

# Virtual Memory: Systems

15-213/18-243: Introduction to Computer Systems  
18<sup>th</sup> Lecture, Mar. 22, 2011

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# Last Time: Virtual Memory Concepts

- **Allow for memory space larger than physical memory**
- **Processes can have identical memory addresses**
  - Simplifies Linking
  - Simplifies Loading
  - Simplifies Allocation (request more Heap etc)
- **Memory Protection**
- **Memory Sharing**
- **Caching Mechanism**

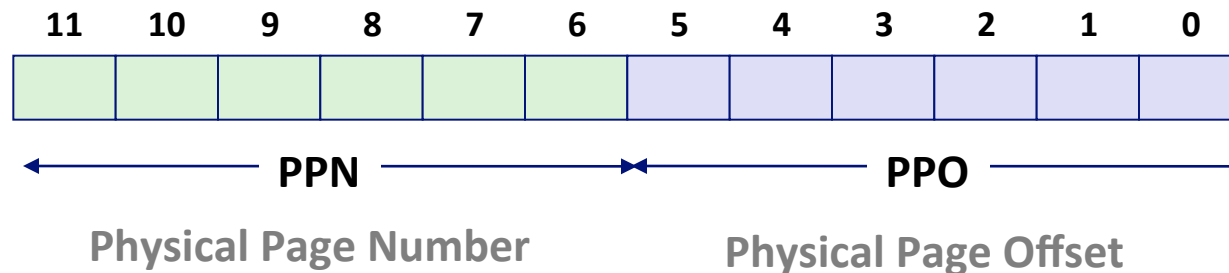
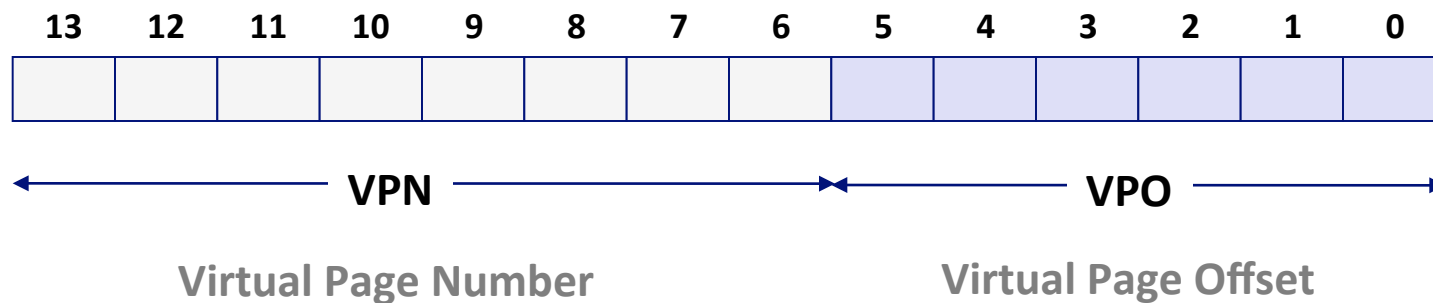
# Today

- **Simple memory system example**
- Case study: Core i7/Linux memory system
- Memory mapping

# Simple Memory System Example

## ■ Addressing

- 14-bit virtual addresses
- 12-bit physical address
- Page size = 64 bytes



# Simple Memory System Page Table

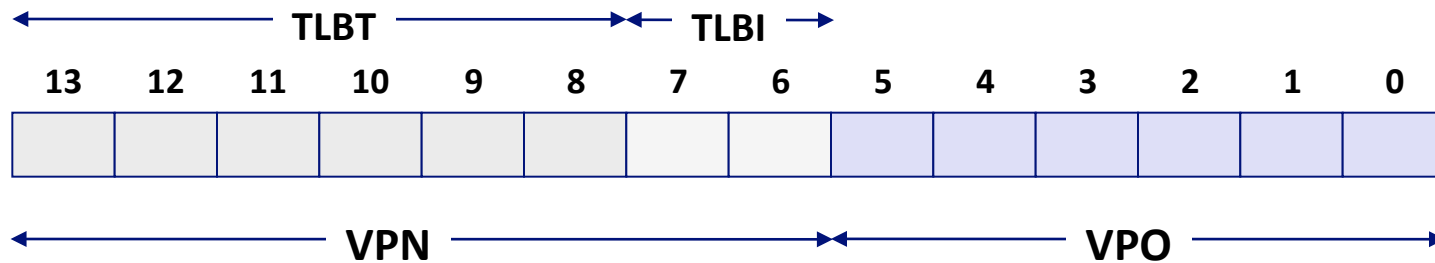
Only show first 16 entries (out of 256)

<i>VPN</i>	<i>PPN</i>	<i>Valid</i>
<b>00</b>	<b>28</b>	<b>1</b>
<b>01</b>	<b>–</b>	<b>0</b>
<b>02</b>	<b>33</b>	<b>1</b>
<b>03</b>	<b>02</b>	<b>1</b>
<b>04</b>	<b>–</b>	<b>0</b>
<b>05</b>	<b>16</b>	<b>1</b>
<b>06</b>	<b>–</b>	<b>0</b>
<b>07</b>	<b>–</b>	<b>0</b>

<i>VPN</i>	<i>PPN</i>	<i>Valid</i>
<b>08</b>	<b>13</b>	<b>1</b>
<b>09</b>	<b>17</b>	<b>1</b>
<b>0A</b>	<b>09</b>	<b>1</b>
<b>0B</b>	<b>–</b>	<b>0</b>
<b>0C</b>	<b>–</b>	<b>0</b>
<b>0D</b>	<b>2D</b>	<b>1</b>
<b>0E</b>	<b>11</b>	<b>1</b>
<b>0F</b>	<b>0D</b>	<b>1</b>

# Simple Memory System TLB

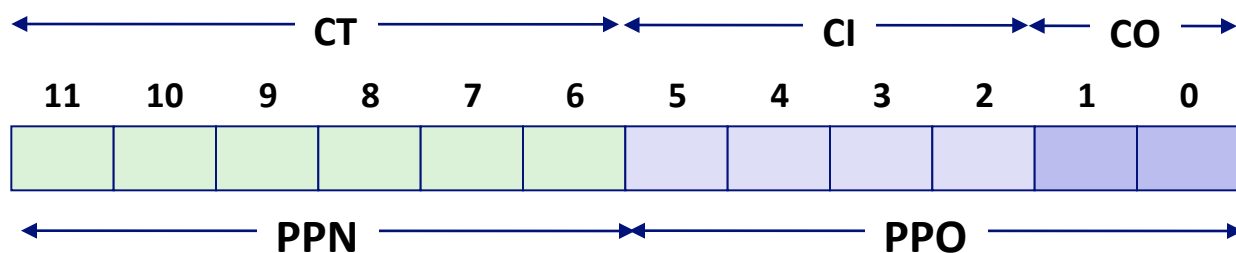
- 16 entries
- 4-way associative



<i>Set</i>	<i>Tag</i>	<i>PPN</i>	<i>Valid</i>	<i>Tag</i>	<i>PPN</i>	<i>Valid</i>	<i>Tag</i>	<i>PPN</i>	<i>Valid</i>	<i>Tag</i>	<i>PPN</i>	<i>Valid</i>
<b>0</b>	03	–	0	09	0D	1	00	–	0	07	02	1
<b>1</b>	03	2D	1	02	–	0	04	–	0	0A	–	0
<b>2</b>	02	–	0	08	–	0	06	–	0	03	–	0
<b>3</b>	07	–	0	03	0D	1	0A	34	1	02	–	0

