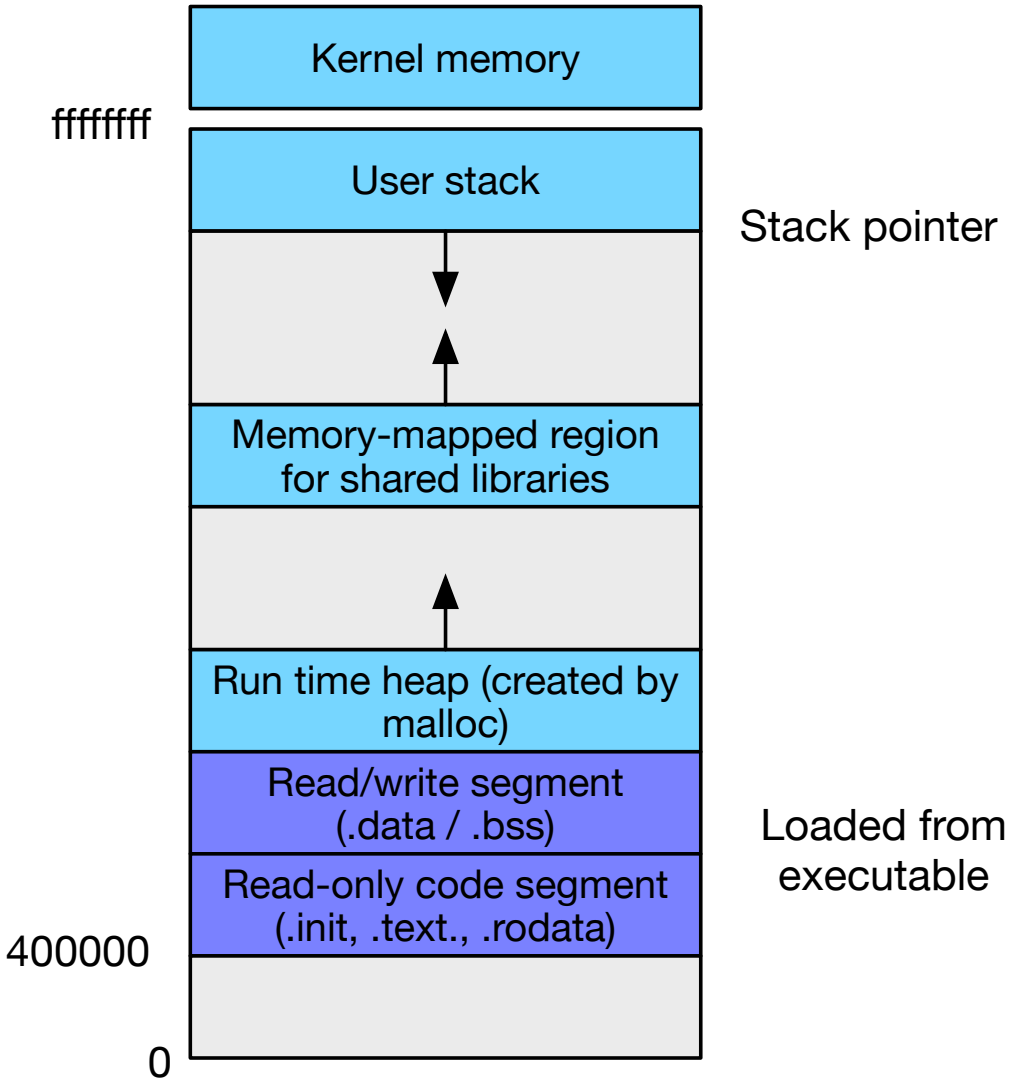
25 April 2018

Recall: Process Address Space



Virtual Memory

- Abstraction of physical memory

- Purpose
  - appearance of more available memory than physically exists (DRAM)
  - handles disk caching / loading
  - insulates memory of each process

- Page table: maps from virtual address to physical addresses

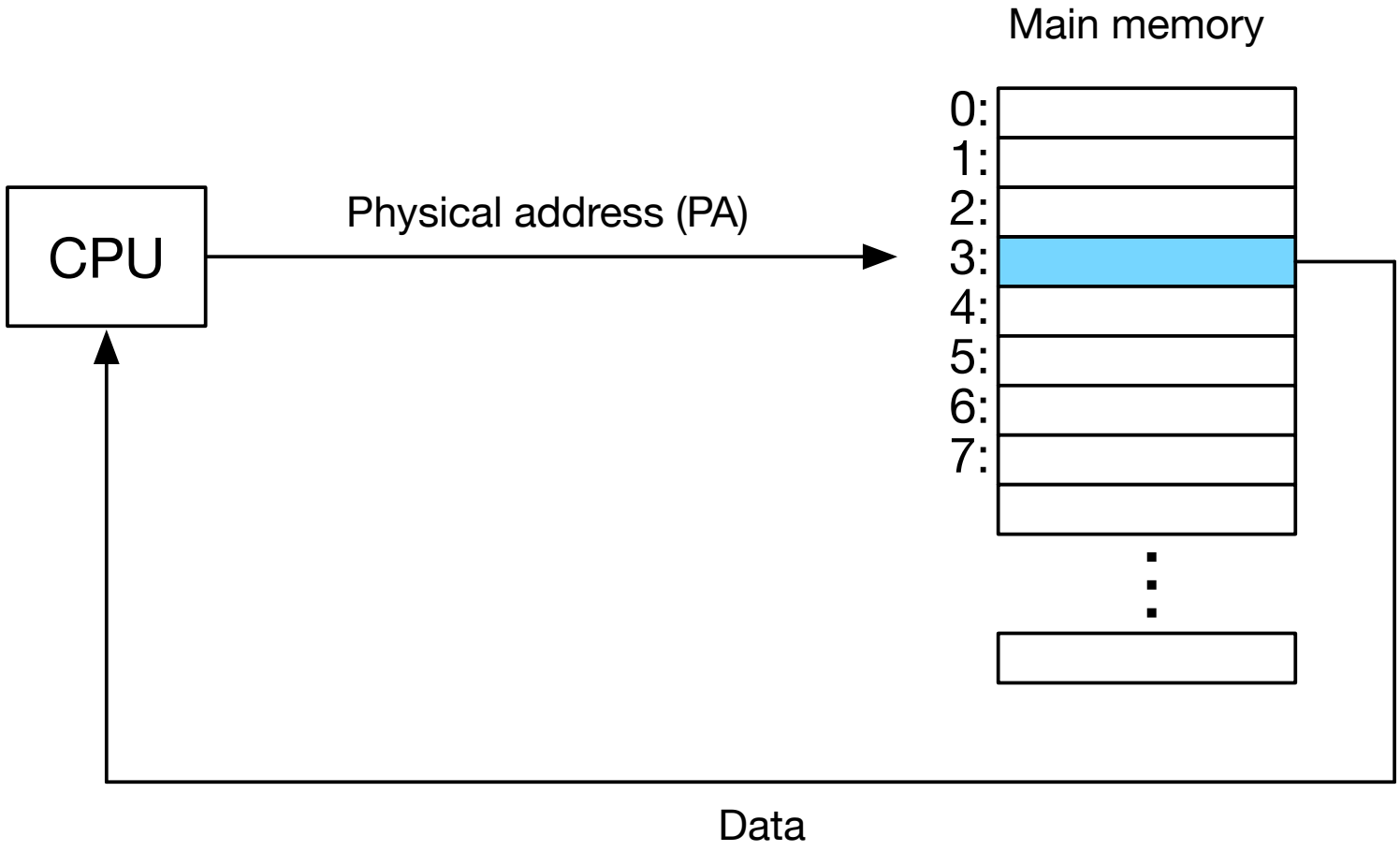
- Memory management unit (MMU):
  hardware implementation of address translation

Warning

- This is going to get very complex
- Closely tied with multi-tasking (multiple processes)
- Partly managed by hardware,
  partly managed by software

