CSE320 System Fundamentals II
Virtual Memory 2

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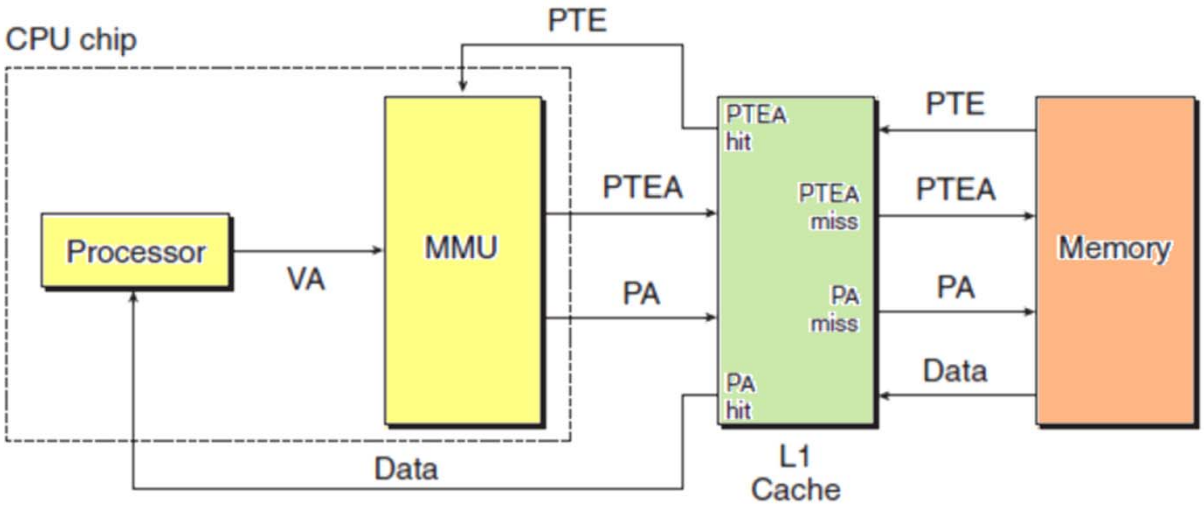
Integrating Caches and VM

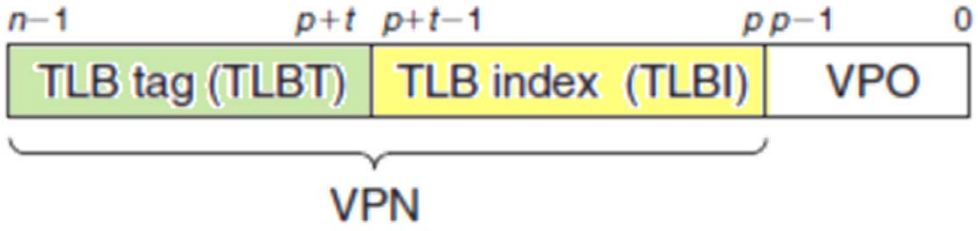


- Whether to use Virtual or Physical addresses to access the SRAM cache?
  - Most system opt for physical addresses
  - Easy for multiple processes to have blocks in the cache
  - No need to deal with the memory protection

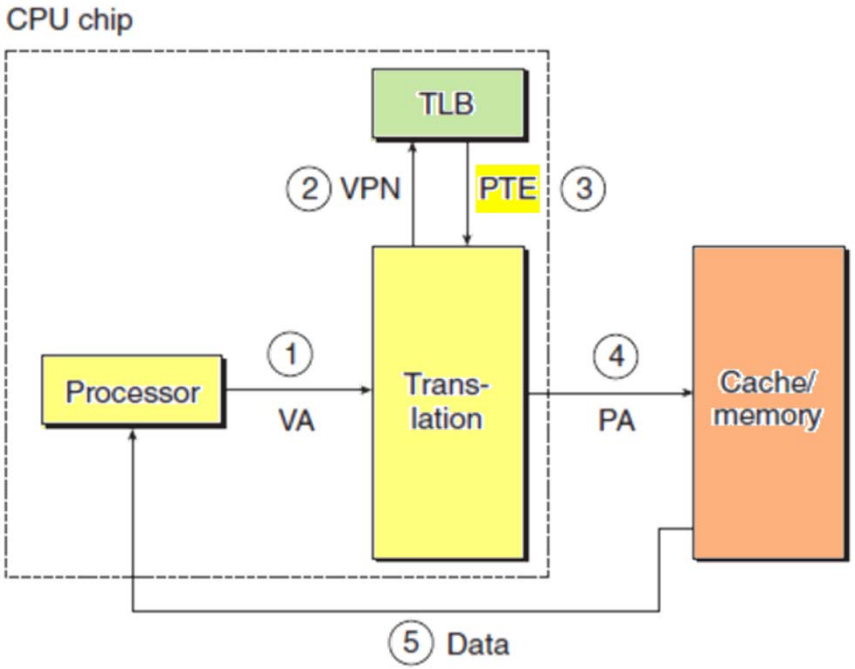
Translation Lookaside Buffer (TLB)

- A small cache of PTEs in MMU
  - Use virtual address
  - Each line holds a block consisting of a single PTE