# Simple Memory System Cache

- 16 lines, 4-byte block size
- Physically addressed
- Direct mapped



<i>Idx</i>	<i>Tag</i>	<i>Valid</i>	<i>B0</i>	<i>B1</i>	<i>B2</i>	<i>B3</i>
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

<i>Idx</i>	<i>Tag</i>	<i>Valid</i>	<i>B0</i>	<i>B1</i>	<i>B2</i>	<i>B3</i>
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

# Review of Symbols

## ■ Basic Parameters

- $N = 2^n$  : Number of addresses in virtual address space
- $M = 2^m$  : Number of addresses in physical address space
- $P = 2^p$  : Page size (bytes)

## ■ Components of the virtual address (VA)

- **TLBI**: TLB index
- **TLBT**: TLB tag
- **VPO**: Virtual page offset
- **VPN**: Virtual page number

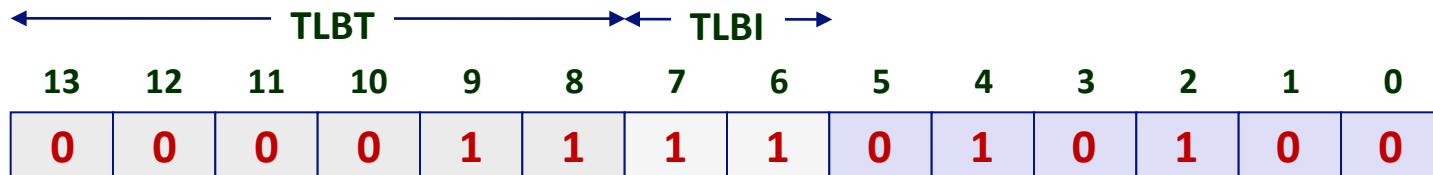
## ■ Components of the physical address (PA)

- **PPO**: Physical page offset (same as VPO)
- **PPN**: Physical page number
- **CO**: Byte offset within cache line
- **CI**: Cache index
- **CT**: Cache tag