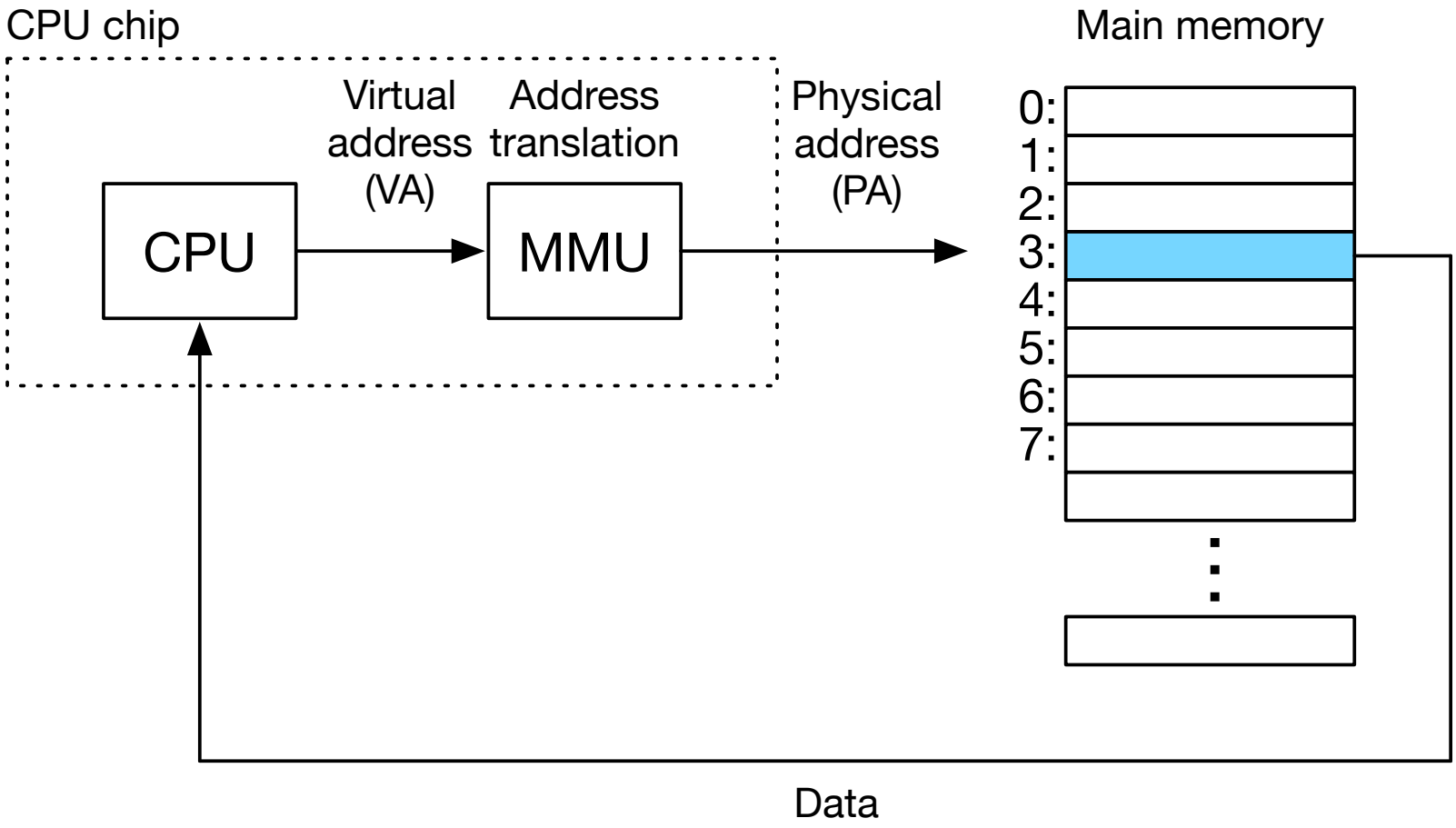
virtual addressing

Physical Addressing



- So far, assumed CPU addresses physical memory

Virtual Addressing



- Memory management unit (MMU): maps virtual to physical addresses

Address Space

- Virtual memory size: $N = 2^n$ bytes, e.g., 256TB
- Physical memory size: $M = 2^m$ bytes, e.g., 16GB
- Page (block of memory): $P = 2^p$ bytes, e.g., 4KB
- A virtual address can be encoded in n bits

caching

Caching... Again?

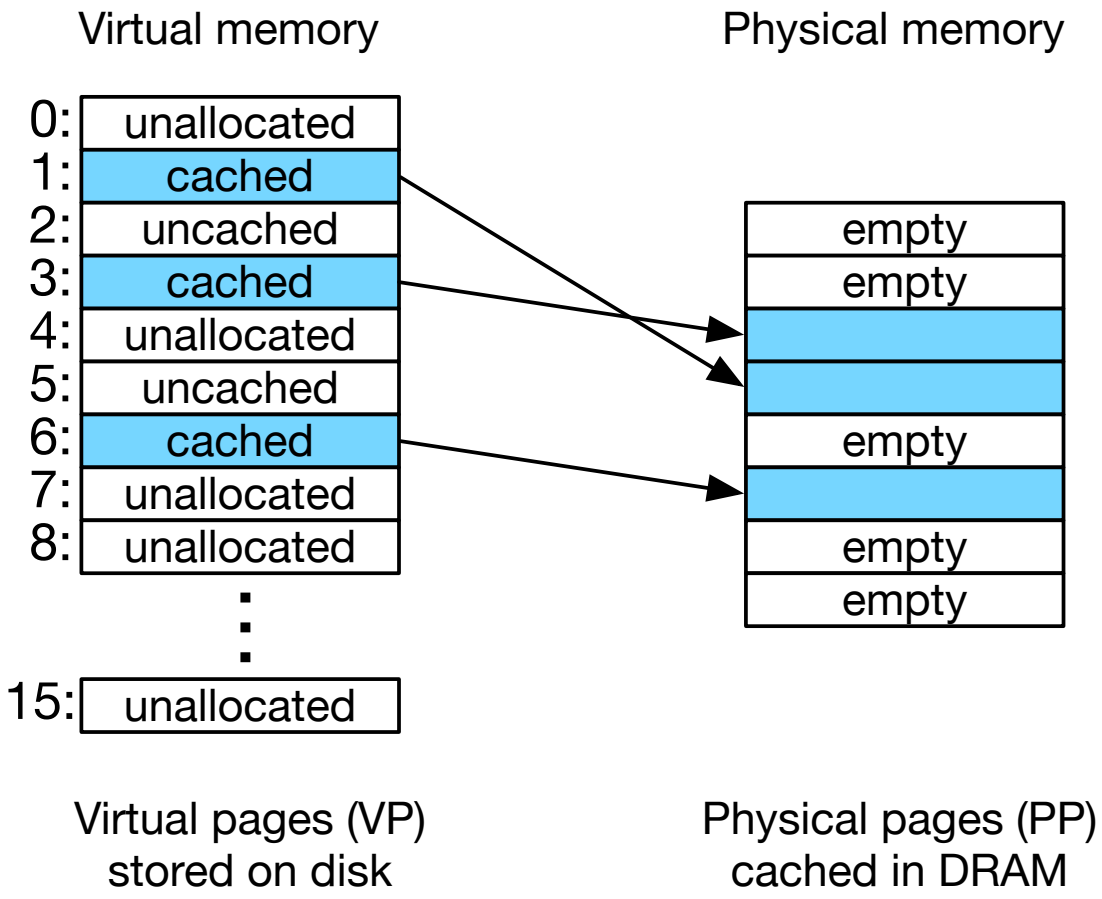
- Yes, we already discussed caching

  but: for on-chip cache of DRAM memory

- Now
  - caching between RAM and disk
  - driven by a large virtual memory address space
  - to avoid unnecessary and duplicate loading

- Jargon
  - previously "block", now "page"
  - now: "swapping" or "paging"

Mapping


Virtual memory
Physical memory
0:
1:
2:
3:
4:
5:
6:
7:
8:
15:
unallocated
cached
uncached
cached
unallocated
uncached
cached
unallocated
unallocated
unallocated
empty
empty
empty
empty
empty
Virtual pages (VP)
stored on disk
Physical pages (PP)
cached in DRAM

State of Virtual Memory Page

- Cached
  - allocated page
  - stored in physical memory
- Uncached
  - allocated page
  - not in physical memory
- Unallocated
  - not used by virtual memory system so far

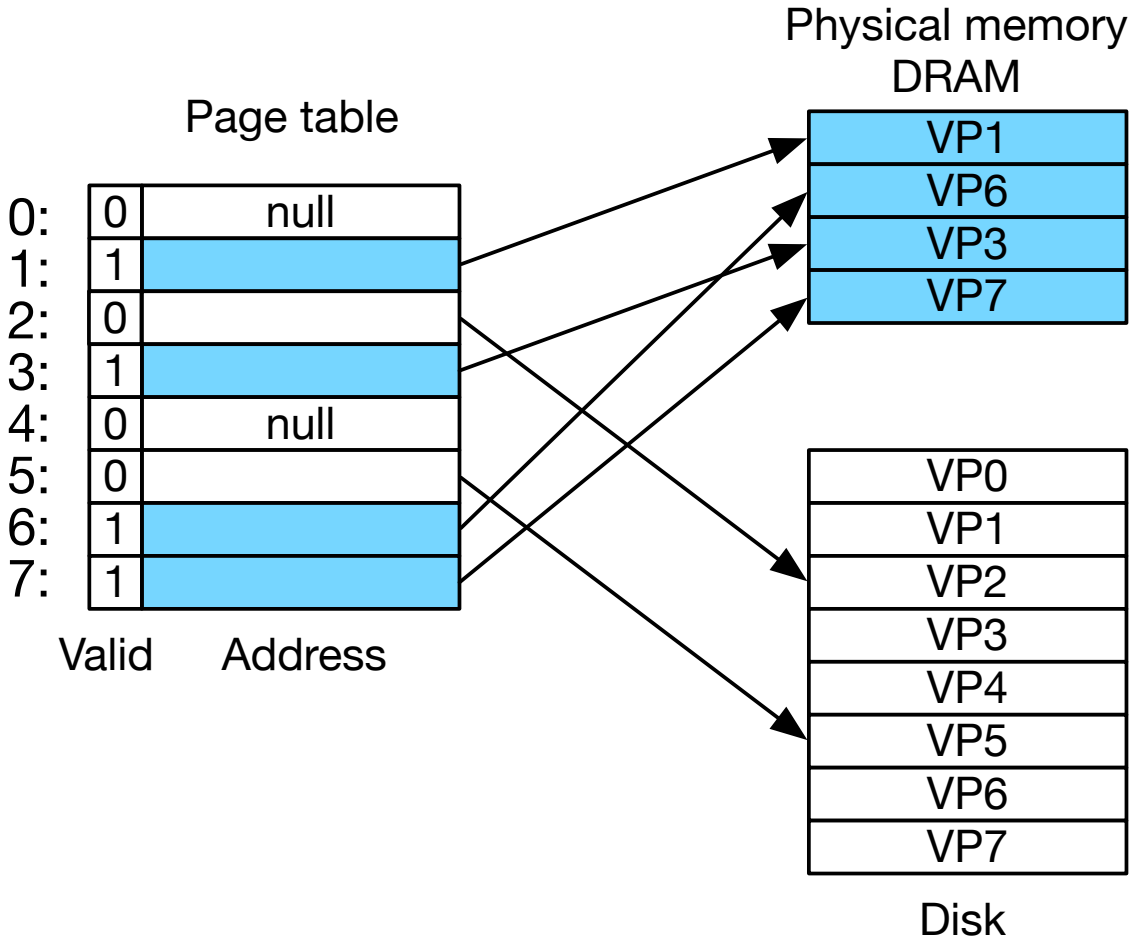
Page Table

- Array of page table entries (PTE)