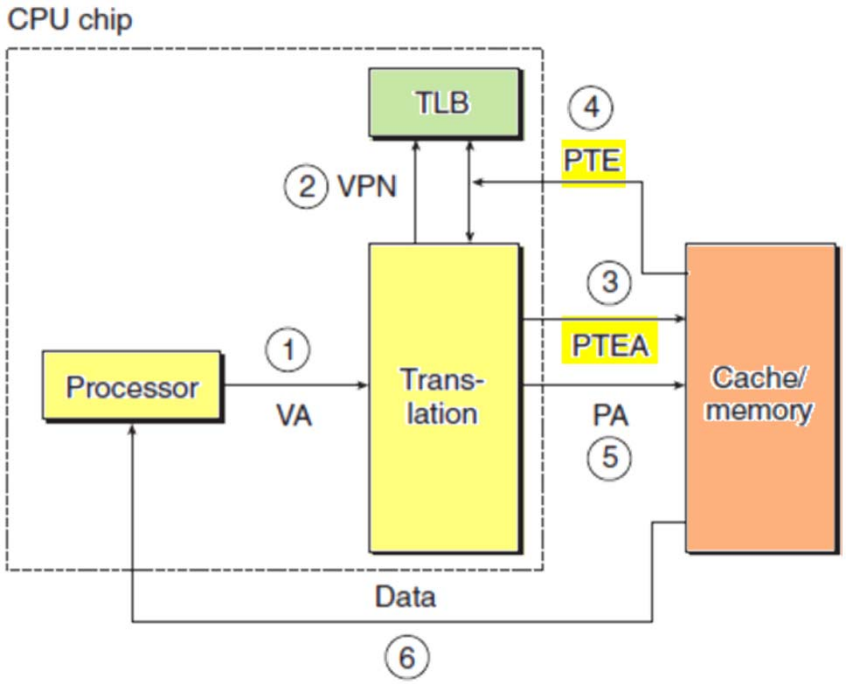
- If a TLB has $T=2^t$ sets,
  - TLB Index (TLBI) consists of the *t* least significant bits of the VPN
  - TLB Tag (TLBT) consists of the remaining bits in VPN