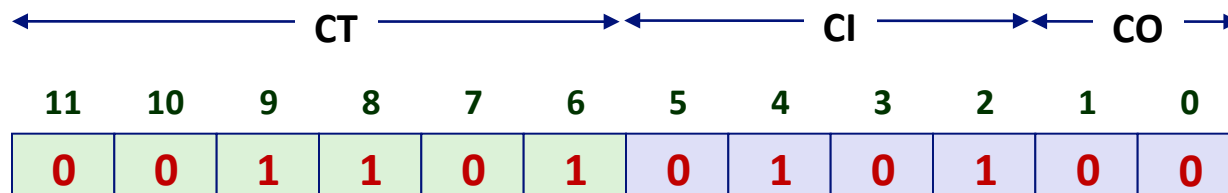
# Address Translation Example #1

Virtual Address: 0x03D4



VPN 0x0F    TLBI 0x3    TLBT 0x03    TLB Hit? Y    Page Fault? N    PPN: 0x0D

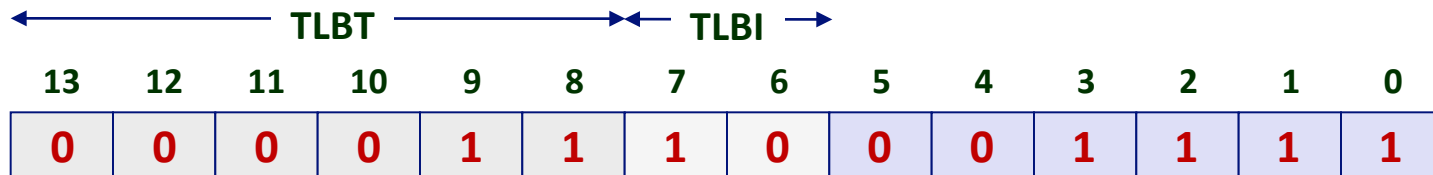
## Physical Address



CO 0    CI 0x5    CT 0x0D    Hit? Y    Byte: 0x36

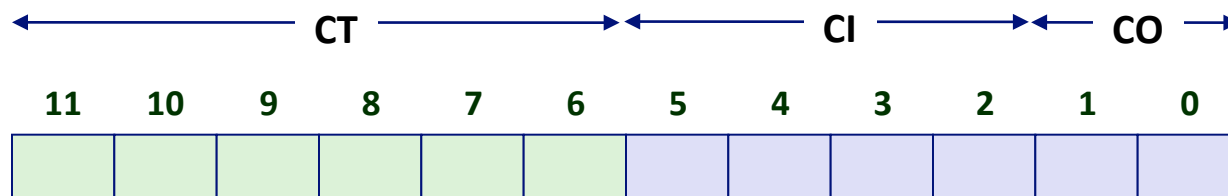
# Address Translation Example #2

Virtual Address: 0x01CF



VPN 0x7    TLBI 0x3    TLBT 0x01    TLB Hit? N    Page Fault? Y    PPN: TBD

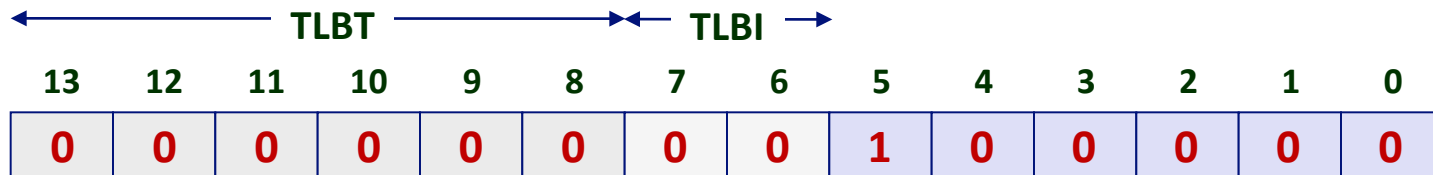
## Physical Address



CO \_\_\_    CI \_\_\_    CT \_\_\_    Hit? \_\_\_    Byte: \_\_\_

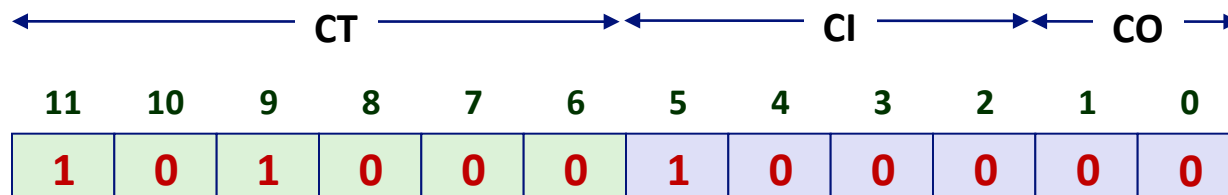
# Address Translation Example #3

Virtual Address: 0x0020



VPN 0x00    TLBI 0    TLBT 0x00    TLB Hit? N    Page Fault? N    PPN: 0x28

## Physical Address



CO 0    CI 0x8    CT 0x28    Hit? N    Byte: Mem

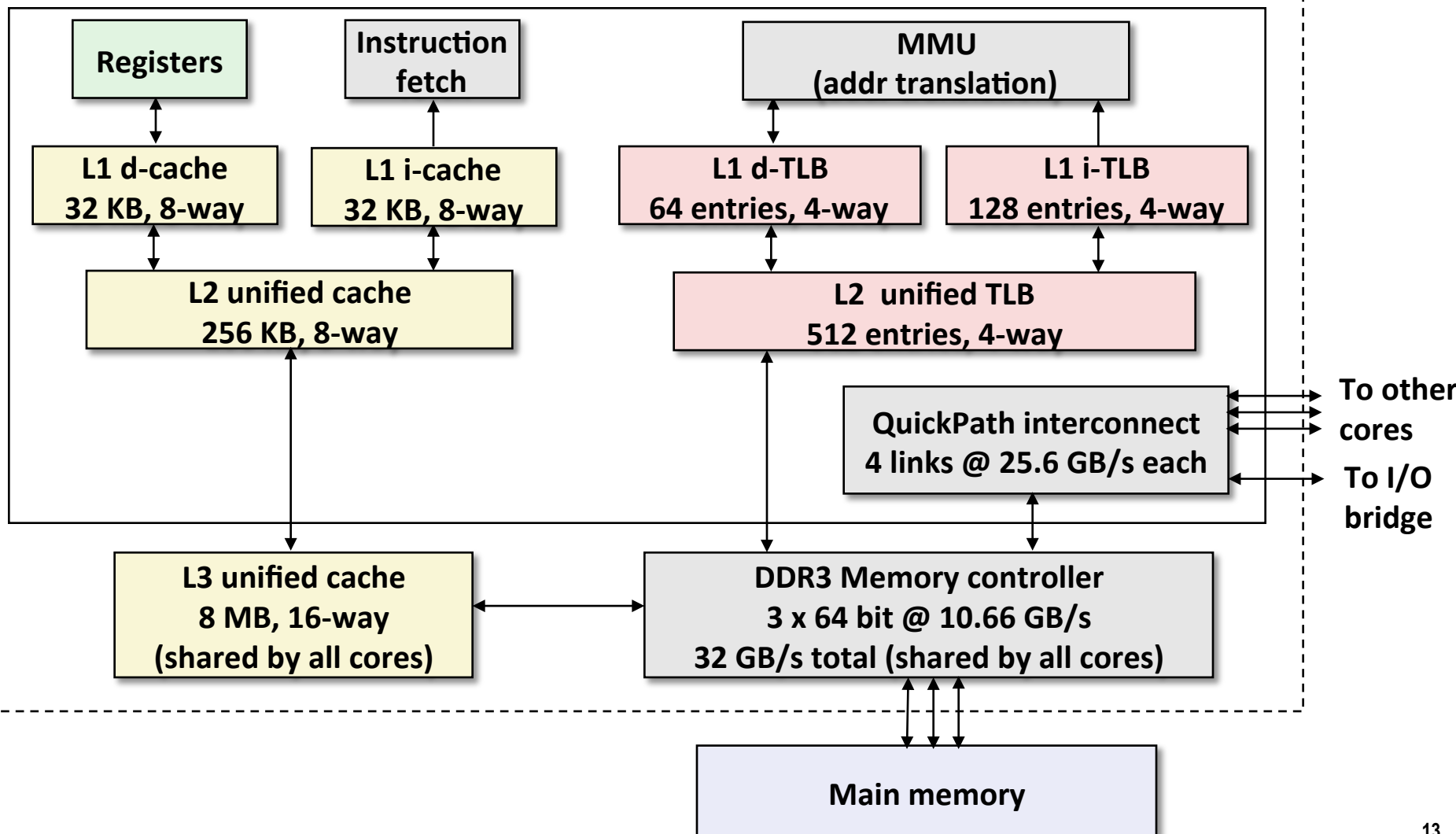
# Today

- Simple memory system example
- **Case study: Core i7/Linux memory system**
- Memory mapping