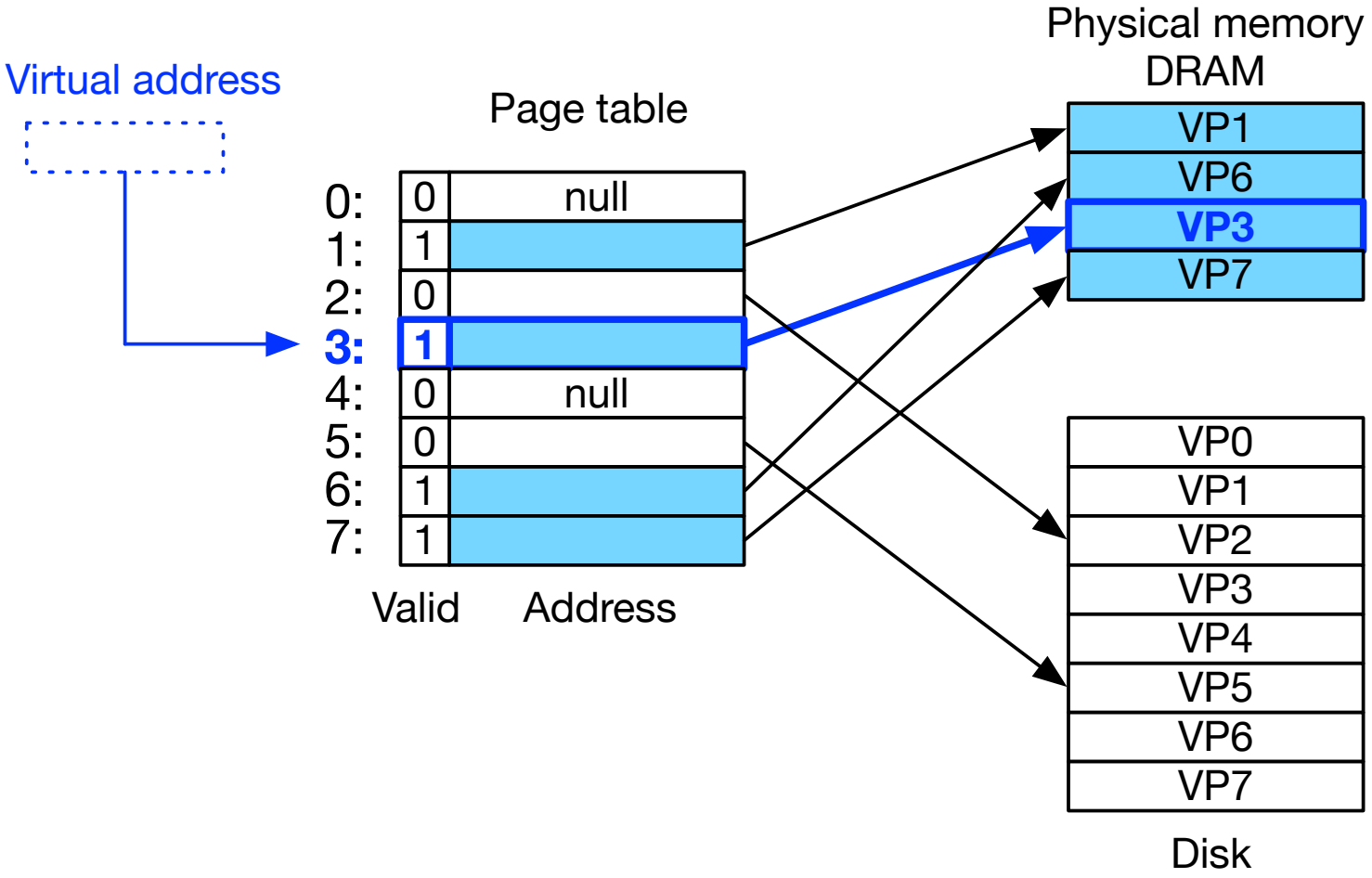
- Valid bit
  - set if PTE currently maps to physical address (cached)
  - not set otherwise (uncached or unallocated)

- Mapped address
  - if cached: physical address in DRAM
  - if not cached: physical address on disk

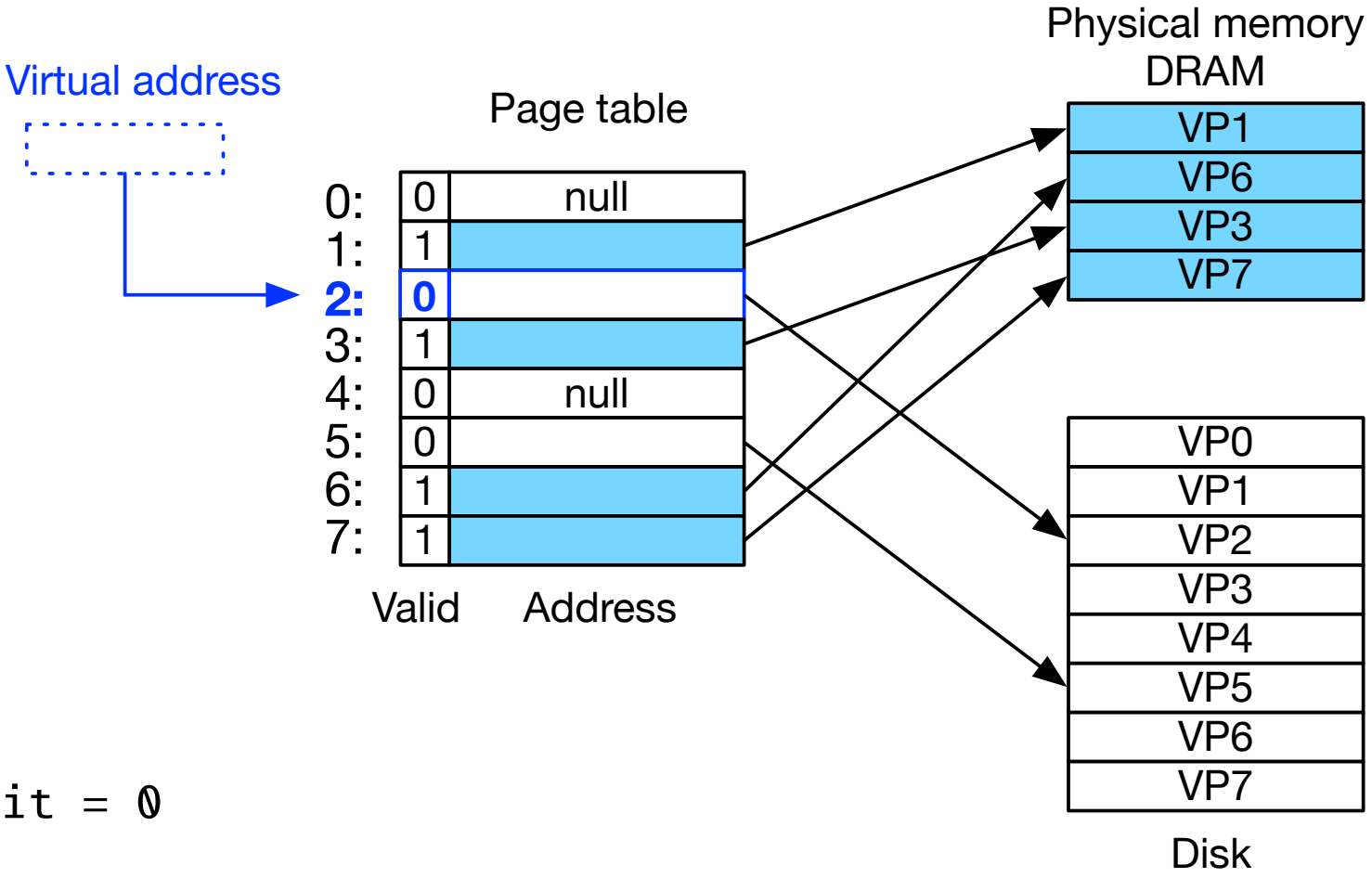
Page Table


Physical memory
DRAM
Page table
0:
1:
2:
3:
4:
5:
6:
7:
0
1
0
1
0
0
1
1
null
null
VP1
VP6
VP3
VP7
VP0
VP1
VP2
VP3
VP4
VP5
VP6
VP7
Valid
Address
Disk

