CS 153
Design of Operating Systems

Fall 21

Lecture 12: Advanced Paging

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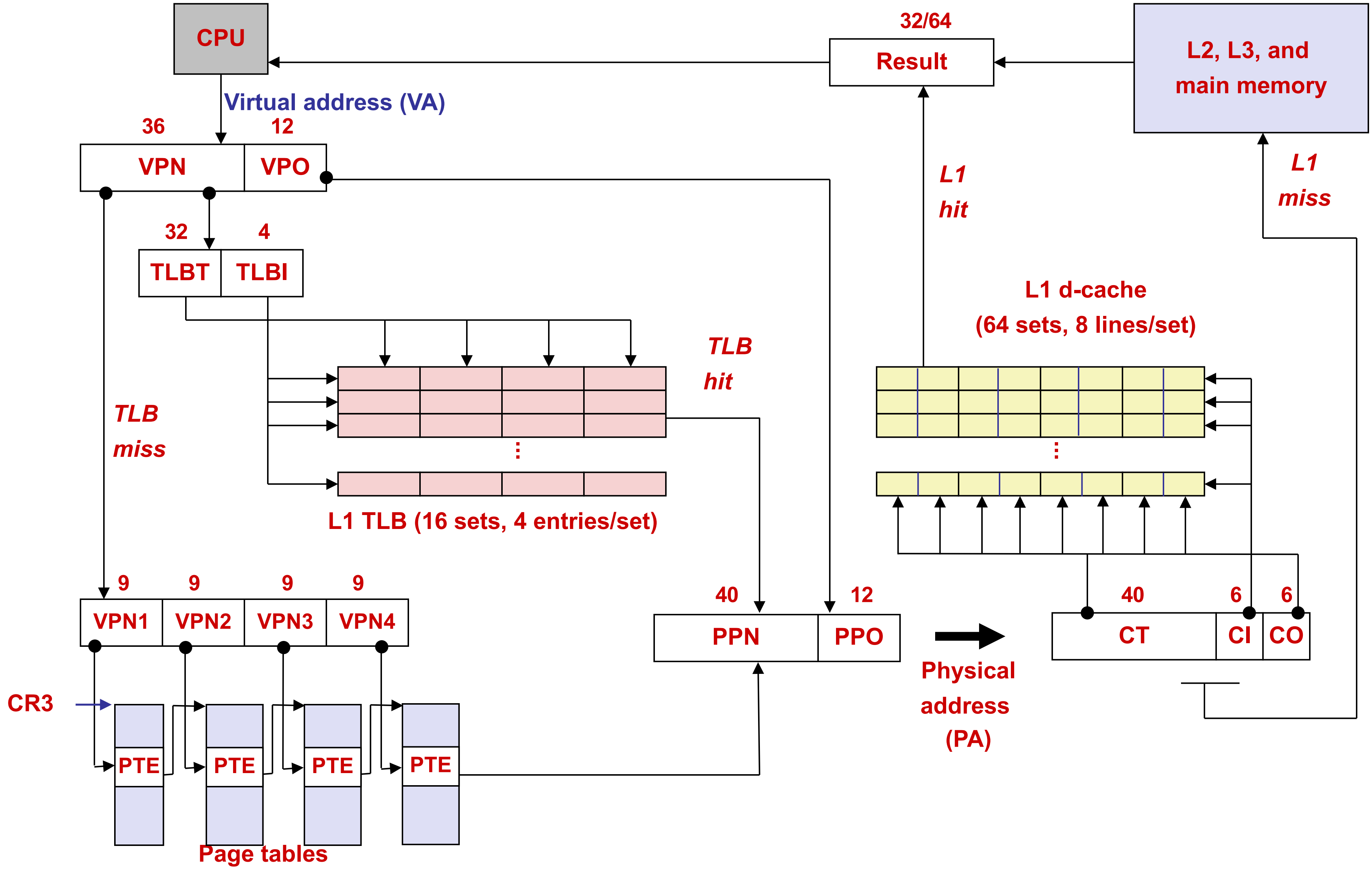
Some slides modified from originals by Dave O'hallaron

End-to-end Core i7 Address Translation



Advanced Paging

- So far we have discussed how to make memory access faster under paging
- Next, we will discuss interesting tricks on using paging (how those bits in the PTE are used)
    - Sharing
    - Copy-on-Write
    - Memory mapped file
    - On-demand mapping
    - Virtual memory

Core i7 Level 1-3 Page Table Entries

63	62–52	51–12	11–9	8	7	6	5	4	3	2	1	0
XD	Unused	Page table physical base address	Unused	G	PS		A	CD	WT	U/S	R/W	P=1

Available for OS (page table location on disk)	P=0

P: Child page table present in physical memory (1) or not (0).