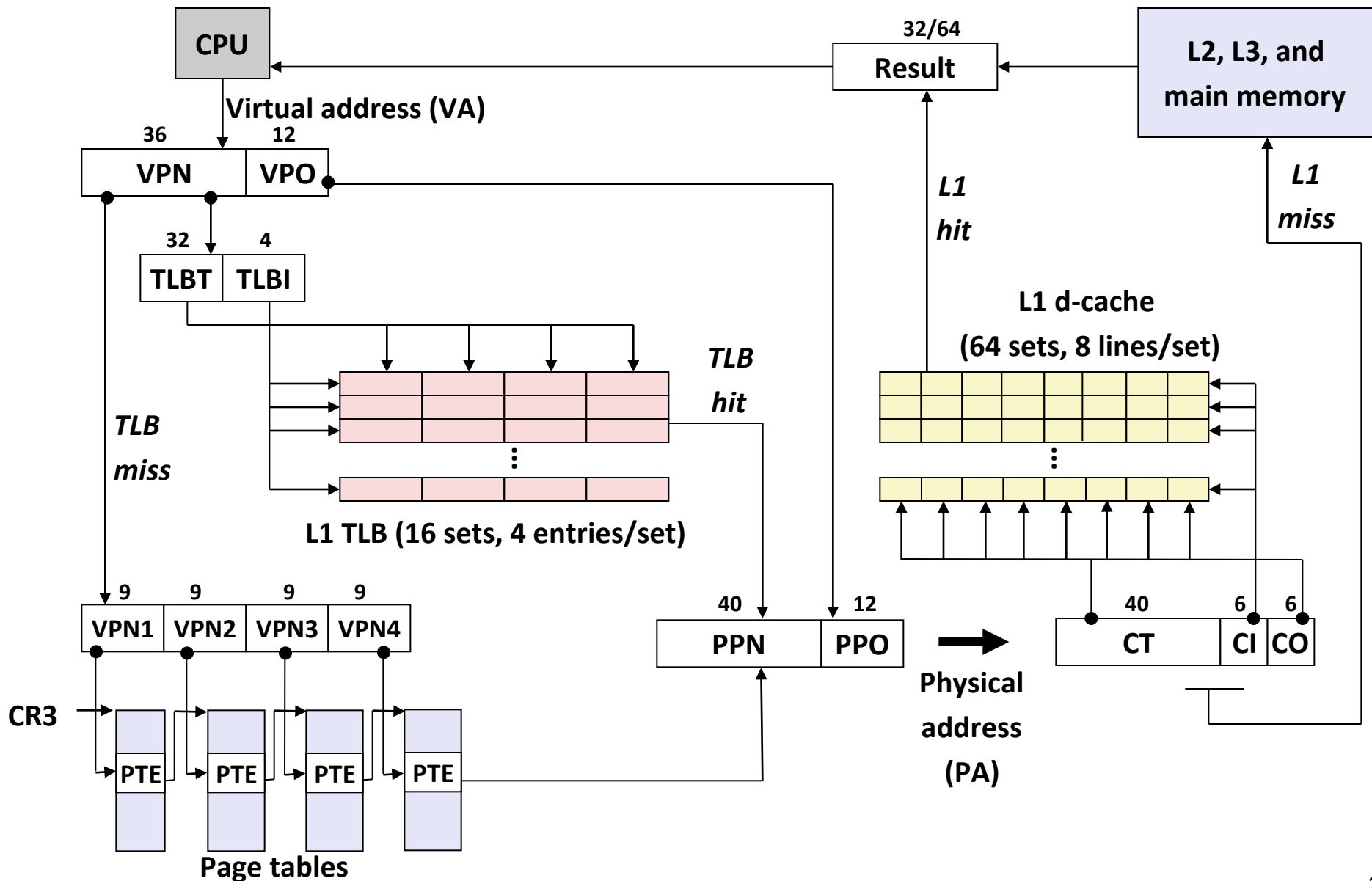
# Intel Core i7 Memory System

Processor package

Core x4



# End-to-end Core i7 Address Translation



# 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	

## Each entry references a 4K child page table

**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 4 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)

# Core i7 Level 4 Page Table Entries

63	62	52	51	12	11	9	8	7	6	5	4	3	2	1	0
XD	Unused	Page physical base address				Unused	G		D	A	CD	WT	U/S	R/W	P=1
Available for OS (page location on disk)														P=0	

## Each entry references a 4K child page

**P:** Child page is present in memory (1) or not (0)

**R/W:** Read-only or read-write access permission for child page

**U/S:** User or supervisor mode access

**WT:** Write-through or write-back cache policy for this page

**CD:** Cache disabled (1) or enabled (0)

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

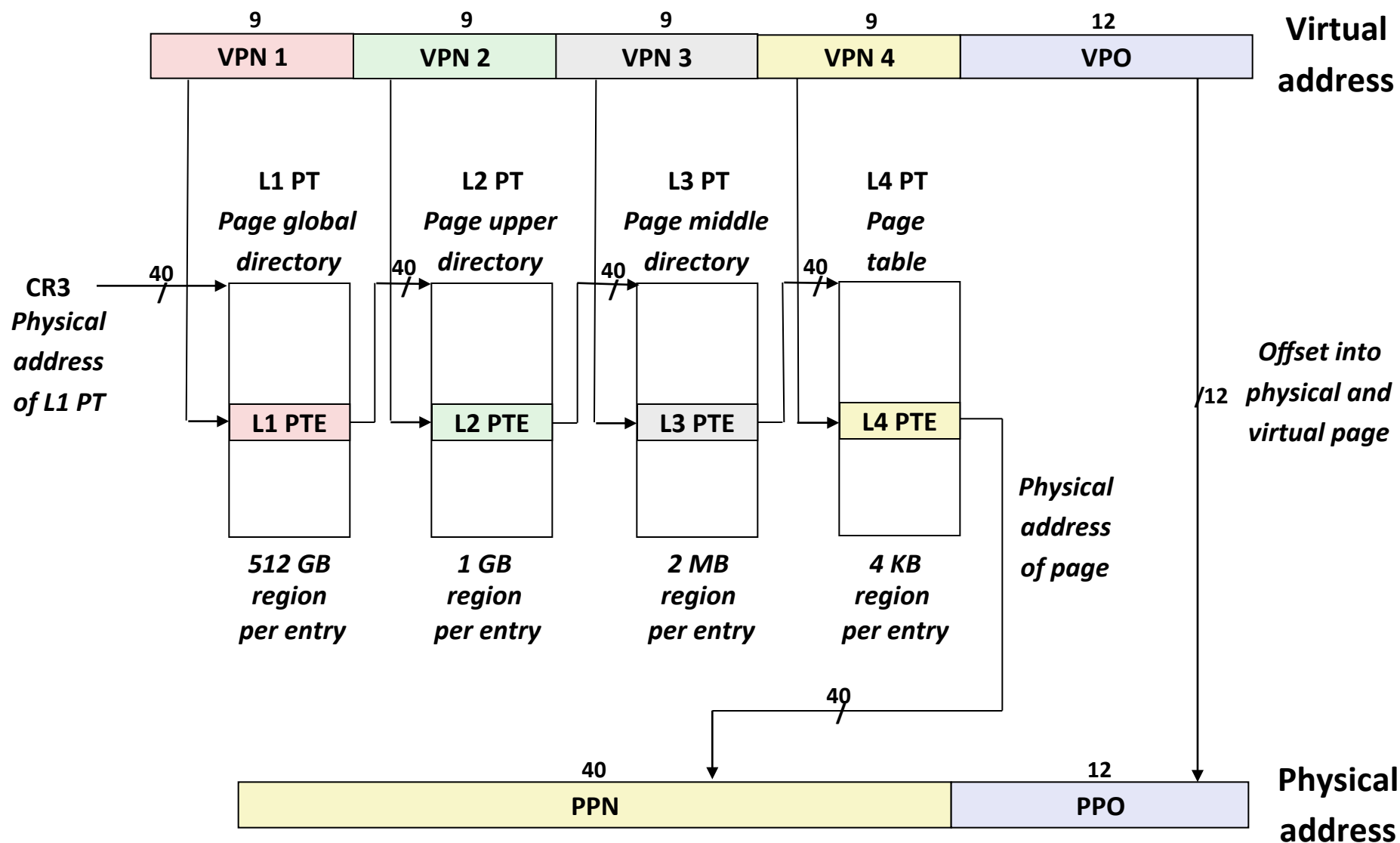
**D:** Dirty bit (set by MMU on writes, cleared by software)

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

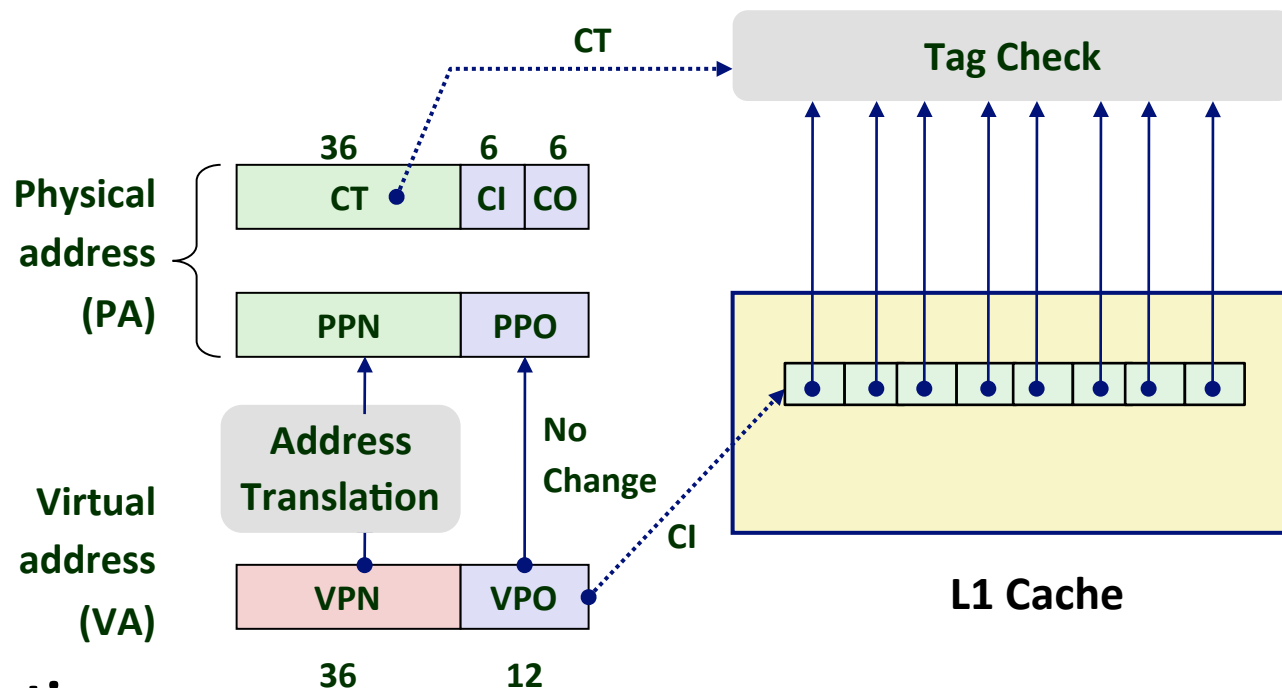
**Page physical base address:** 40 most significant bits of physical page address  
(forces pages to be 4KB aligned)