Page Hit

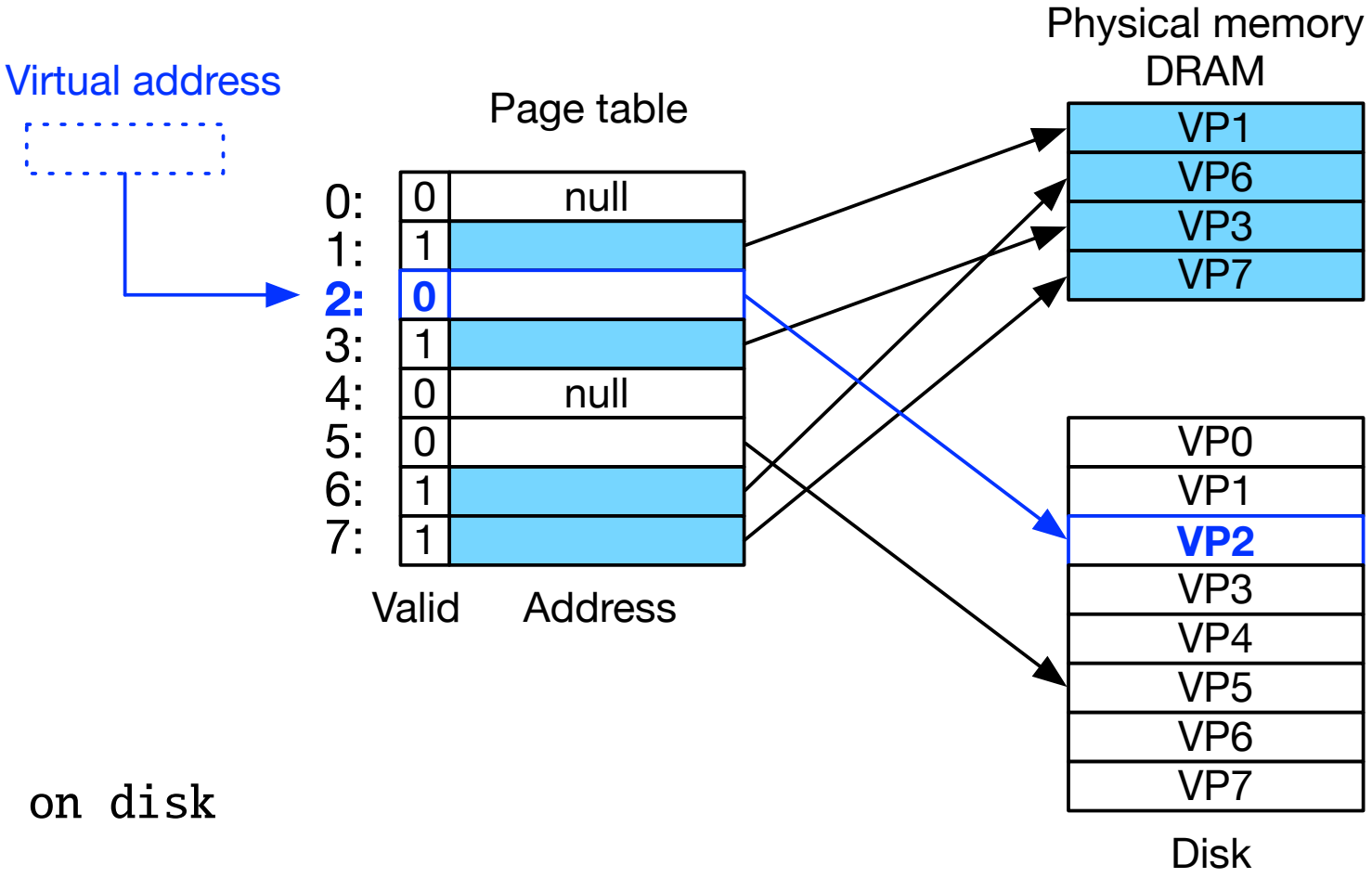

Virtual address
Page table
Physical memory
DRAM
0:
1:
2:
3:
4:
5:
6:
7:
0
1
0
1
0
0
1
1
null
null
VP1
VP6
VP3
VP7
VP0
VP1
VP2
VP3
VP4
VP5
VP6
VP7
Valid
Address
Disk