TLB Hit and Miss Operations



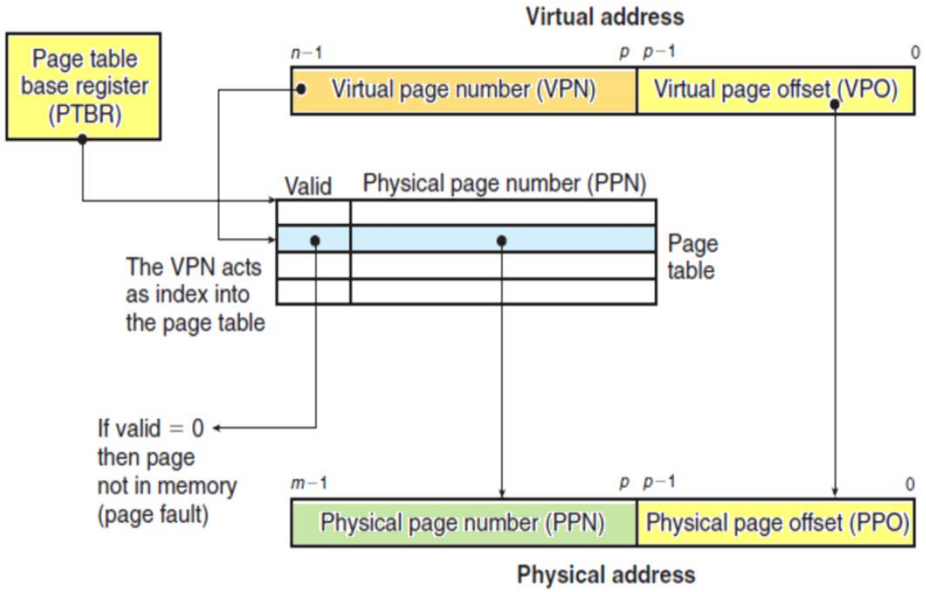
TLB Hit



TLB Miss

Multi-Level Page Table

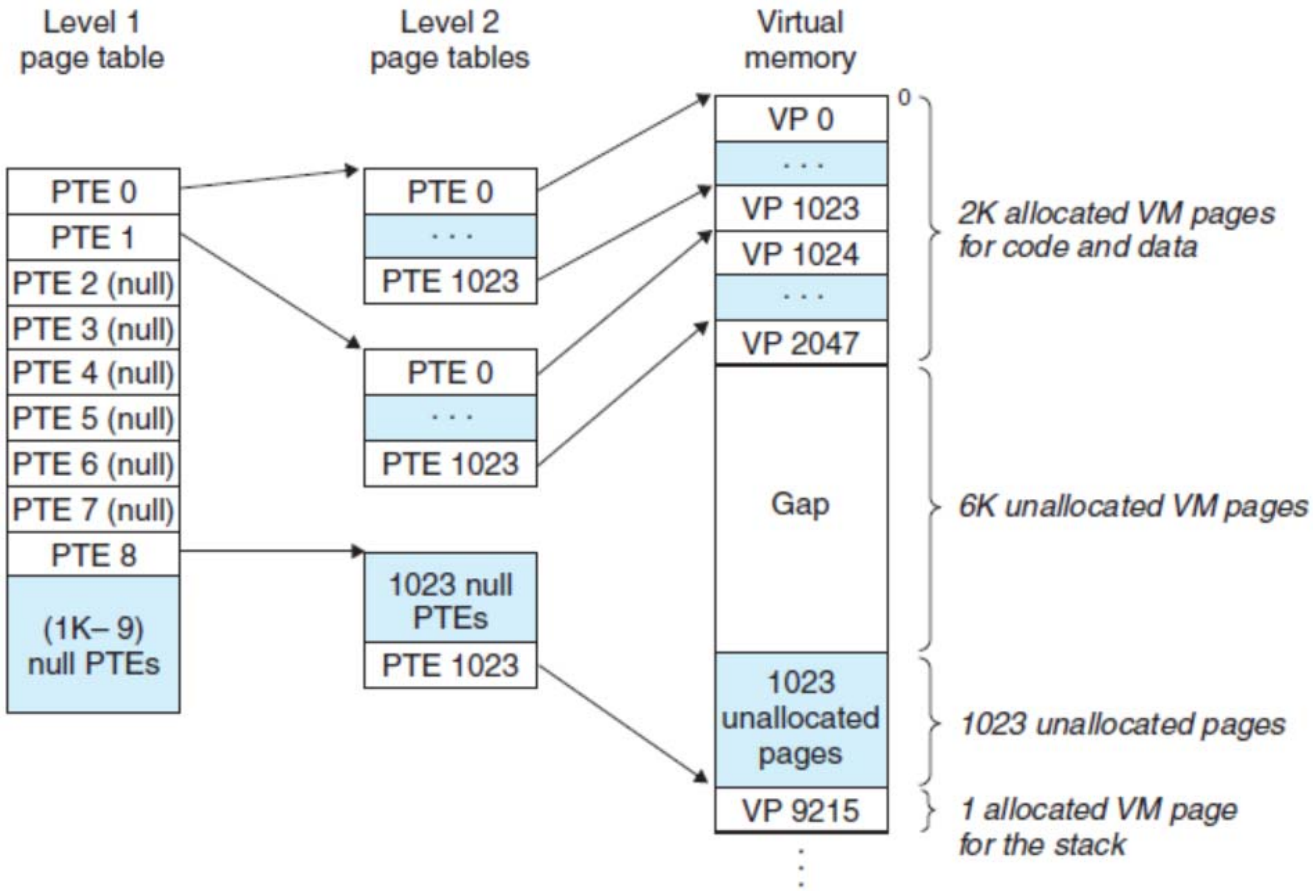
- Issue
  - 32bit address space, 4KB pages, 4B PTEs
    ⇒ 4MB page table in memory all the time



Multi-Level Page Table

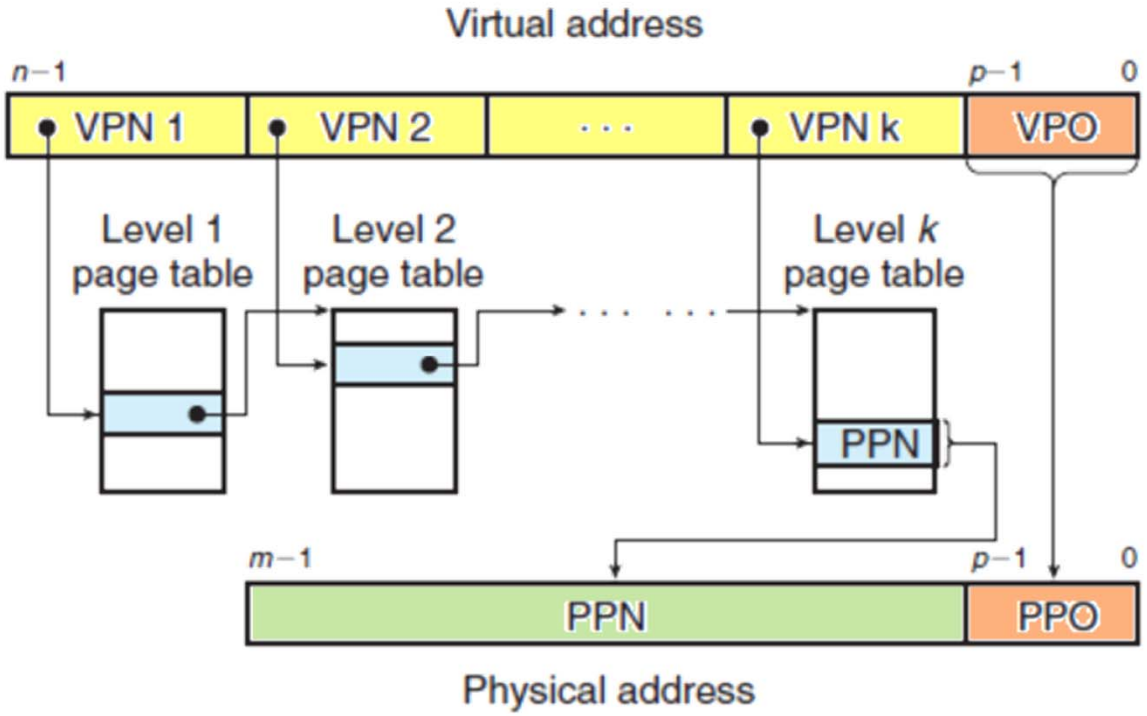
- Solution: hierarchy of page tables
  - E.g. 2 level page tables:
    - *Level 1* has a page table of 1024 PTEs (4KB)
    - *Level 2* page tables have 1024 PTEs (4KB) each.
    - Each PTE in level 1 is responsible for 4MB chunk of address space
    - If every page in chunk *i* is unallocated, PTE *i* in level 1 table is empty
    - If at least 1 page in chunk *i* is allocated, PTE *i* in level 1 points to the base of level 2 page table