# Core i7 Page Table Translation



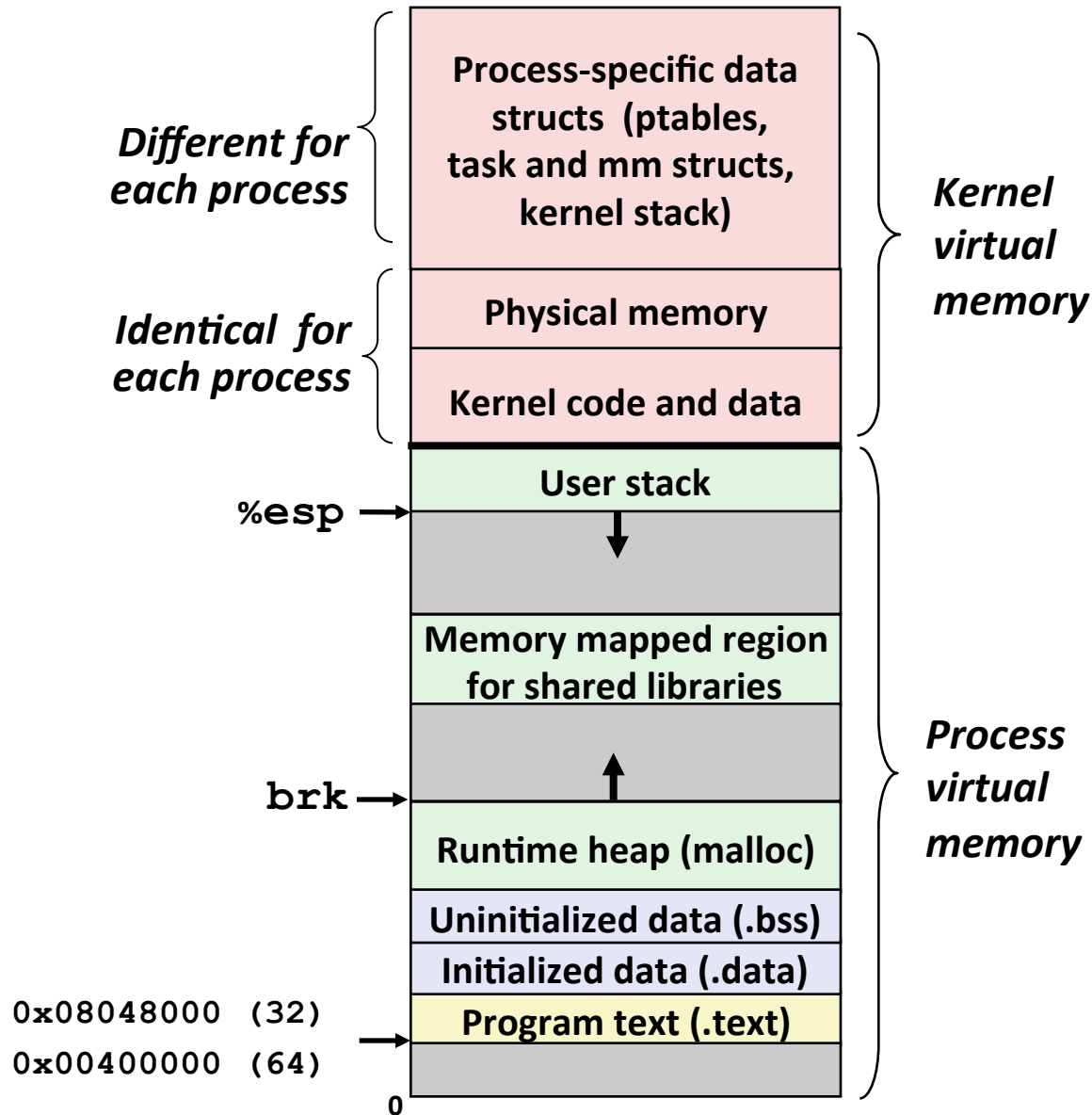
# Cute Trick for Speeding Up L1 Access



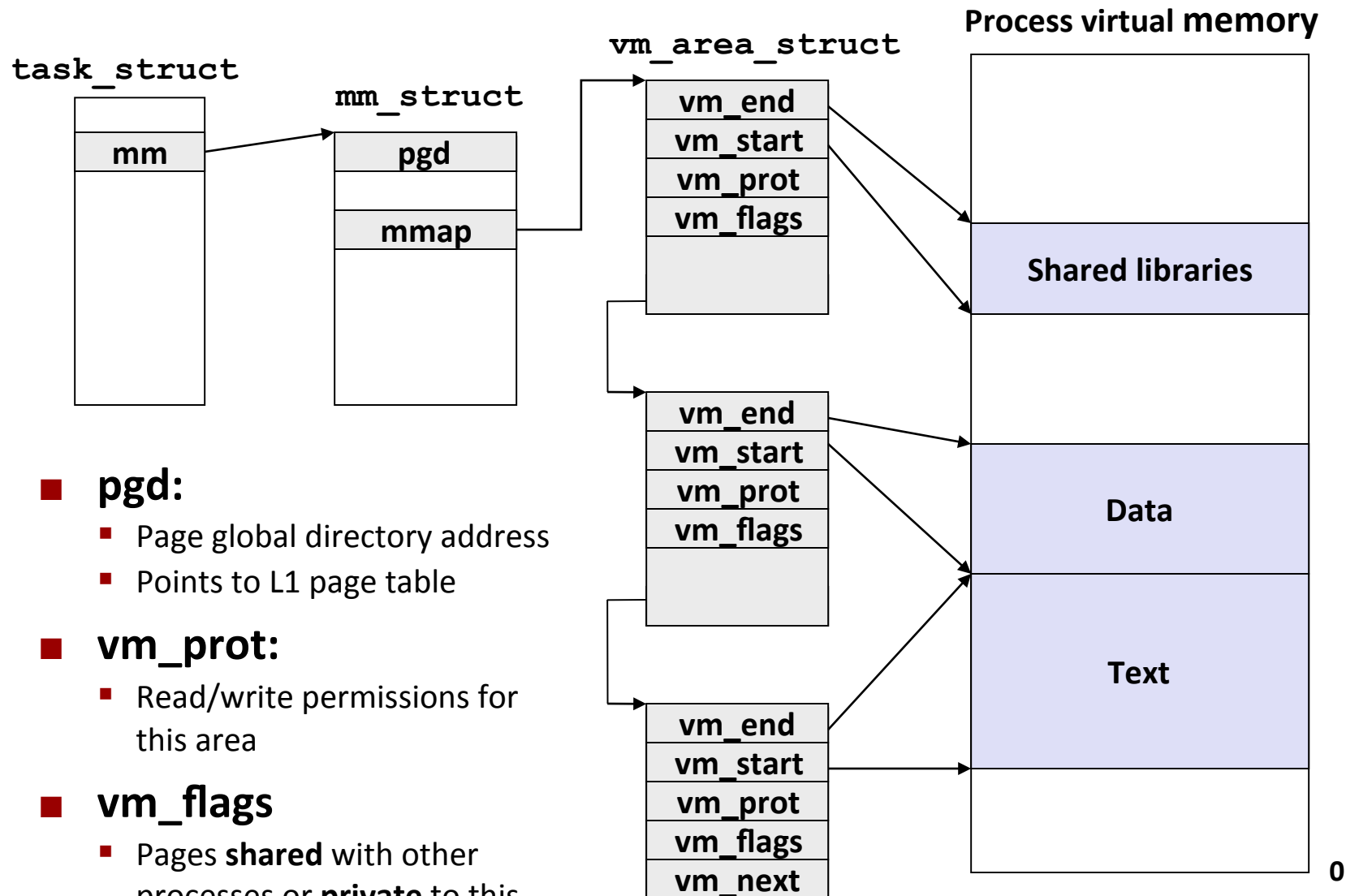
## ■ Observation

- Bits that determine CI identical in virtual and physical address
- Can index into cache while address translation taking place
- Generally we hit in TLB, so PPN bits (CT bits) available next
- “Virtually indexed, physically tagged”
- Cache carefully sized to make this possible

# Virtual Memory of a Linux Process

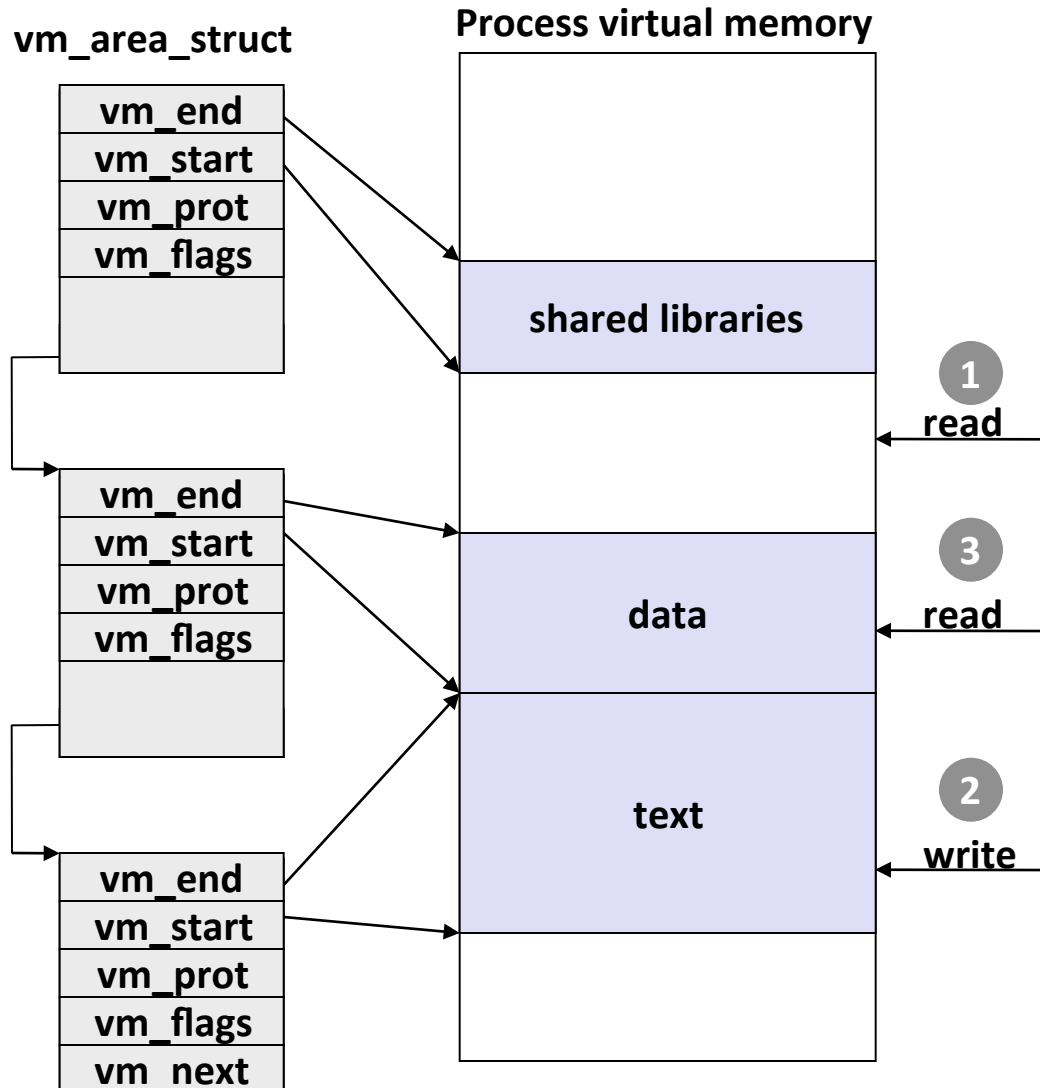


# Linux Organizes VM as Collection of “Areas”



- **pgd:**
  - Page global directory address
  - Points to L1 page table
- **vm\_prot:**
  - Read/write permissions for this area
- **vm\_flags**
  - Pages **shared** with other processes or **private** to this process

# Linux Page Fault Handling



**Segmentation fault:**  
accessing a non-existing page

**Normal page fault**

**Protection exception:**  
e.g., violating permission by  
writing to a read-only page (Linux  
reports as Segmentation fault)