Page Fault



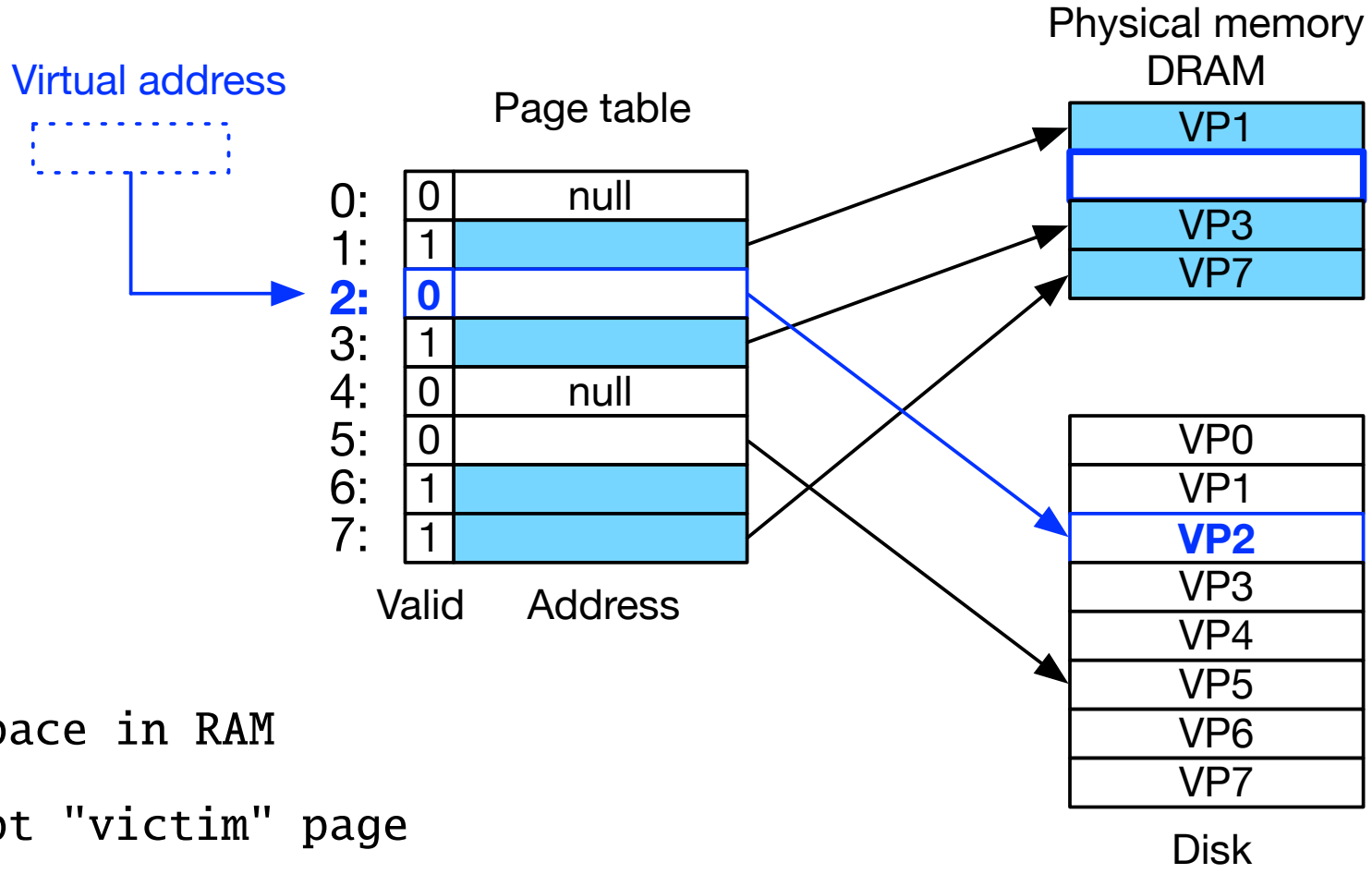
- Valid bit = 0
- Page not in RAM

Page Fault



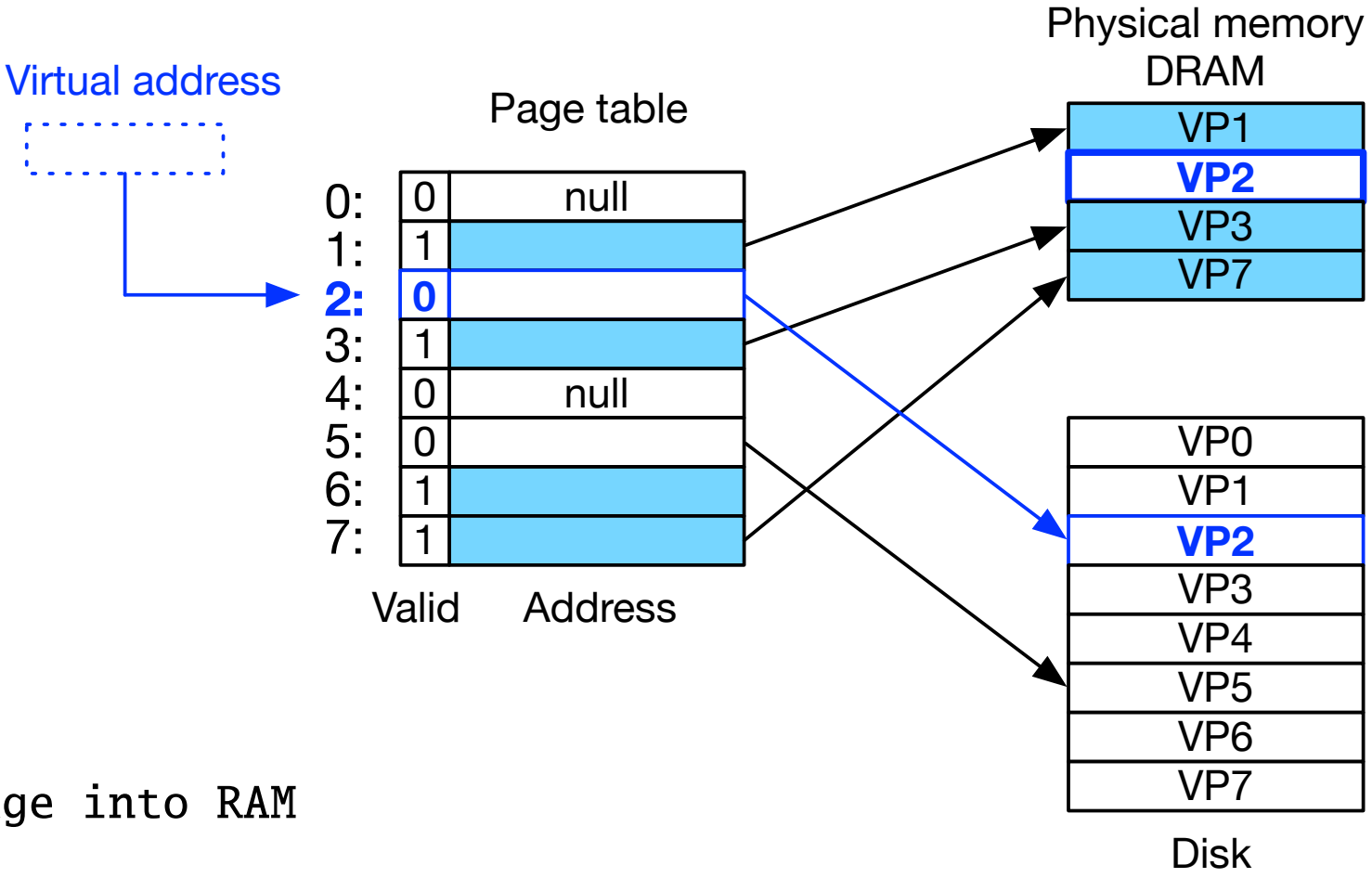
- Page is on disk

Page Fault



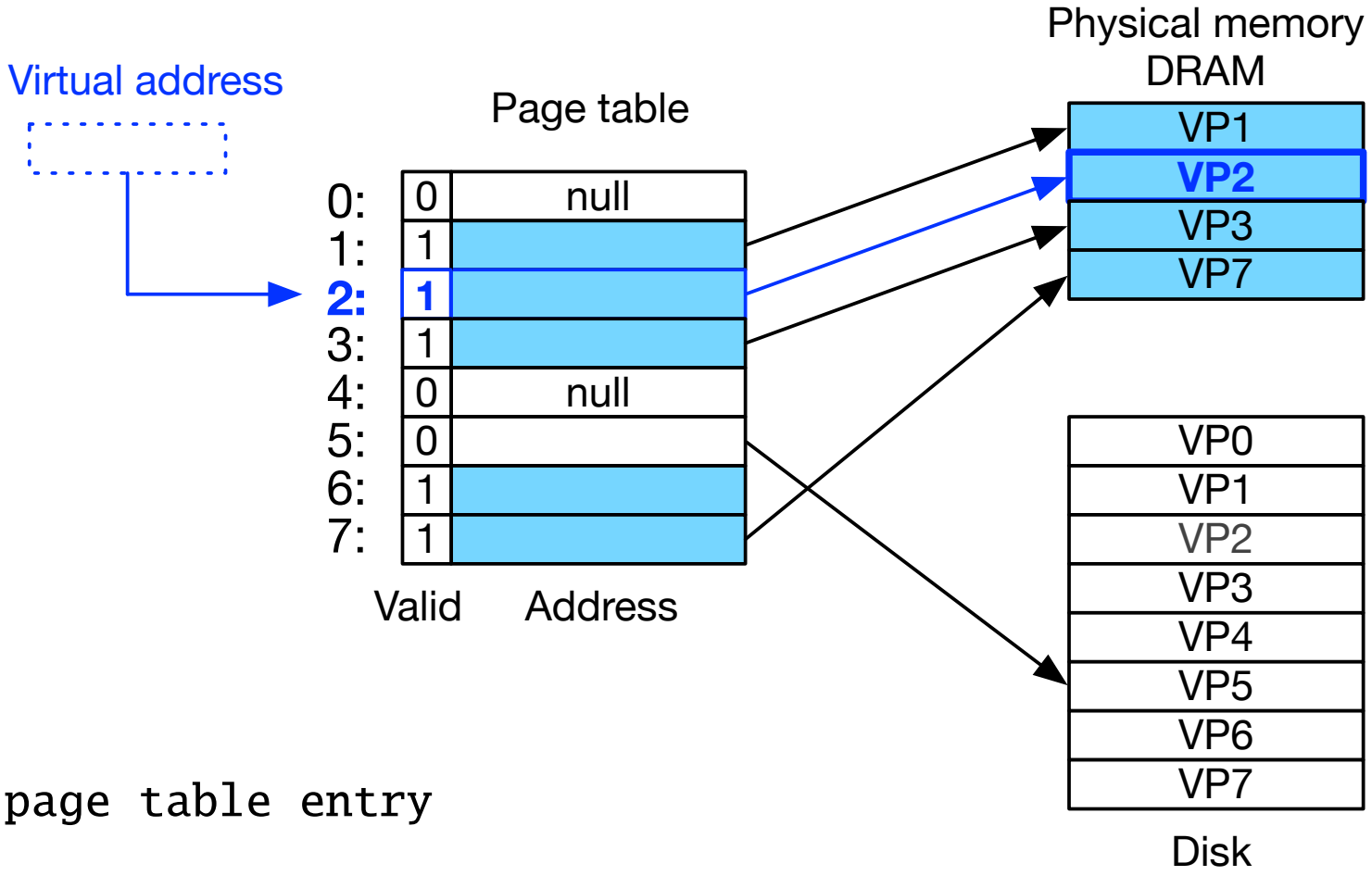
- Make space in RAM
- Pre-empt "victim" page
- Typically out-dated cached page