2 Level Page Tables

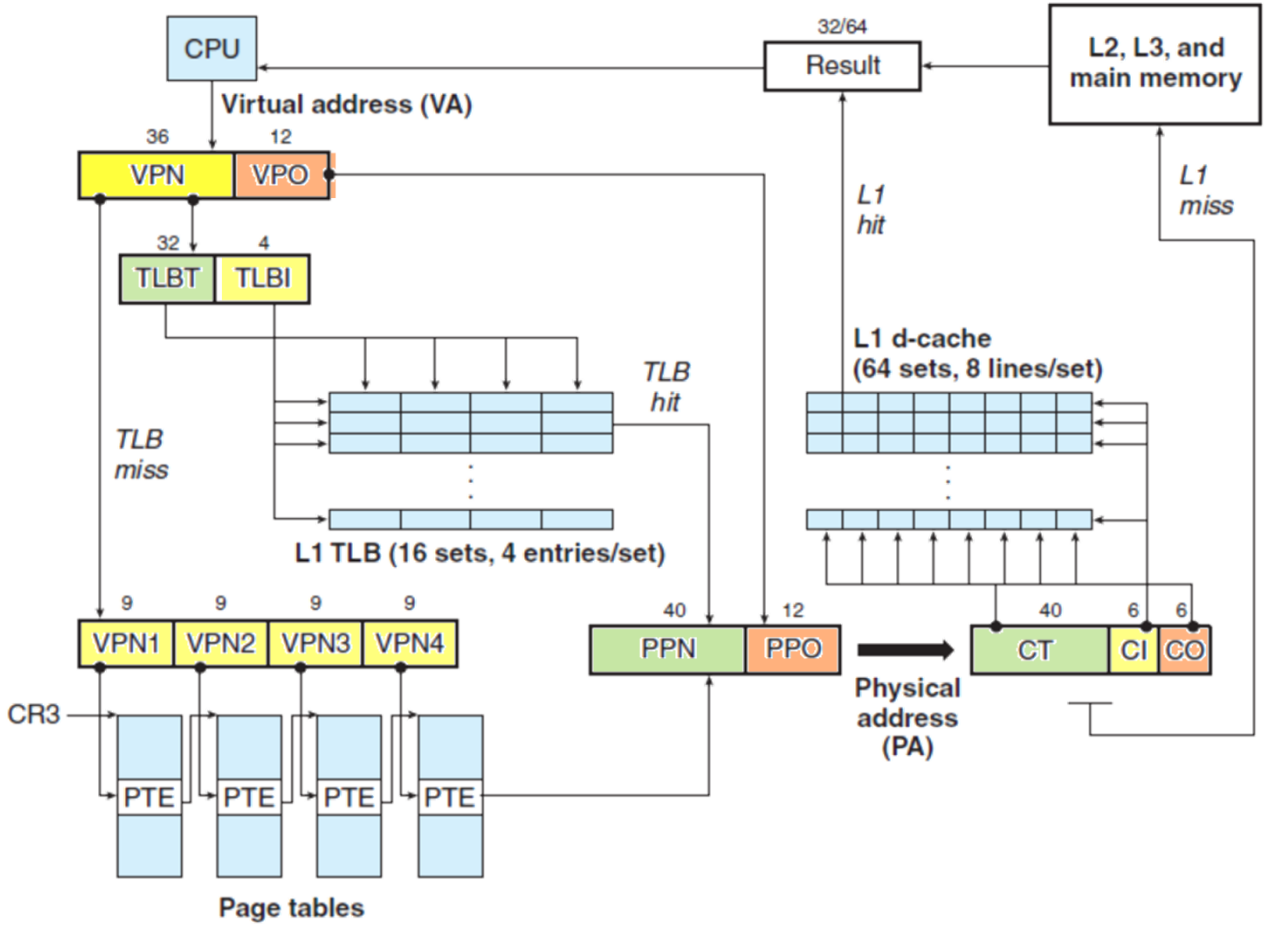


- If PTE in level 1 table is NULL, no need to have a level 2 table in memory
- Only the level 1 table needs to be in memory at all times