R/W: Read-only or read-write access access permission for all reachable pages.

U/S: user or supervisor (kernel) mode access permission for all reachable pages.

WT: Write-through or write-back cache policy for the child page table.

CD: Caching disabled or enabled for the child page table.

A: Reference bit (set by MMU on reads and writes, cleared by software).

PS: Page size either 4 KB or 2 MB (defined for Level 1 PTEs only).

G: Global page (don’t evict from TLB on task switch)

Page table physical base address: 40 most significant bits of physical page table address (forces page tables to be 4KB aligned)

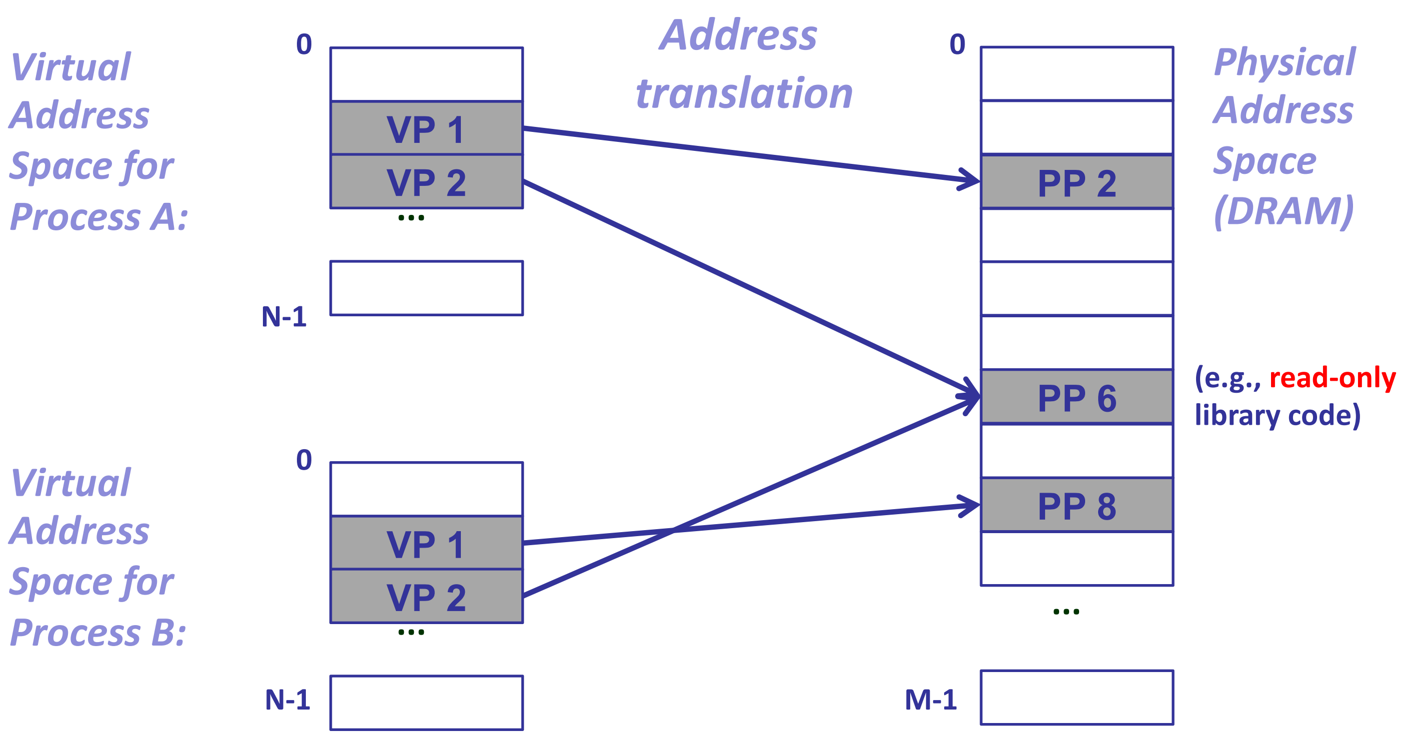
XD: Non-executable pages

Sharing

- Private virtual address spaces protect applications from each other
  - Usually exactly what we want
- But this makes it difficult to share data (have to copy)
  - Parents and children in a forking Web server or proxy will want to share an in-memory cache without copying
- We can use shared memory to allow processes to share data using direct memory references
  - Both processes see updates to the shared memory segment
    - Process B can immediately read an update by process A

Sharing (2)

- Sharing code and data among processes
  - Map virtual pages to the same physical page (here: PP 6)



Sharing (3)