# Today

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- **Memory mapping**

# Memory Mapping

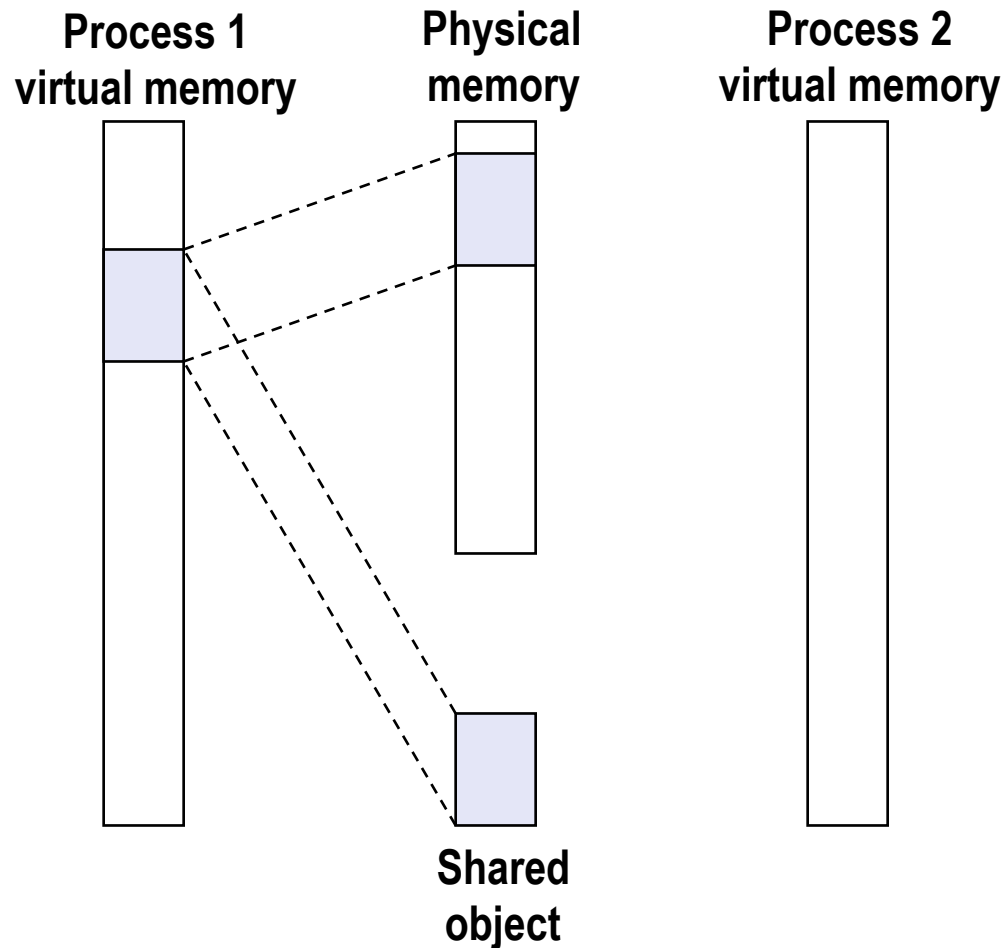
- VM areas initialized by associating them with disk objects.
  - Process is known as *memory mapping*.
- Area can be backed by (i.e., get its initial values from) :
  - *Regular file* on disk (e.g., an executable object file)
    - Initial page bytes come from a section of a file
  - *Anonymous file* (e.g., nothing)
    - First fault will allocate a physical page full of 0's (*demand-zero page*)
    - Once the page is written to (*dirtied*), it is like any other page
- Dirty pages are copied back and forth between memory and a special *swap file*.

# Demand paging

- ***Key point:*** no virtual pages are copied into physical memory until they are referenced!
  - Known as ***demand paging***
- **Crucial for time and space efficiency**

