

# Lecture 22: Virtual Memory

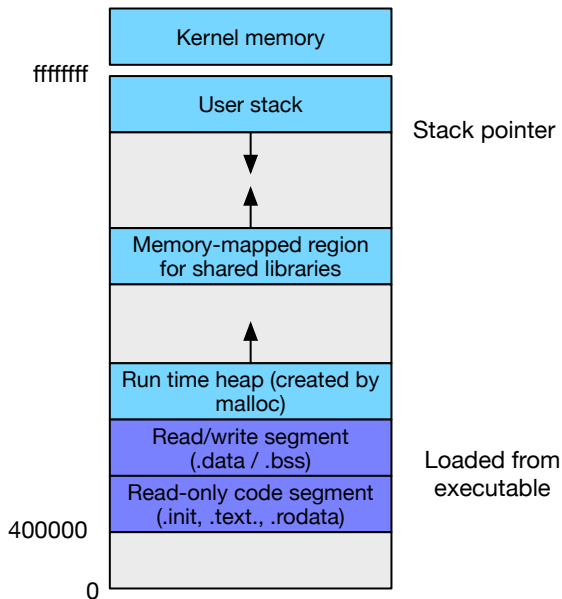
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601.229 Computer Systems Fundamentals



# 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

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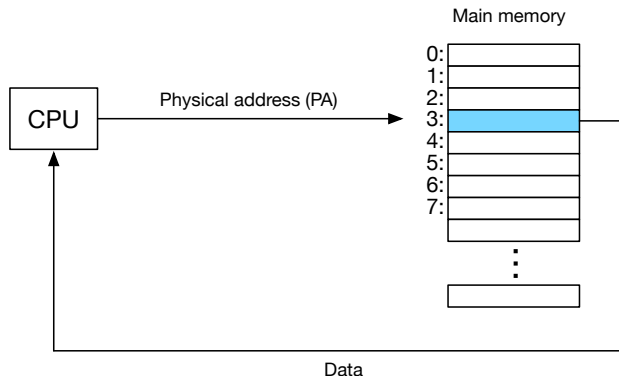
- ▶ Abstraction of physical memory
- ▶ Purpose
  - ▶ appearance of more available memory than physically exists (DRAM)
  - ▶ handles disk caching / loading
  - ▶ insulates memory of each process
- ▶ Page table: maps from virtual address to physical addresses
- ▶ Memory management unit (MMU):  
hardware 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