Page Fault



- Load page into RAM

Page Fault

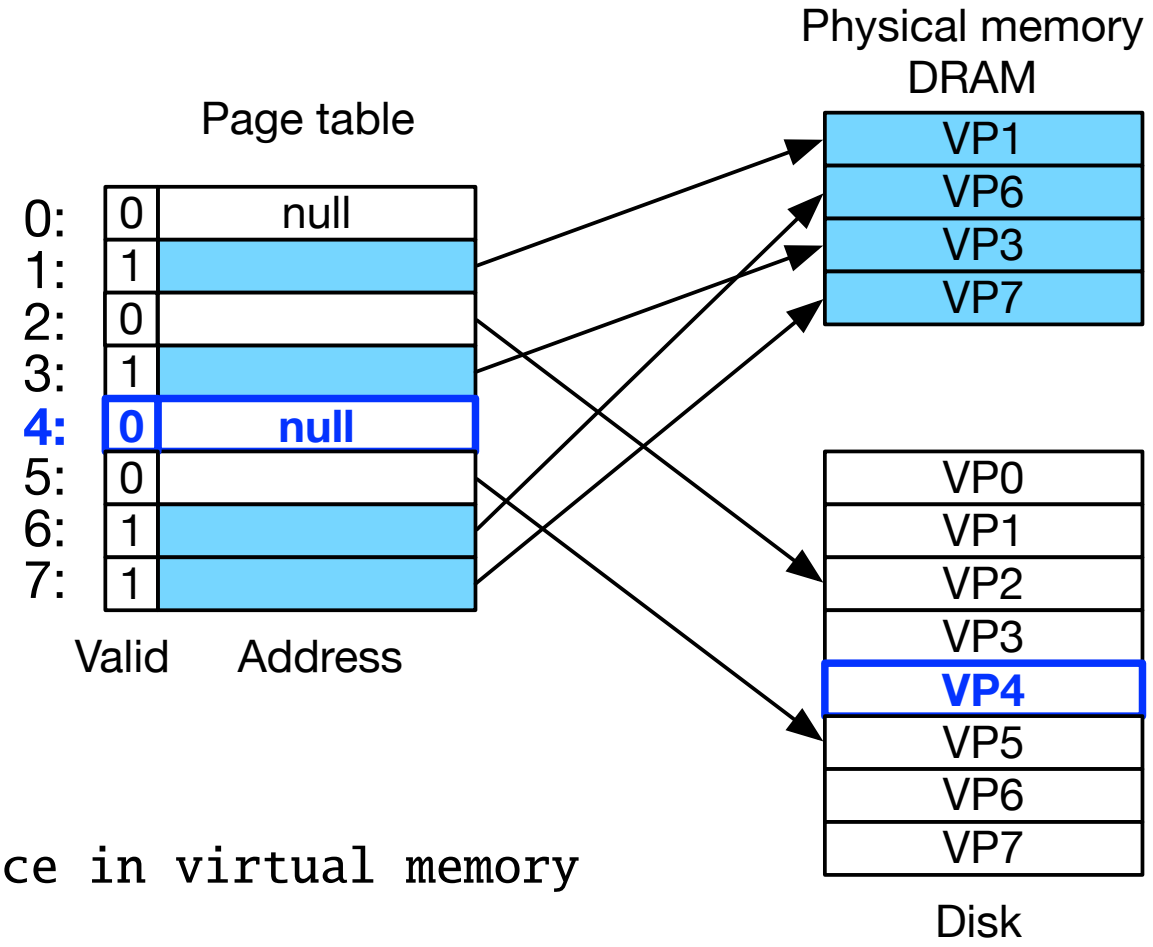


- Update page table entry

Allocating Pages

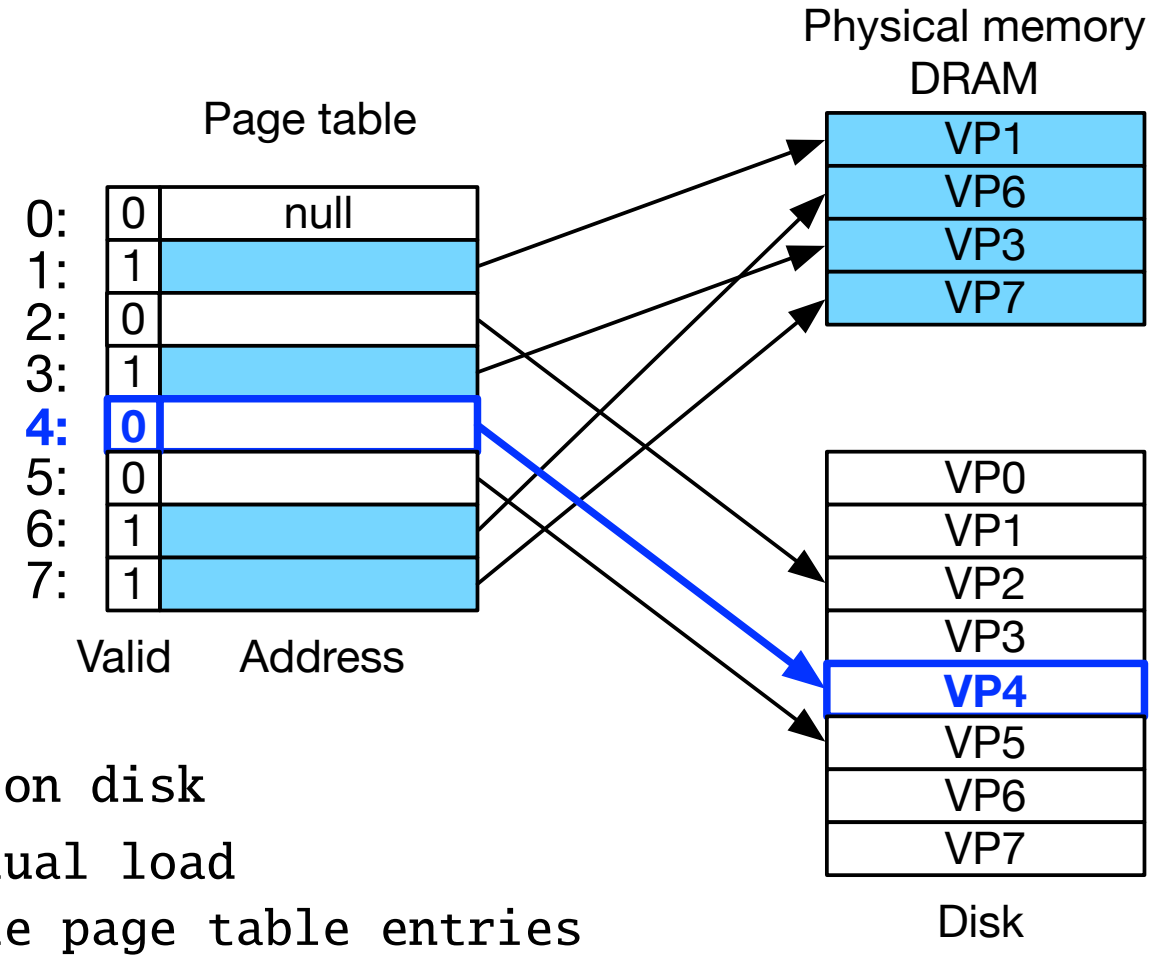
- What happens when we load a program?
- We need to load its executable into memory
- Similar: create data objects when program is running ("allocating" memory)

Allocating Page



- Identify space in virtual memory

Allocating Page



- Map to data on disk
  - do not actual load
  - just create page table entries
  - let virtual memory system handle loading

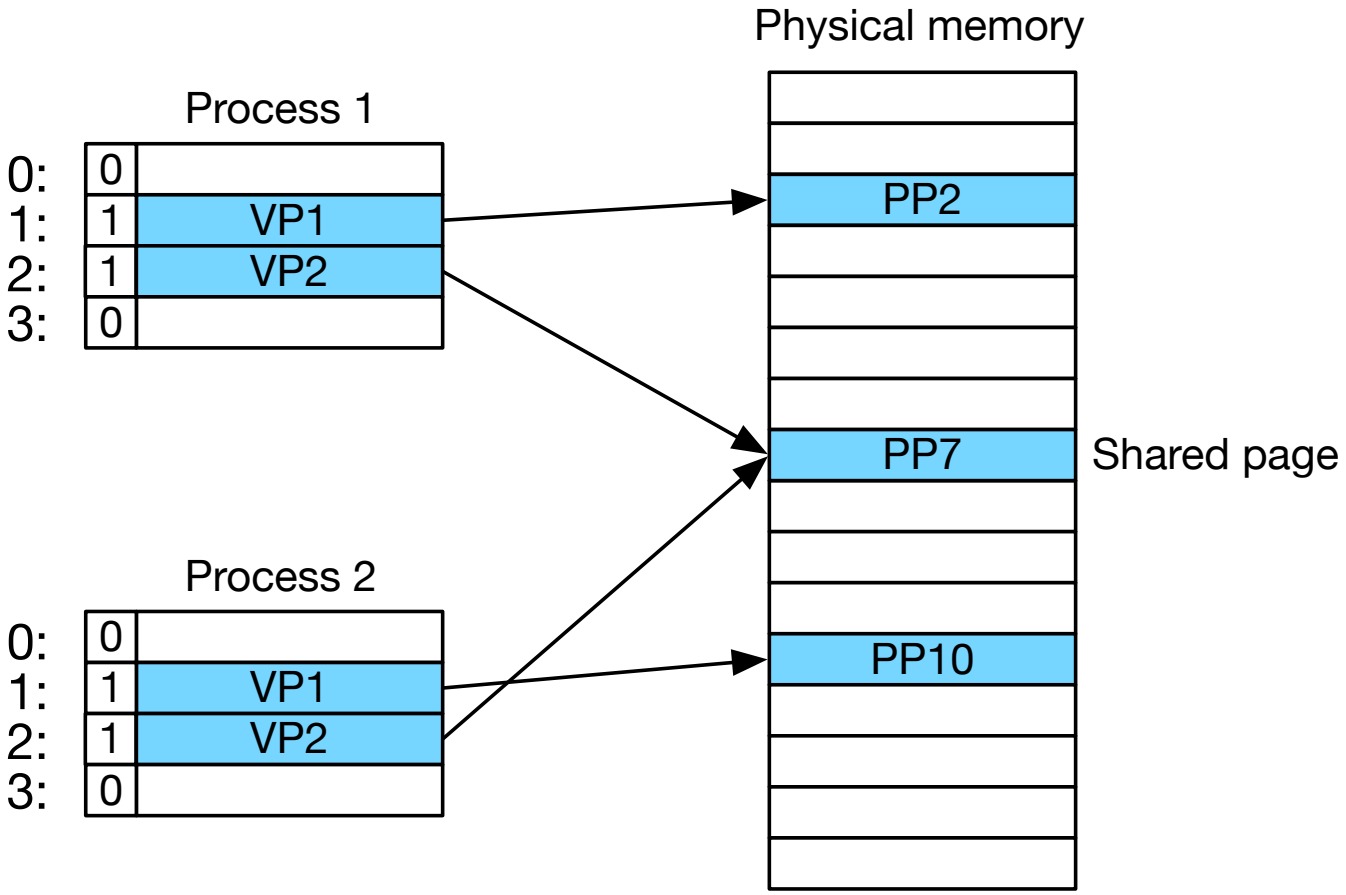
⇒ On-demand loading

Process Memory

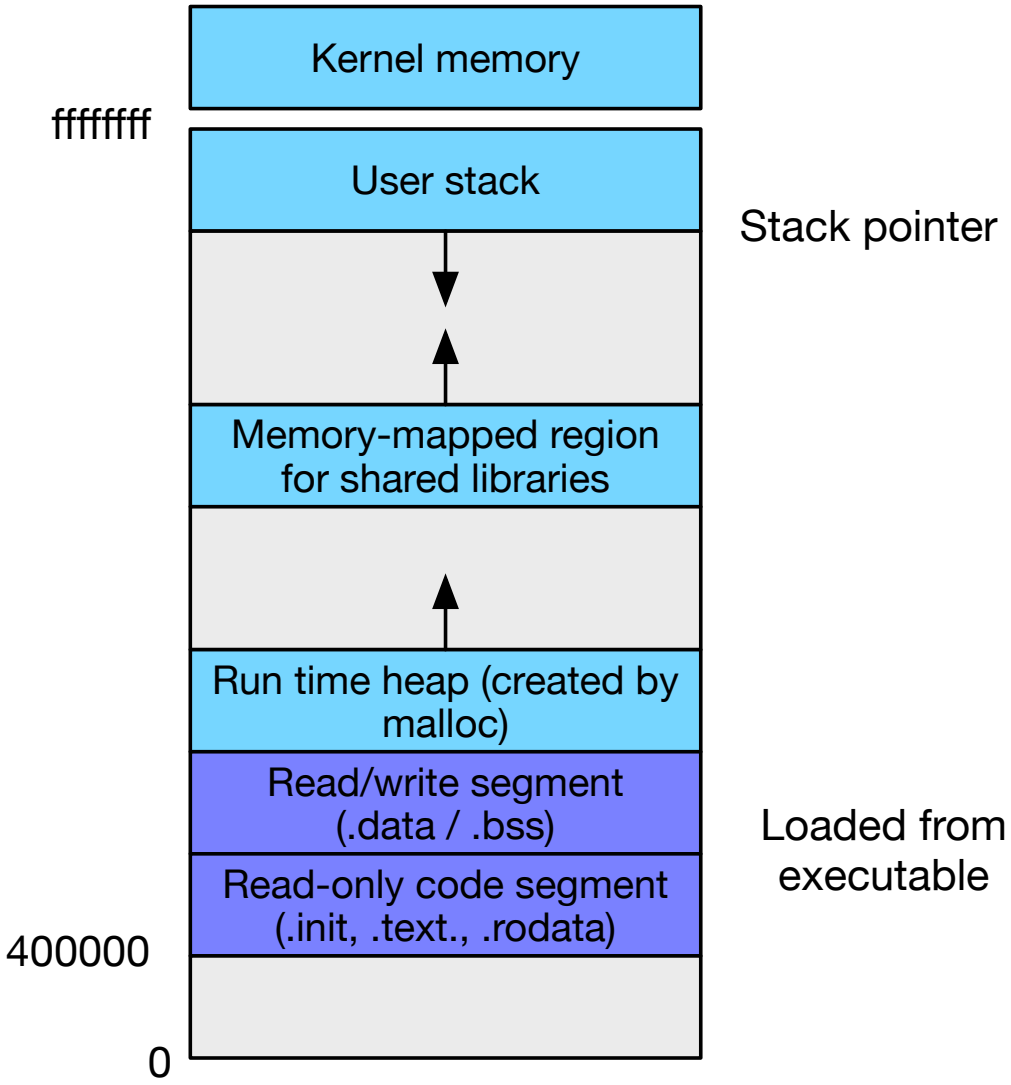
- Nothing loaded at startup
- Working set (or resident set)
  - pages of a process that are currently in DRAM
  - loaded by virtual memory system on demand
- Thrashing
  - memory actively required by all processes larger than physically available
  - frequent swapping of memory to/from disk
  - very bad: slows down machine dramatically