- Can map shared memory at same or different virtual addresses in each process' address space
  - Different:
    - 10^{th} virtual page in P1 and 7^{th} virtual page in P2 correspond to the 2^{nd} physical page
    - Flexible (no address space conflicts), but pointers inside the shared memory segment are invalid
  - Same:
    - 2^{nd} physical page corresponds to the 10^{th} virtual page in both P1 and P2
    - Less flexible, but shared pointers are valid

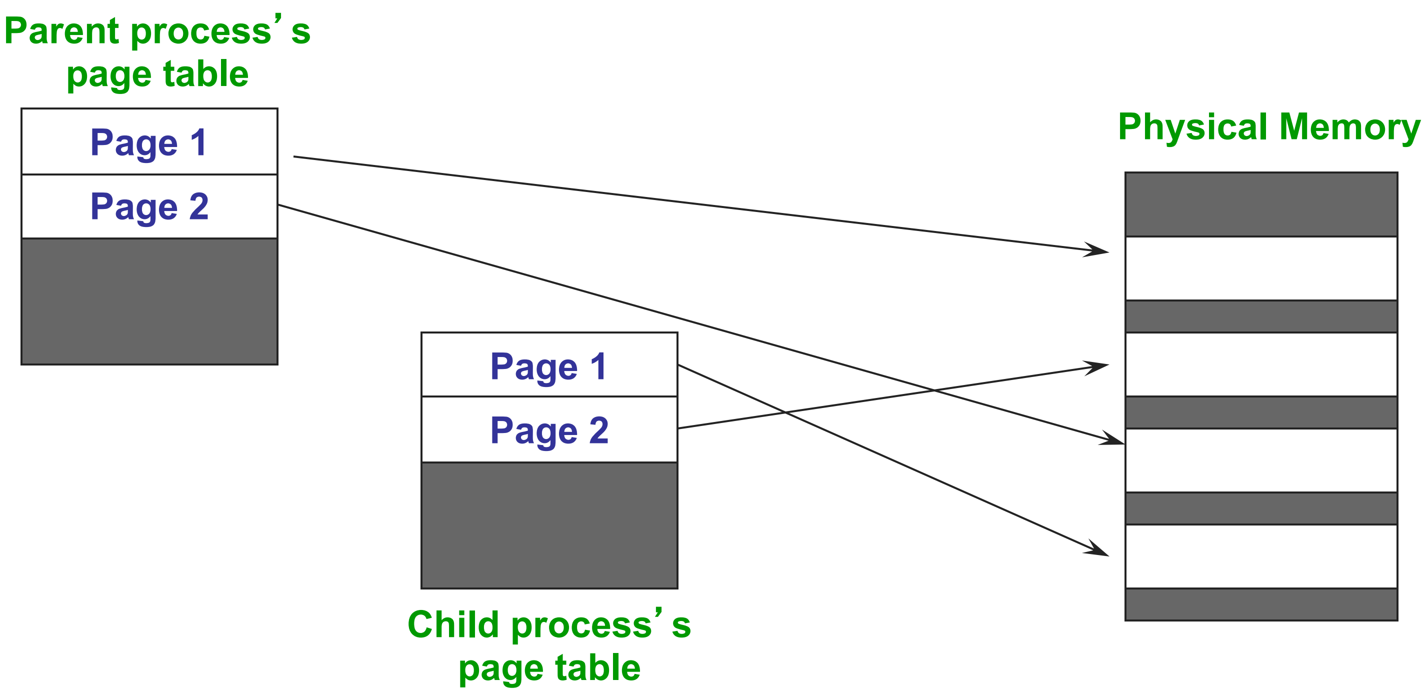
Sharing (4)

- Linux API
  - Map to different address
    - `shm_open()`: create and open a new object, or open an existing object.
    - `mmap()`: map the shared memory object into the virtual address space of the calling process.
  - Map to the same address
    - `mmap()`: with MAP_SHARED