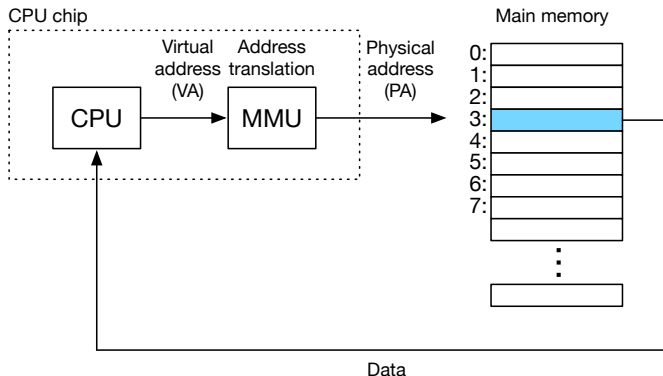
# Virtual addressing

# Physical Addressing



- So far, assumed CPU addresses physical memory

# Virtual Addressing



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

# Address Space

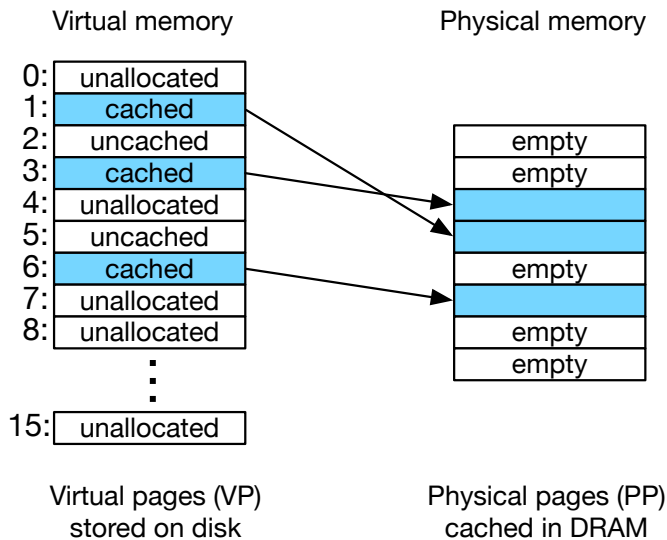
- ▶ Virtual memory size:  $N = 2^n$  bytes, e.g., 256TB
- ▶ Physical memory size:  $M = 2^m$  bytes, e.g., 16GB
- ▶ Page (block of memory):  $P = 2^p$  bytes, e.g., 4KB
- ▶ A virtual address can be encoded in  $n$  bits

# 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



# State of Virtual Memory Page

- ▶ Cached
  - ▶ allocated page
  - ▶ stored in physical memory

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# 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

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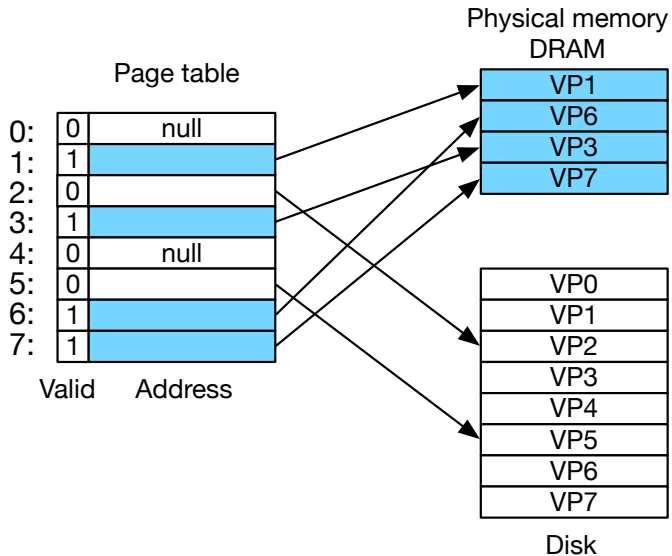
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(actually, a tree where the leaves store the page table entries)
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- ▶ Valid bit
  - ▶ set if PTE currently maps to physical address (cached)
  - ▶ not set otherwise (uncached or unallocated)

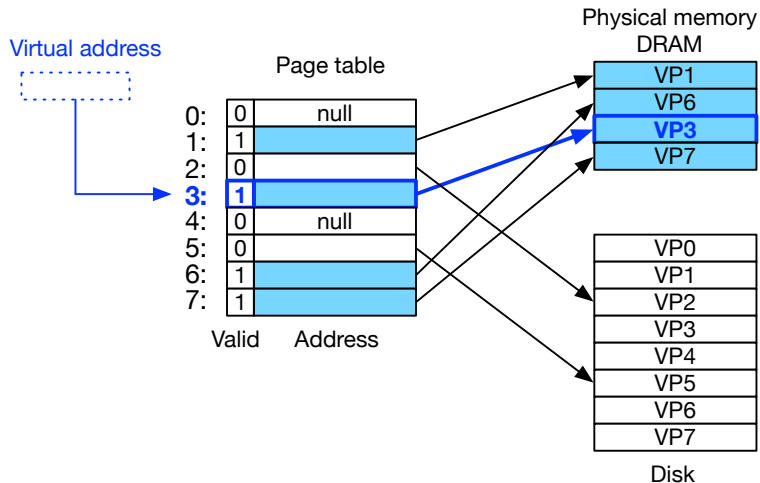
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- ▶ Valid bit
  - ▶ set if PTE currently maps to physical address (cached)
  - ▶ not set otherwise (uncached or unallocated)
- ▶ Mapped address
  - ▶ if cached: physical address in DRAM
  - ▶ if not cached: physical address on disk