k-level Page Tables



Intel Core i7 Memory System



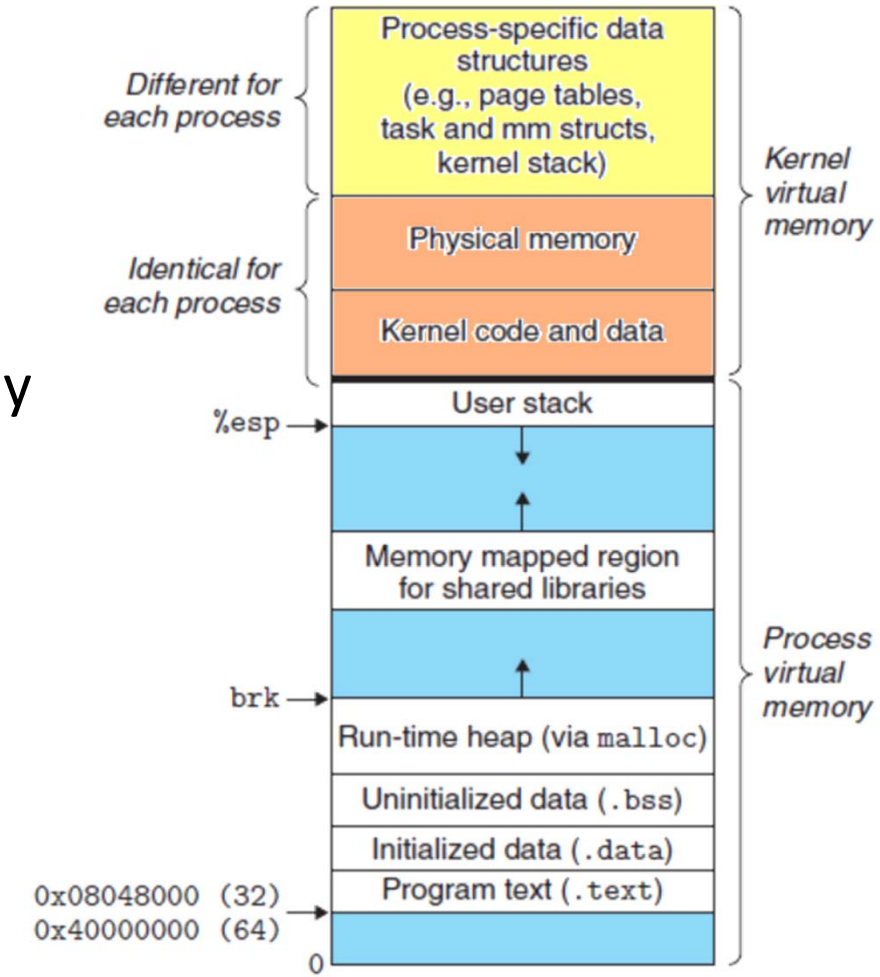
CR3 register: (PTBR) points to the level 1 page table

PTE: R/W bit (read, write), U/S (user, super user), XD (execute disable)

Address space: 48bit VA, 52bit PA

Linux Virtual Memory System

- Shared kernel virtual memory
  - Kernel's code, global data structure
  - Virtual pages mapped directly to physical pages
- Private kernel virtual memory
  - Page tables, kernel stacks, task structs, mm structs, …

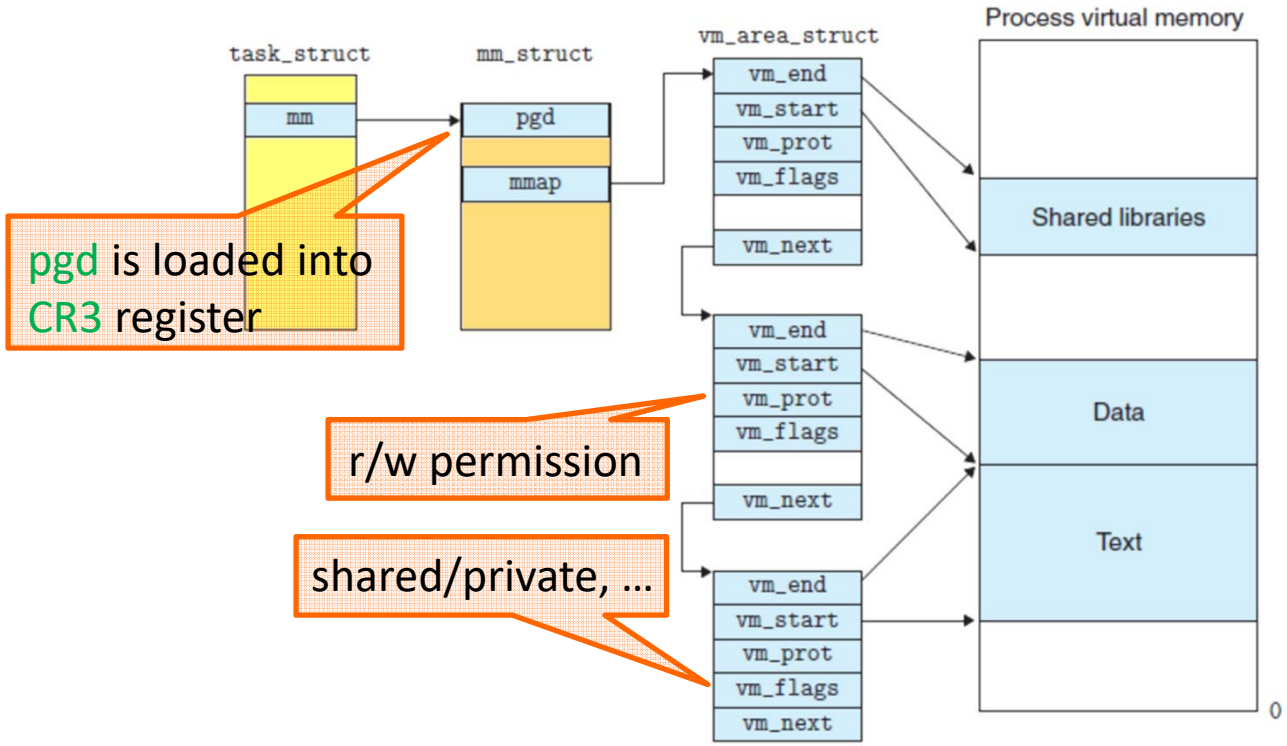


Linux Virtual Memory Areas

- Area
  - A contiguous chunk of existing (allocated) virtual memory whose pages are related
  - E.g., code area, data area, heap, shared library area, user stack