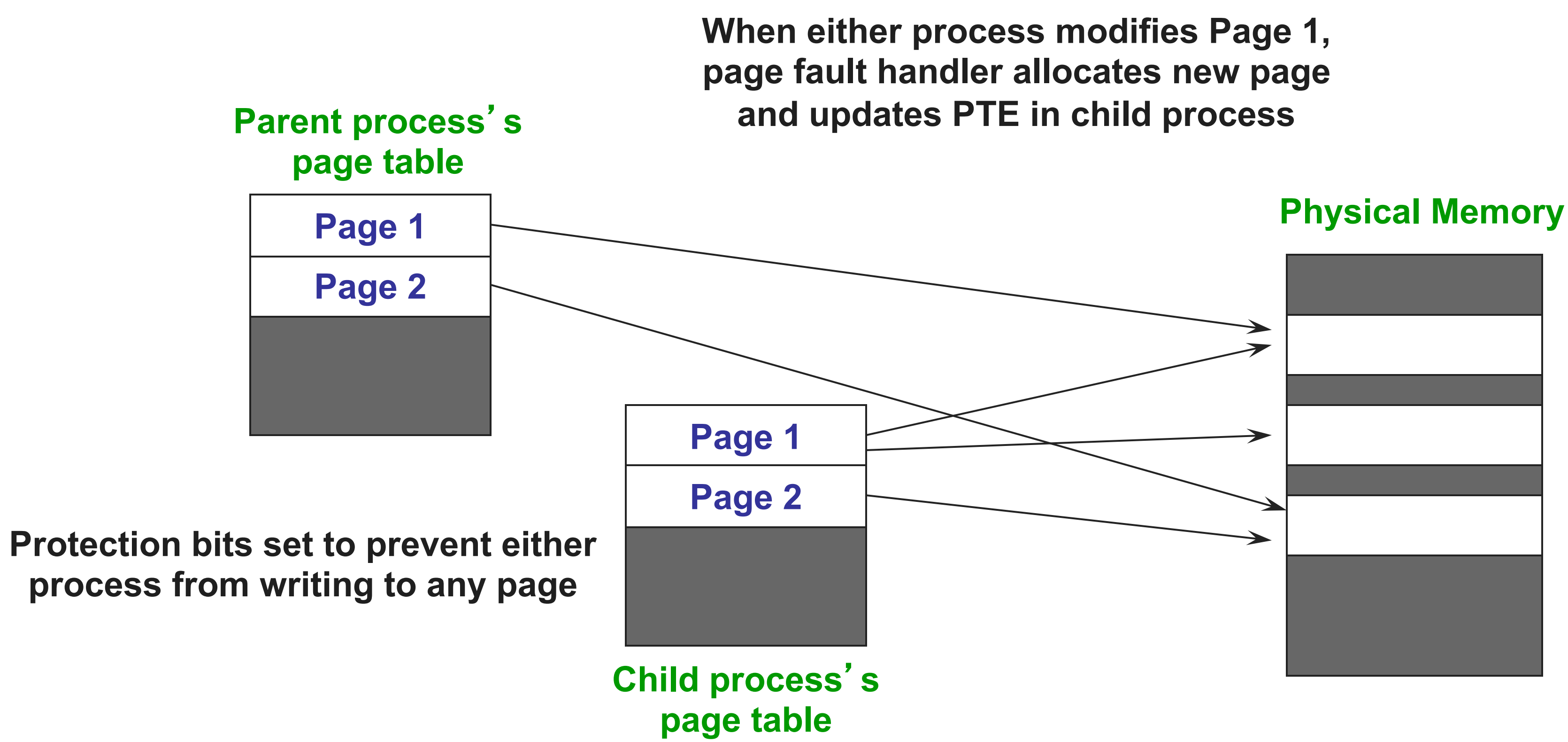
Copy on Write

- Recall what happens during `fork()`
  - Entire address spaces needs to be copied
- Use Copy on Write (CoW) to defer large copies as long as possible, hoping to avoid them altogether
  - Instead of copying pages, create shared mappings of parent pages in child virtual address space
  - Shared pages are protected as read-only in parent and child
    - Reads happen as usual
    - Writes generate a protection fault, trap to OS, copy page, change page mapping in client page table, restart write instruction

Execution of fork()