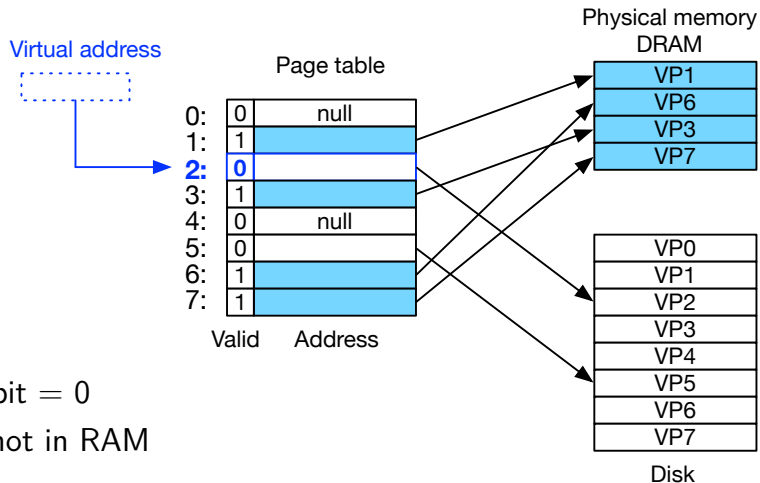
# Page Table



# Page Hit

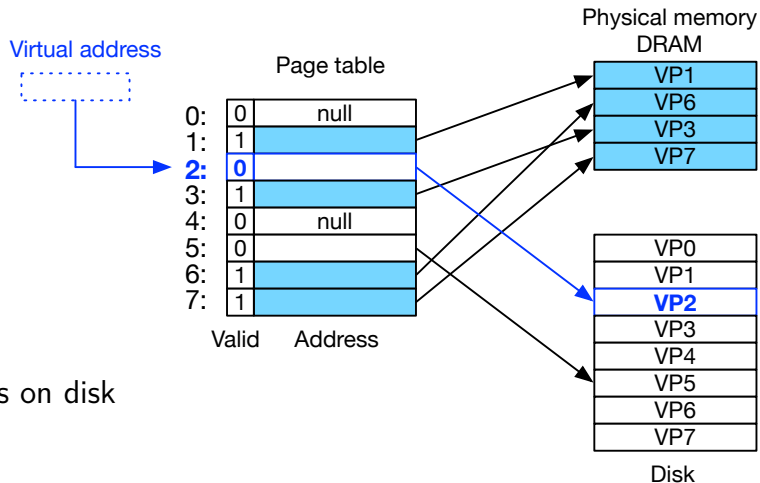


# Page Fault

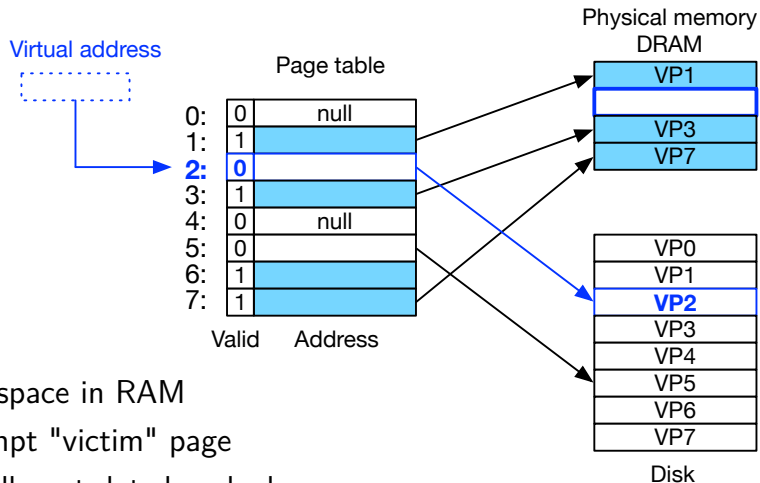


- ▶ Valid bit = 0
- ▶ Page not in RAM

# Page Fault

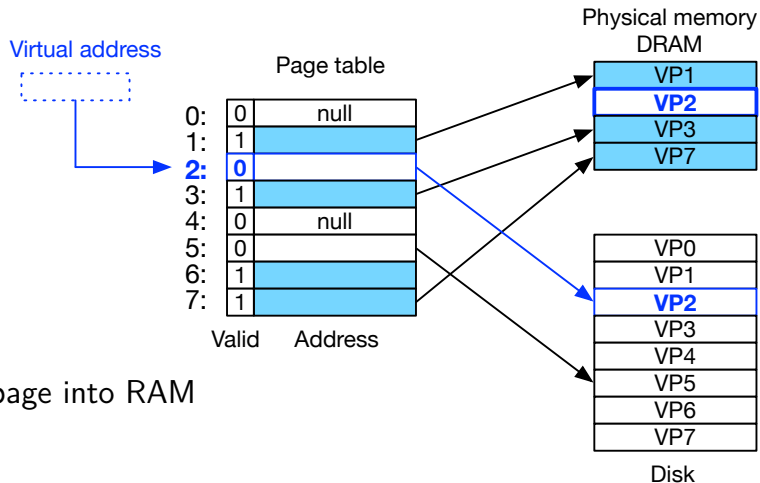


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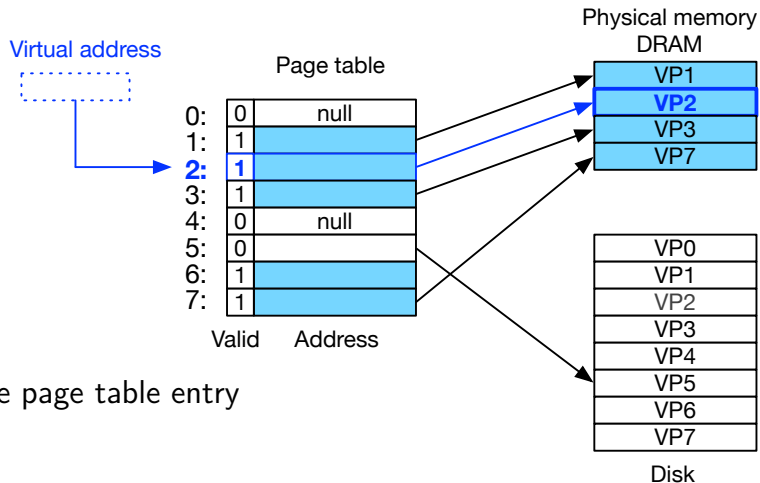


- ▶ Make space in RAM
- ▶ Pre-empt "victim" page
- ▶ Typically out-dated cached page

# Page Fault



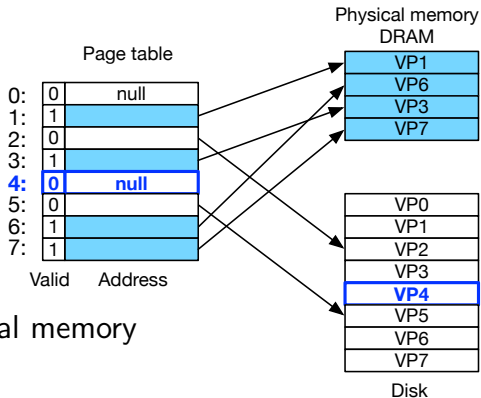
# Page Fault



# Allocating Pages

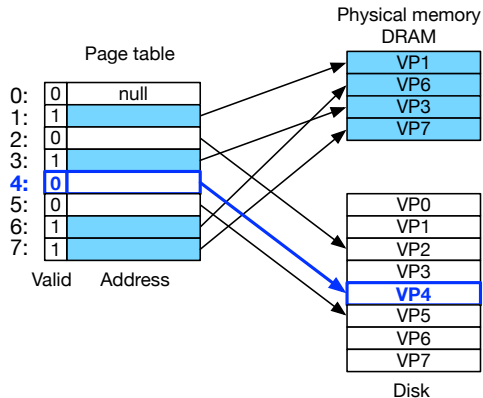
- ▶ What happens when we load a program?
- ▶ We need to load its executable into memory
- ▶ Similar: create data objects when program is running (“allocating” memory)

# 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

# Clicker quiz!

Clicker quiz omitted from public slides

# Process Memory

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  - ▶ pages of a process that are currently in DRAM
  - ▶ loaded by virtual memory system on demand

# 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