  - Each existing virtual page is contained in some area
  - Any virtual page not contained in an area does not exist and cannot be referenced

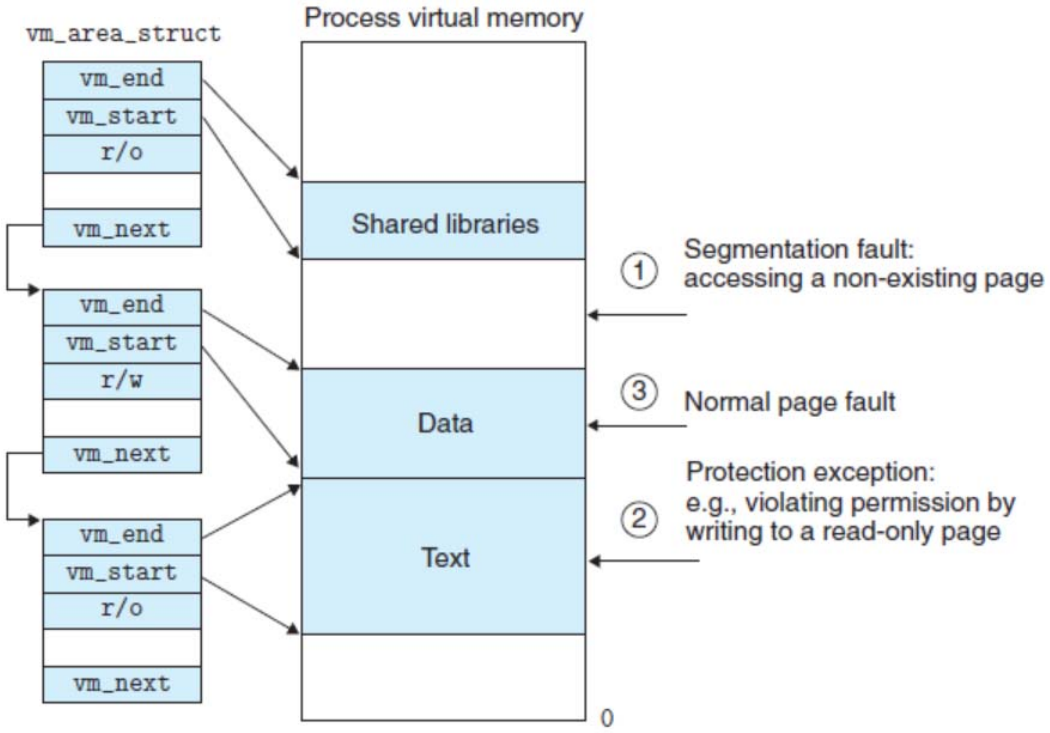
Linux Virtual Memory Area



- task_struct for each task
  - PID, program counter, mm, …
- mm_struct for virtual memory
  - pgd (PTBR), mmap pointing to vm_area_struct list

Linux Page Fault Exception

- Suppose that MMU triggers a page fault while translating a virtual address *A*. The kernel page fault handler does



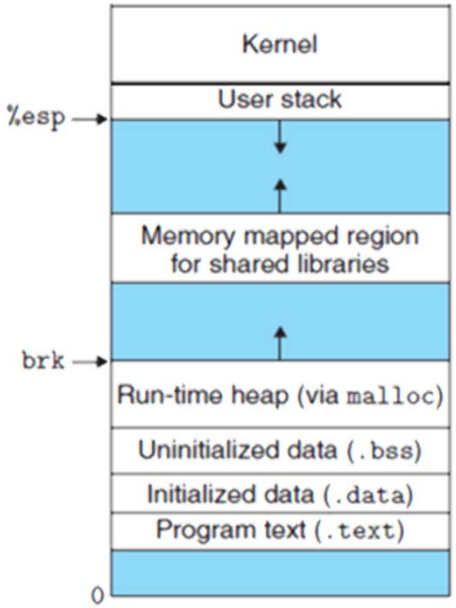
1. Is virtual address *A* legal?
   ⇒ segmentation fault