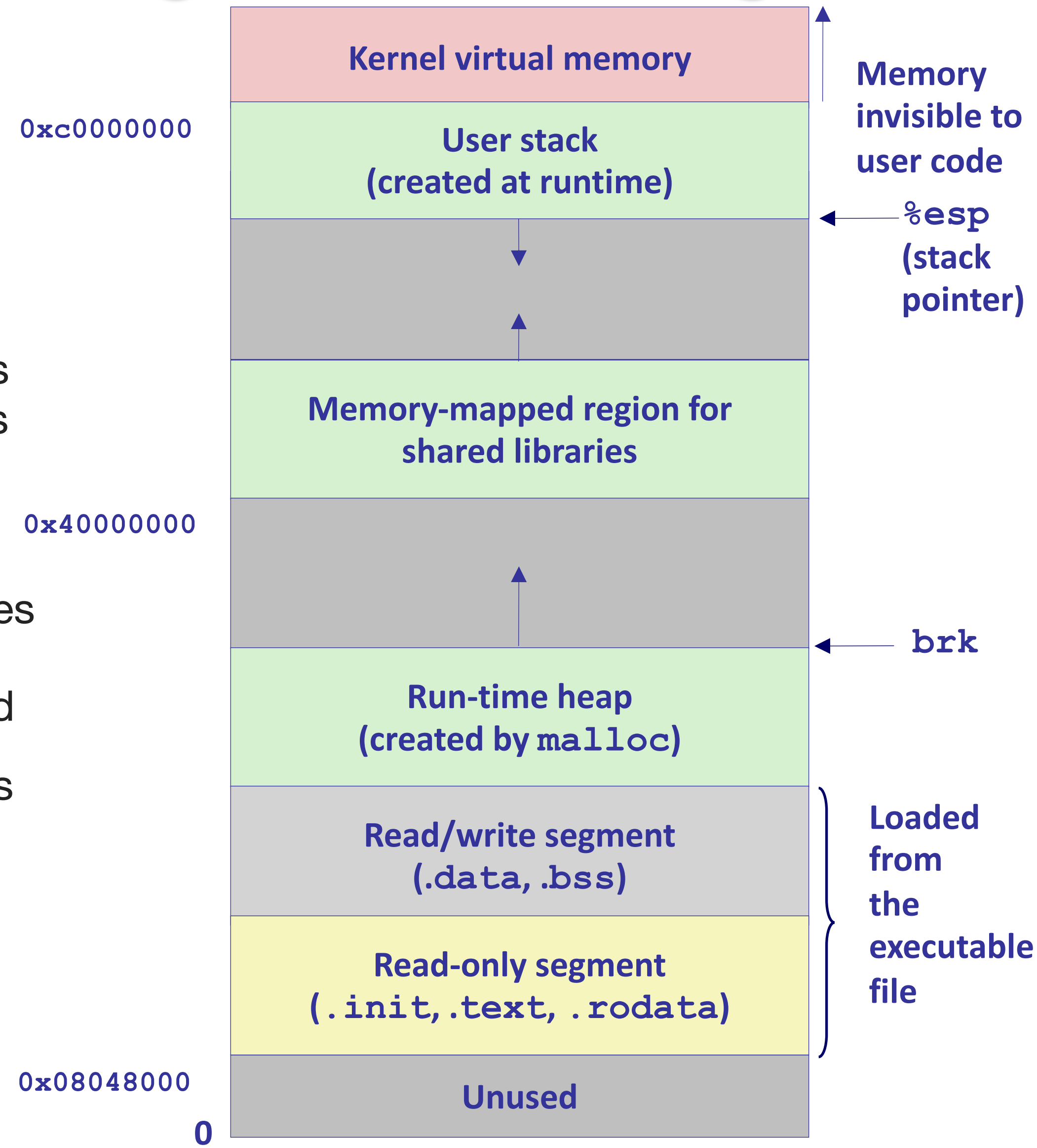


fork() with Copy on Write



Simplifying Linking and Loading

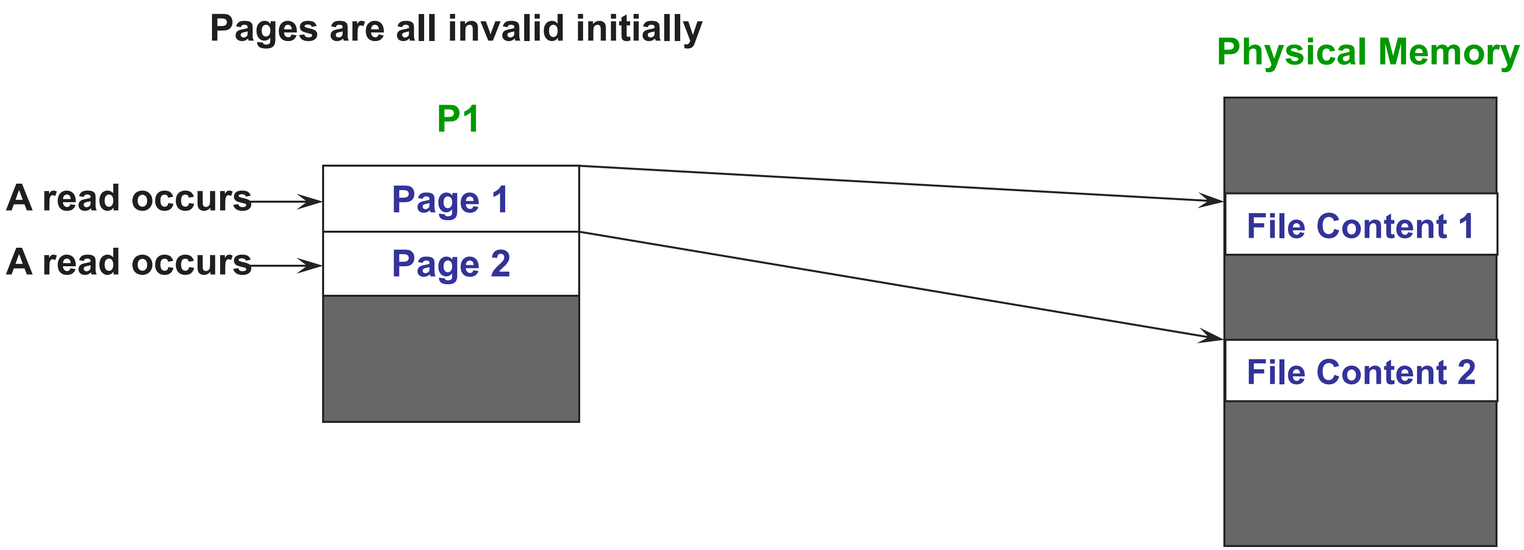
- Linking
  - Each program has similar virtual address space
  - Code, stack, and shared libraries always start at the same address
- Loading
  - **`execve()`** allocates virtual pages for .text and .data sections = creates PTEs marked as invalid
  - The **`.text`** and **`.data`** sections are copied, page by page, on demand by the virtual memory system