memory management

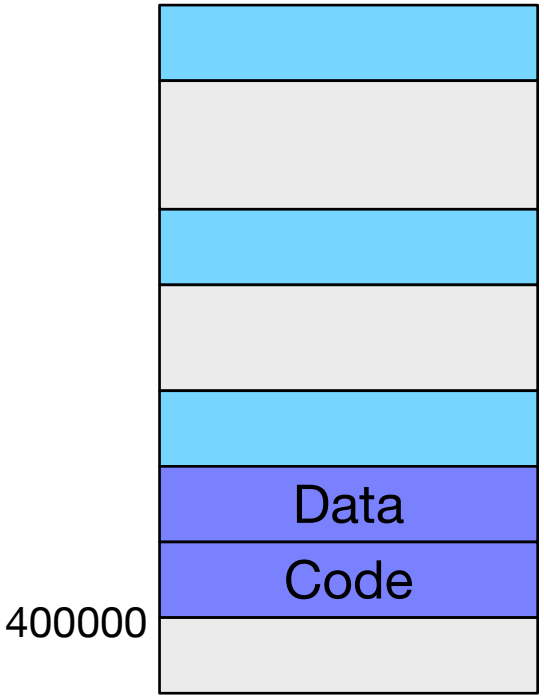
One Page Table per Process



Process Address Space



Simplified Linking



- Each process has its code in address 0x400000
- Easy linking: Linker can establish fixed addresses

Simplified Loading

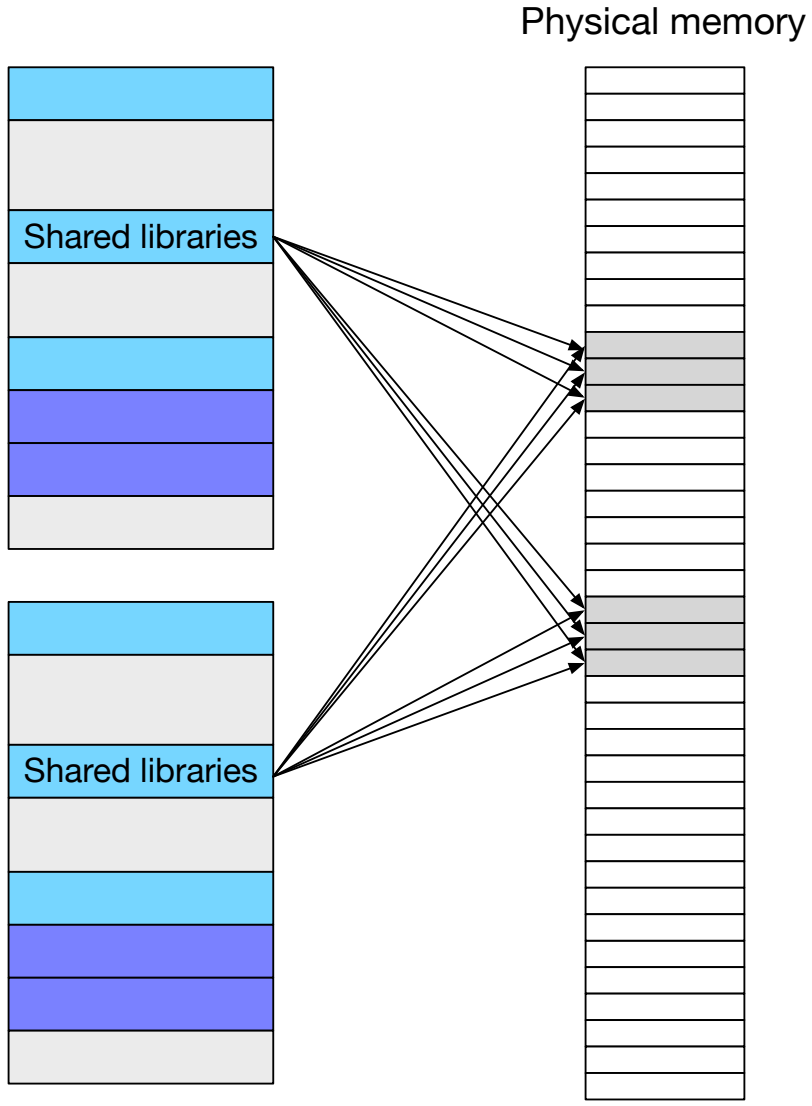
- When loading process into memory...
- Enter .data and .text section into page table
- Mark them as invalid (= not actually in RAM)
- Called memory mapping (more on that later)

Simplified Sharing

- Shared libraries
  used by several processes

  e.g., stdio providing printf,
  scanf, open, close, ...

- Not copied multiple times
  into RAM



Simplified Memory Allocation

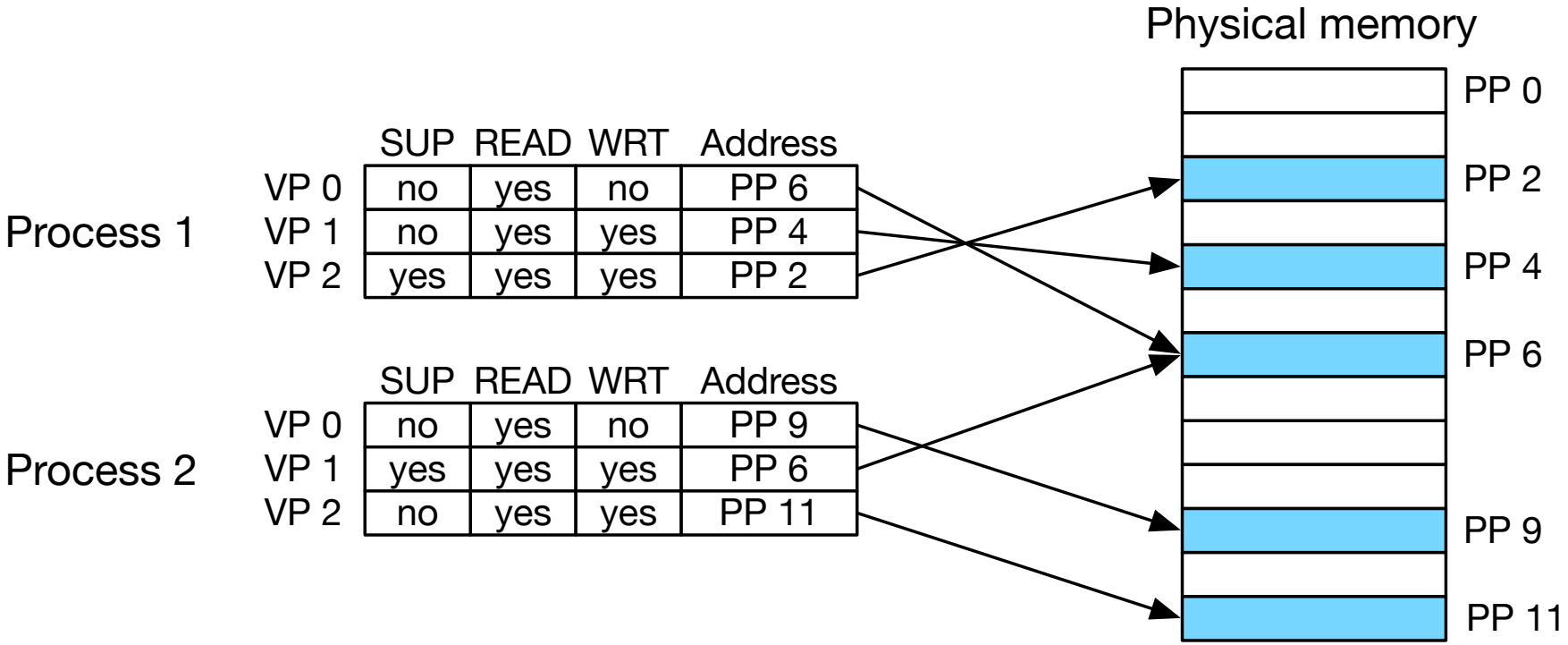
- Process may need more memory (e.g., malloc call)

$\Rightarrow$ New entry in page table

- Mapped to arbitrary pages in physical memory

- Do not have to be contiguous

Memory Protection



- Page may be kernel only: SUP=yes
- Page may be read-only (e.g., code)

address translation

Address Space

- Virtual memory size: $N = 2^n$ bytes
- Physical memory size: $M = 2^m$ bytes
- Page (block of memory): $P = 2^p$ bytes
- A virtual address can be encoded in n bits

Address Translation

- Task: mapping virtual address to physical address
  - virtual address (VA): used by machine code instructions
  - physical address (PA): location in RAM
- Formally