2. Is attempted access legal?
   ⇒ protection exception

3. Otherwise
   ⇒ swap out/in the page and restart the faulting instruction

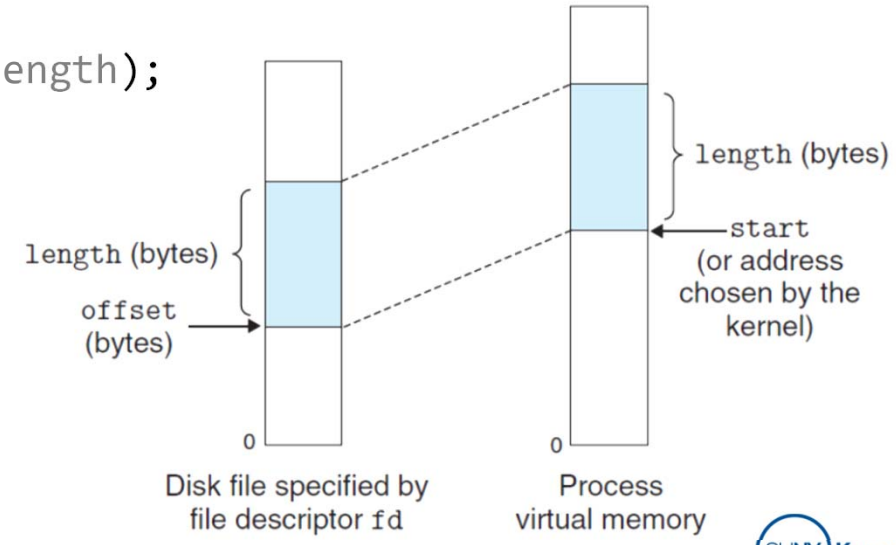
Memory Mapping

- Memory mapping
  - Initialize the contents of virtual memory area by associating it with an object on disk
  - Regular file in the Linux file system
    - File section is divided into page-size pieces
    - Demand paging ⇒ pages are loaded only when they are used
  - Anonymous file
    - A file, created by the kernel, that contains all binary zeros
    - No data are actually transferred between disks and memory
  - Swap file
    - Once a virtual page is initialized, it is swapped back and forth between a special swap file



Memory Mapping

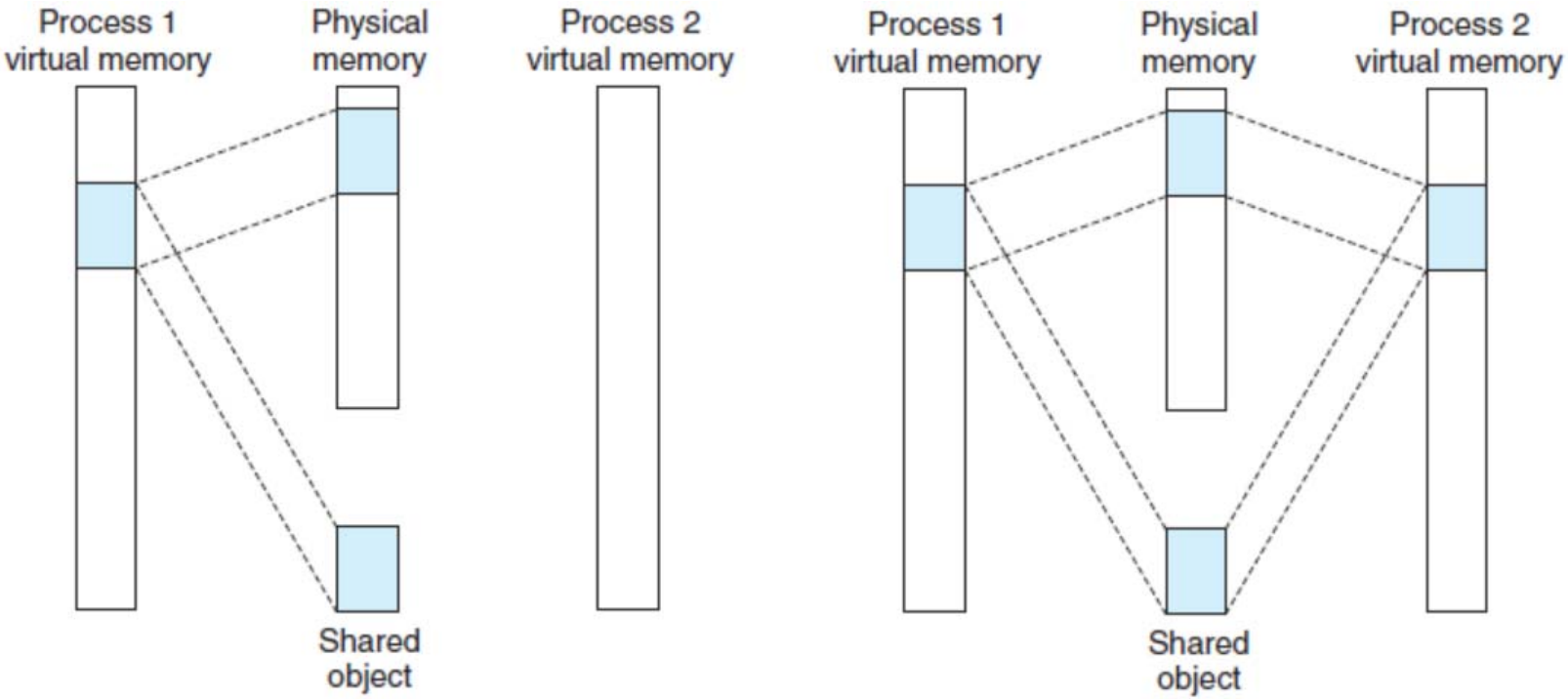
```
#include <sys/mman.h>

//Creates a mapping in the virtual address space (start)
void *mmap(void *start, size_t length, int prot, int flags,
           int fd, off_t offset);
prot:
PROT_EXEC, PROT_READ, PROT_WRITE, …
flags:
MAP_SHARED, MAP_PRIVATE, MAP_ANONYMOUS, MAP_FILE, …


//Deletes the mapping
int munmap(void *start, size_t length);
```