Mapped Files

- Mapped files enable processes to do file I/O using loads and stores
  - Instead of "open, read into buffer, operate on buffer, …"
- Bind a file to a virtual memory region (mmap() in Unix)
  - PTEs map virtual addresses to physical frames holding file data
  - Virtual address base + N refers to offset N in file
- Initially, all pages mapped to file are invalid
  - OS reads a page from file when invalid page is accessed
    - How?

Memory-Mapped Files



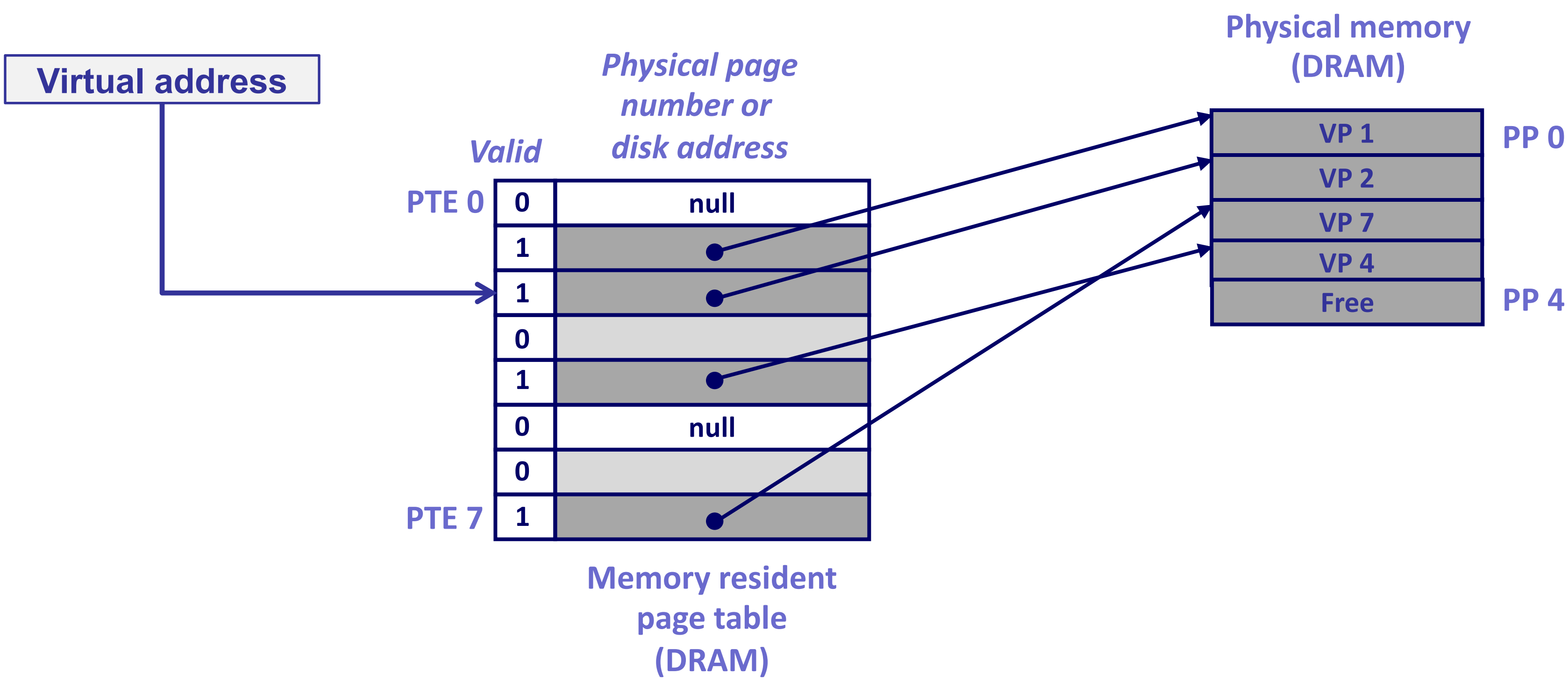
What happens if we unmap the memory?
How do we know whether we need to write changes back to file?