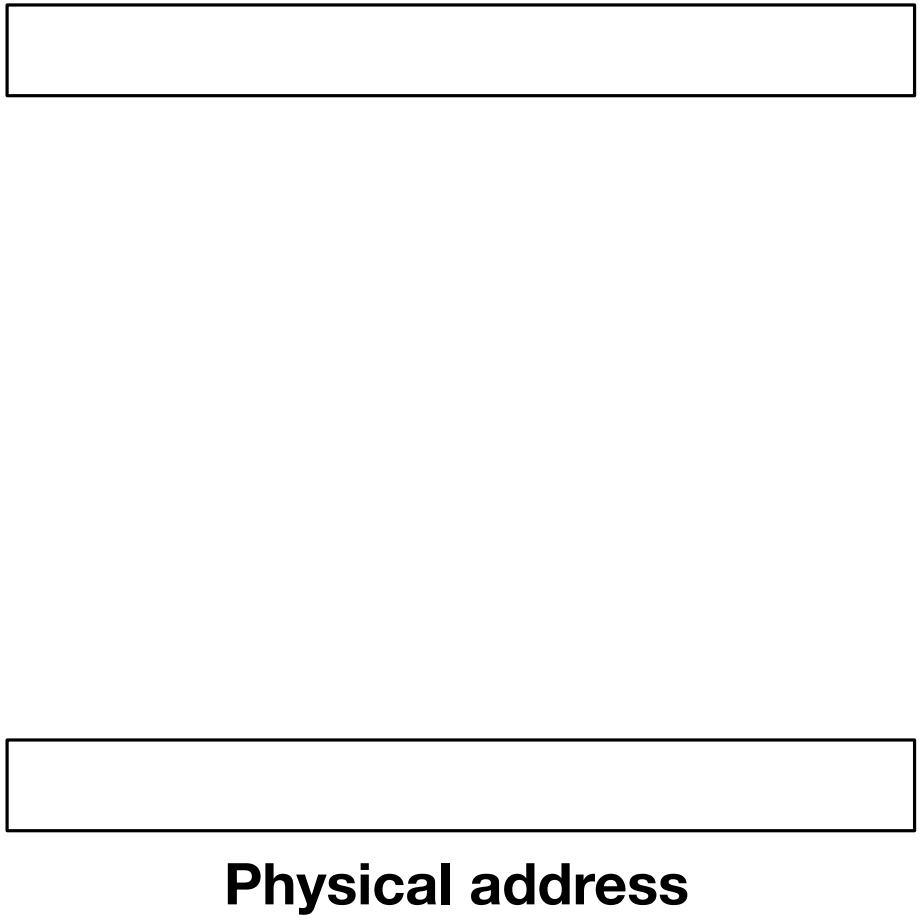
$$\text{MAP: VA} \rightarrow \text{PA} \cup 0$$

  where:

$$\begin{aligned} \text{MAP(A)} &= \text{PA if in RAM} \\ &= 0 \text{ otherwise} \end{aligned}$$

- Note: this happens very frequently in machine code
- We will do this in hardware: Memory Management Unit (MMU)

Basic Architecture



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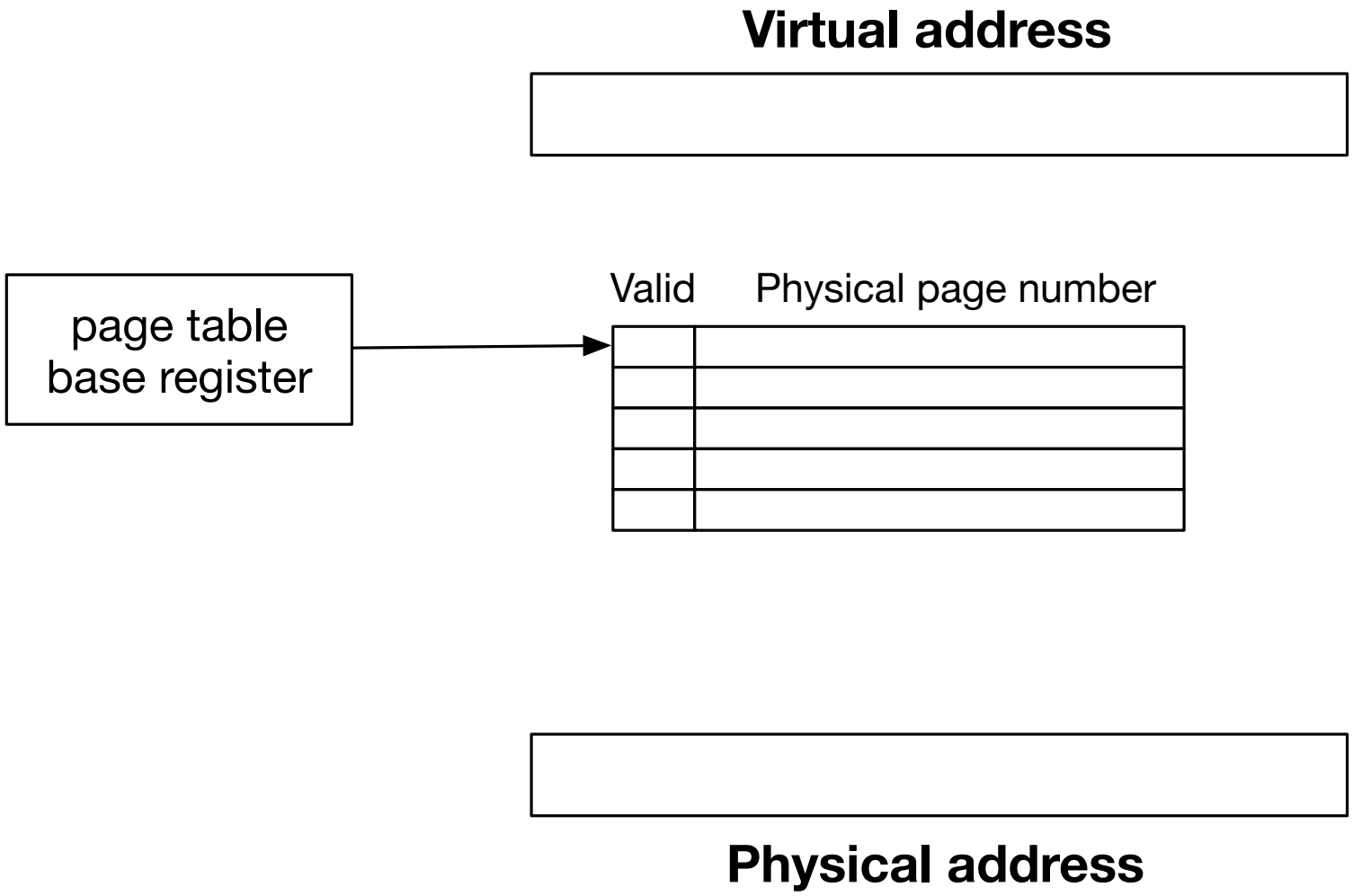

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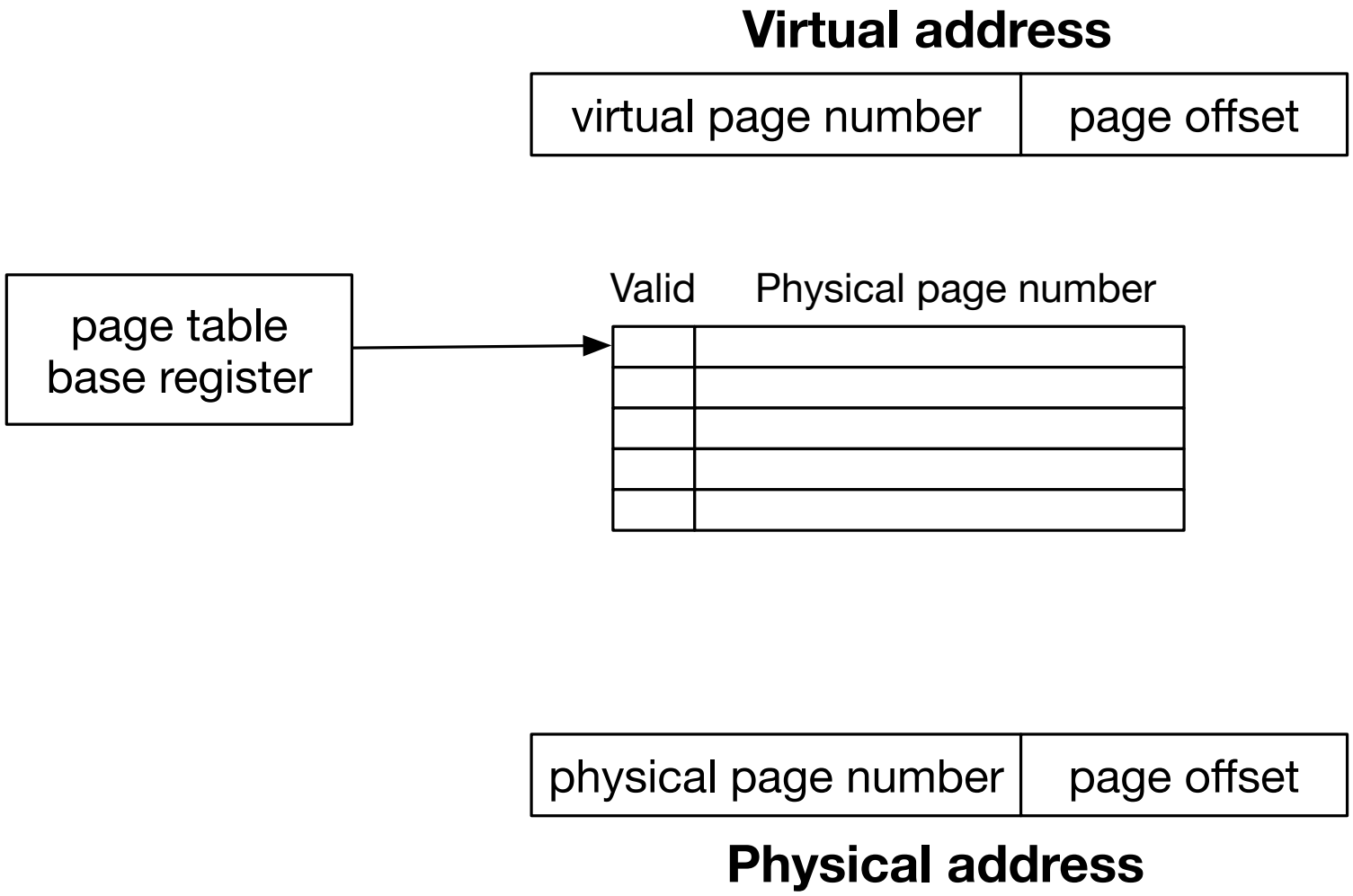

Basic Architecture