Shared Objects

- Many processes have identical read-only code areas
  - Linux shell programs have identical code area
  - Standard C library such as printf are common
  - Wasteful if each process keeps a duplicate copy
- Shared object (e.g. libc.so)
  - If a process writes to an area mapped to a shared object, the change is visible to other processes that mapped the shared object to their virtual memory
  - The shared object on disk is also updated
- Private object
  - Changes made to an area mapped to a private object are not visible to other processes
  - The original object on disk is not updated

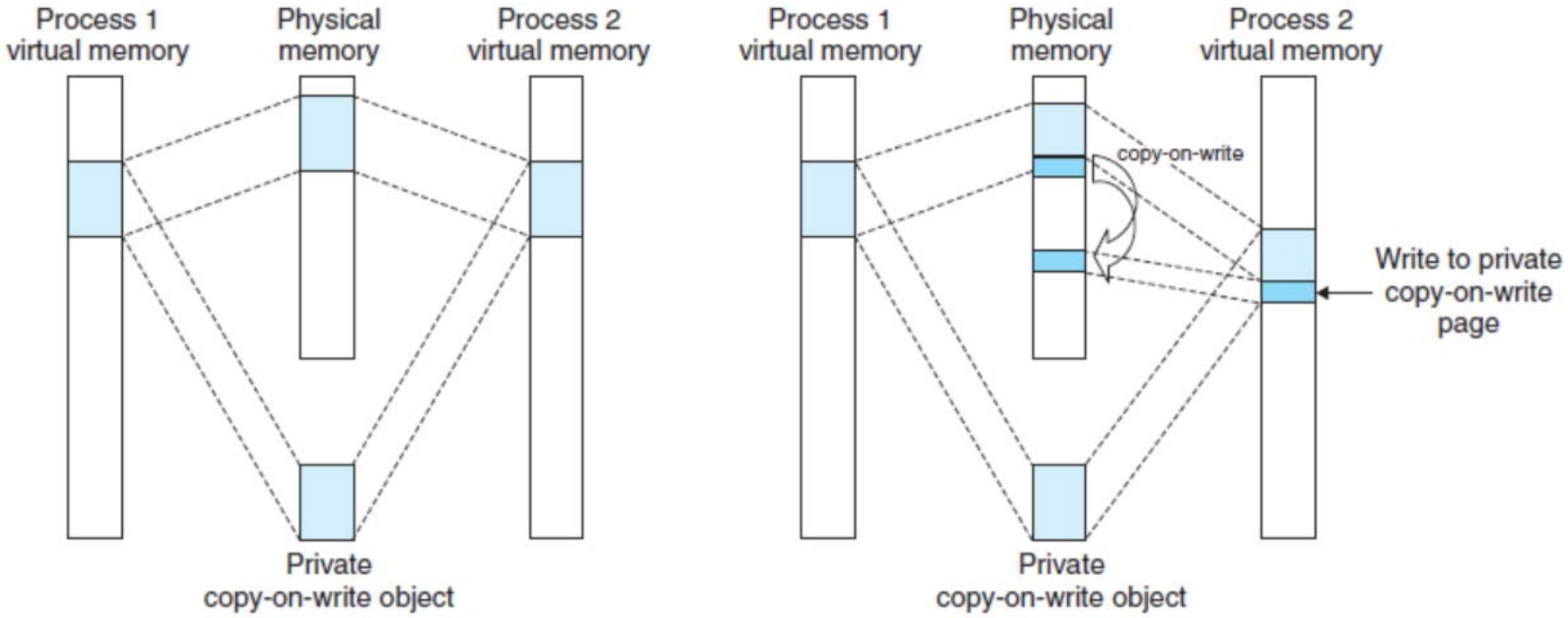
Shared Objects



Copy-on-Write

- Private objects are mapped into virtual memory like shared objects except that
  - Page table entries are flagged as read-only
  - Area struct is flagged as private copy-on-write (cow)
- When a process tries to write to some private areas
  - A protection fault is triggered
  - The fault handler checks that the fault is from the private cow area
  - Creates a new copy of the page, updates the page table entry and restores the permissions to the page

Copy-on-Write



Fork function

- When fork is invoked
  - Kernel creates data structures for the new process
  - To create a virtual memory for the new process
    - The current process' mm_struct, area structs and page tables are copied
    - Flag each page in both processes as read-only
    - Flag each area struct in both processes as private copy-on-write
  - Both processes have exactly the same virtual memory
  - As processes write, new pages are created by the cow

Execve

- Delete existing user areas
- Map private areas
  - Create new area structs for code, data, bss, stack
  - All areas are flagged as private cow
  - Code and data areas are mapped to .text and .data
  - Bss area is demand-zero, mapped to an anonymous file whose size is in the executable file
  - Heap and stack are demand-zero, of 0 length
- Map shared areas
  - Shared objects (e.g. libc.so) are dynamically linked into the program and mapped into the shared region
- Set the program counter (PC)

How the Loader Maps the Areas