Writing Back to File

- OS writes a page to file when evicted, or region unmapped
- Dirty bit trick (not protection bits)
  - If page is not dirty (has not been written to), no write needed

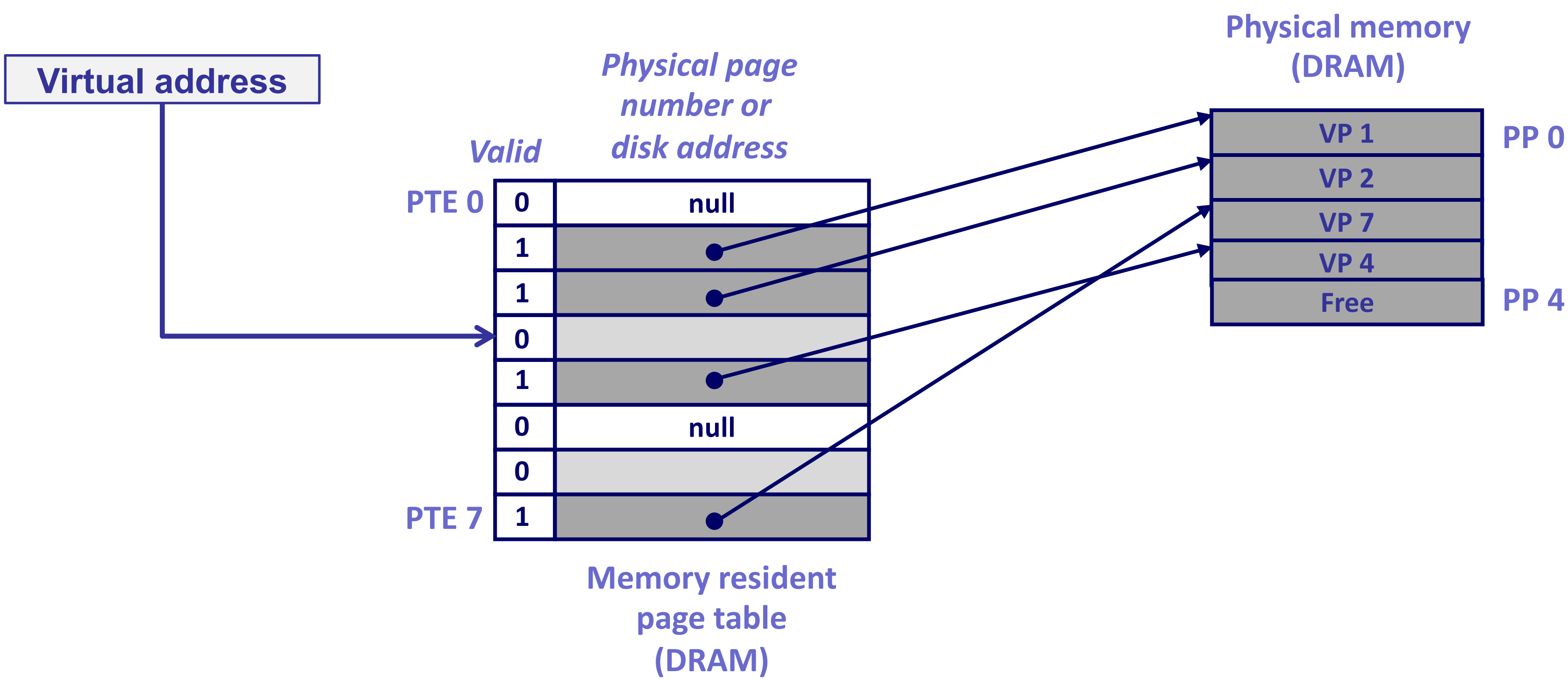
Page Hit

- Page hit: reference to VM word that is in physical memory (DRAM cache hit)



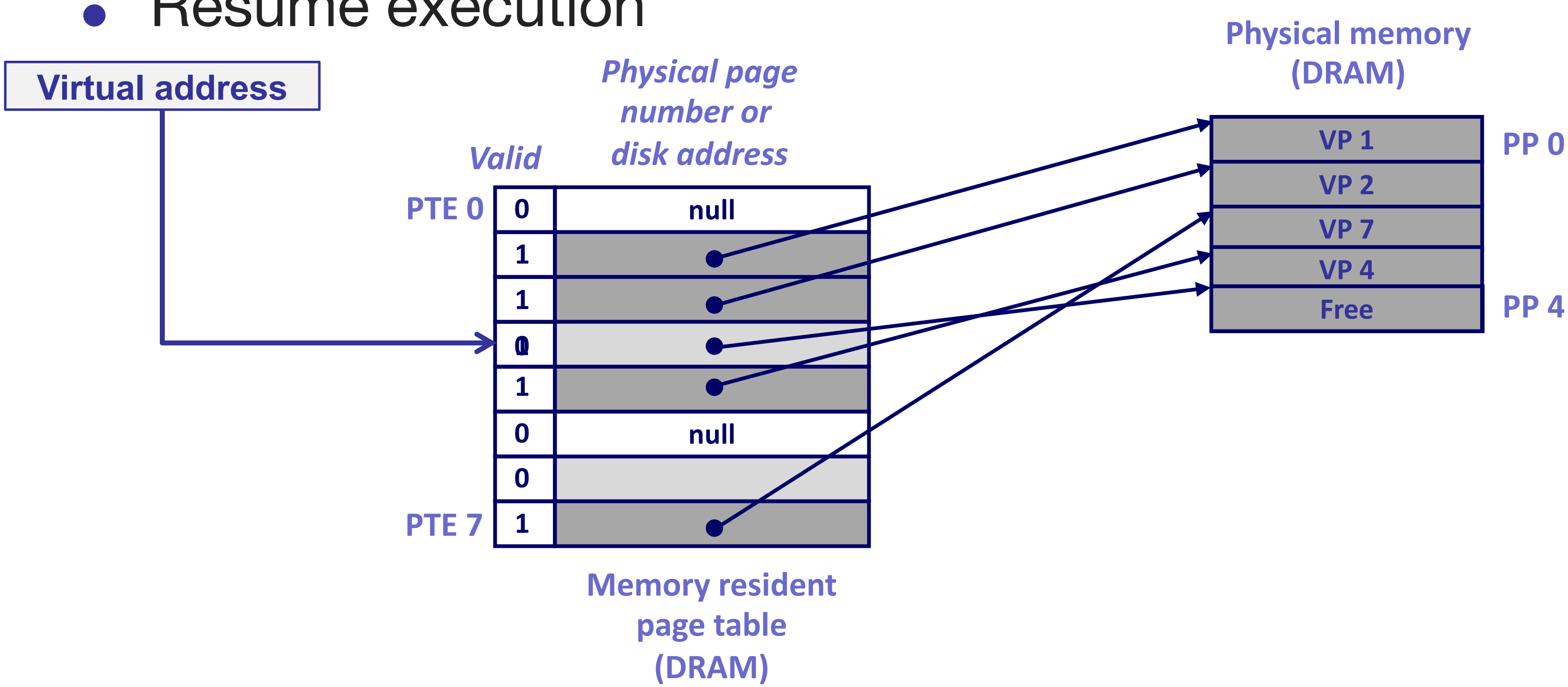
Page Fault

- Page fault: reference to VM word that is not in physical memory (DRAM cache miss)



On-demand Mapping

- Allocate physical page
- Fix the page table
- Resume execution



How do we know whether the fault is fixable?

On-demand Mapping

- When the process calls `mmap()`, the kernel remembers
  - The region [addr, addr+length]
    - What virtual addresses are valid/mapped
  - The backing: just memory (ANONYMOUS) or file
- During page fault handling, the kernel checks
  - If the faulty virtual address is valid
  - If so, fix based on the backing

Memory Protection

- R/W (read-only or writable)
  - We've seen how it is used in CoW
  - It is also important in preventing attacks (e.g., mark code as read-only so attackers cannot modify them)
- U/S (user or kernel)
  - How do we protect the kernel? Give it a different address space?
    - Too expensive for context switch during system calls
    - May not be a bad idea if security is a concern (recent Meltdown attack)

Memory Protection (2)*

- U/S
  - Besides protecting the kernel from directly accessed from user space, this bit is also used to prevent kernel from executing wrong code or access wrong data, why?
    - Attackers can attack the kernel and try to execute user space code under kernel context (privilege)
- XD (executable or not)
  - In the old days there's an attack technique called "code injection" where attacker force the CPU to interpret data as code
  - XD is a response to such attacks by marking data pages as not executable