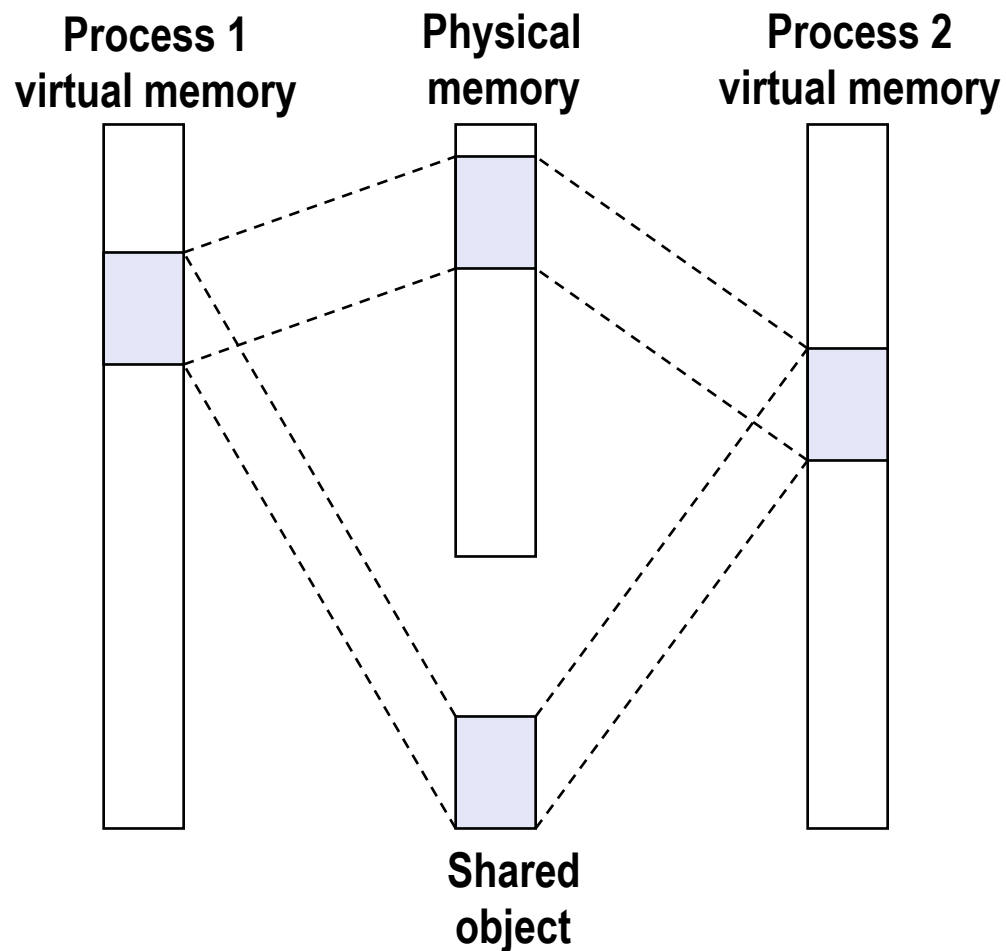


# Sharing Revisited: Shared Objects



- **Process 1 maps the shared object.**

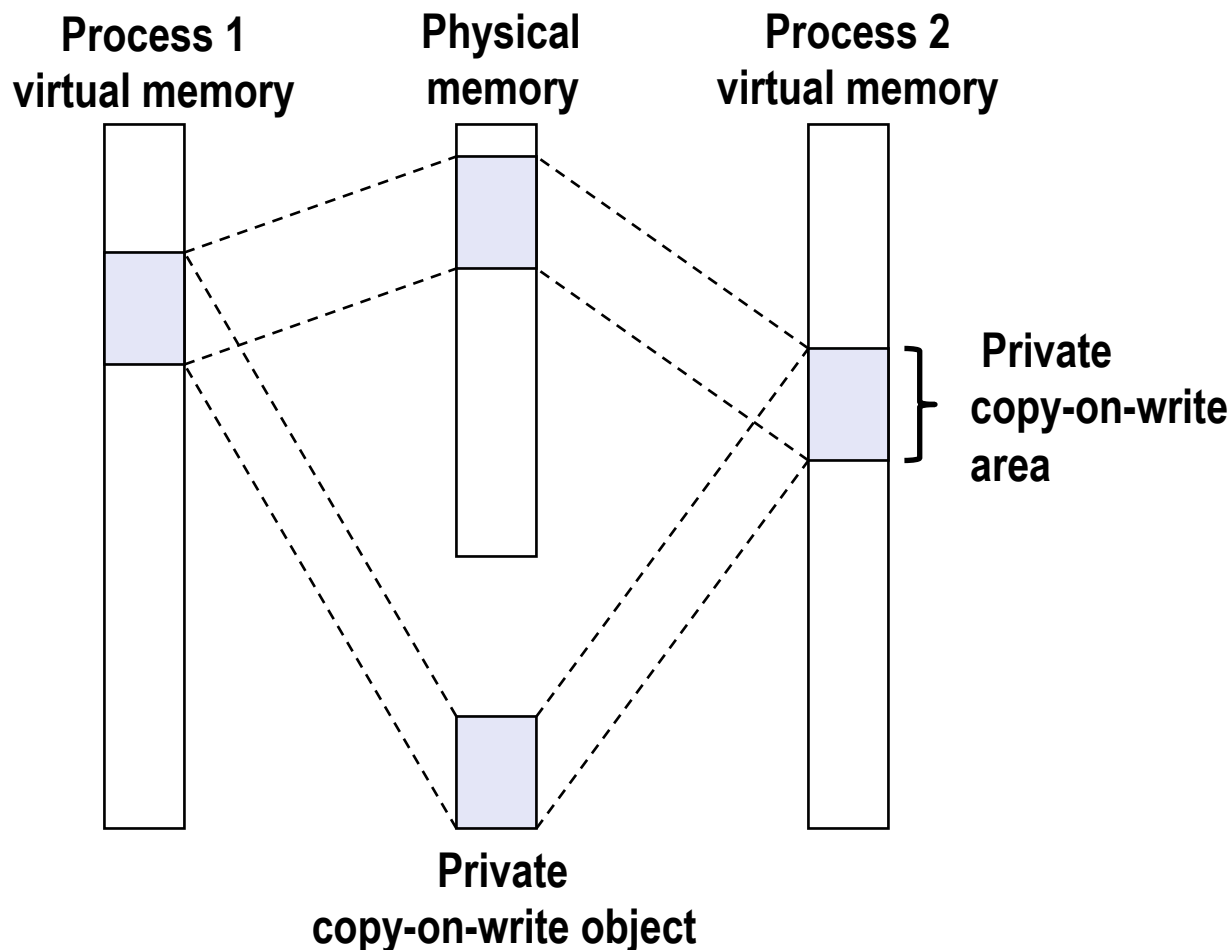
# Sharing Revisited: Shared Objects



- **Process 2 maps the shared object.**
- **Notice how the virtual addresses can be different.**

# Sharing Revisited:

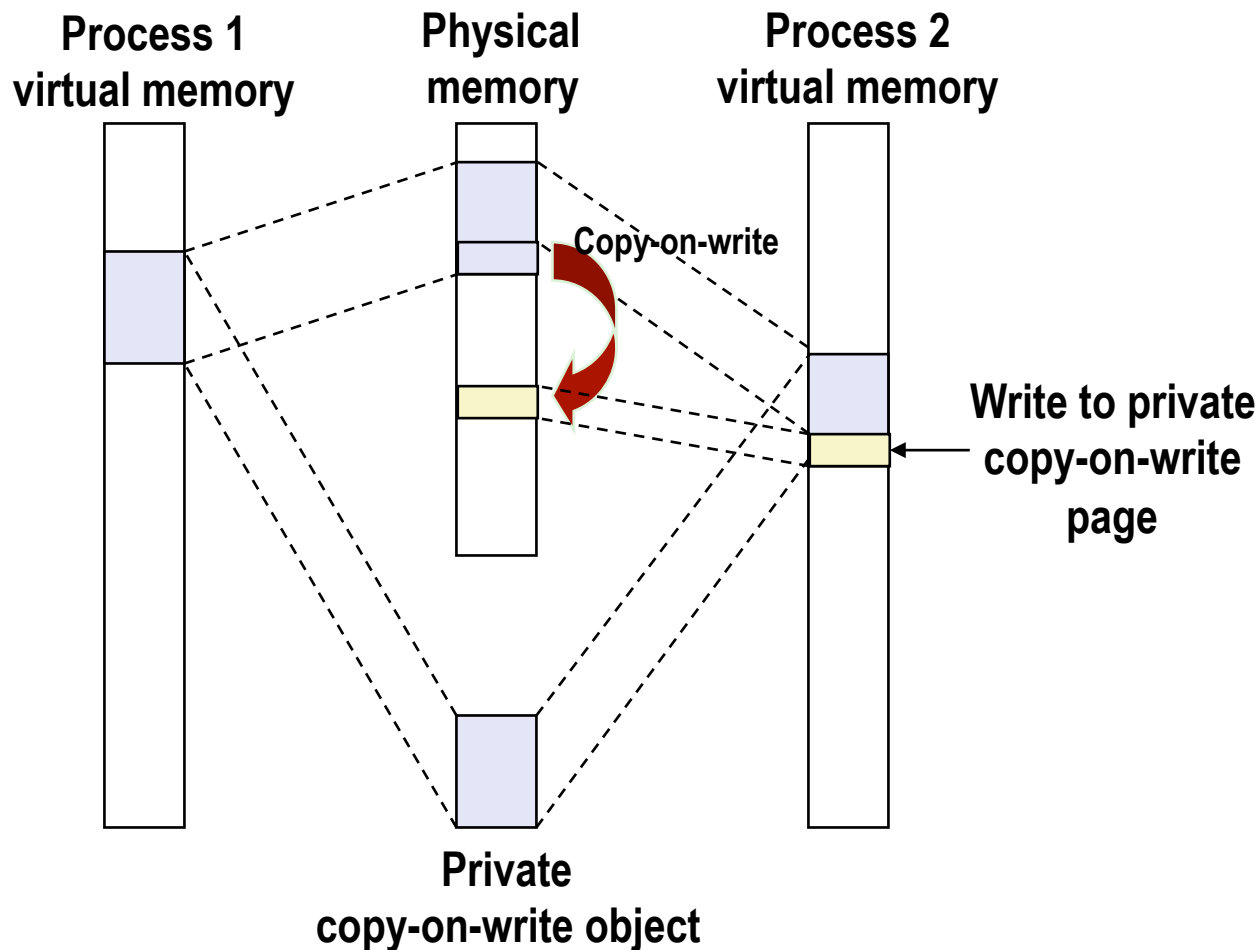
## Private Copy-on-write (COW) Objects



- Two processes mapping a *private copy-on-write (COW)* object.
- Area flagged as private copy-on-write
- PTEs in private areas are flagged as read-only

# Sharing Revisited:

## Private Copy-on-write (COW) Objects

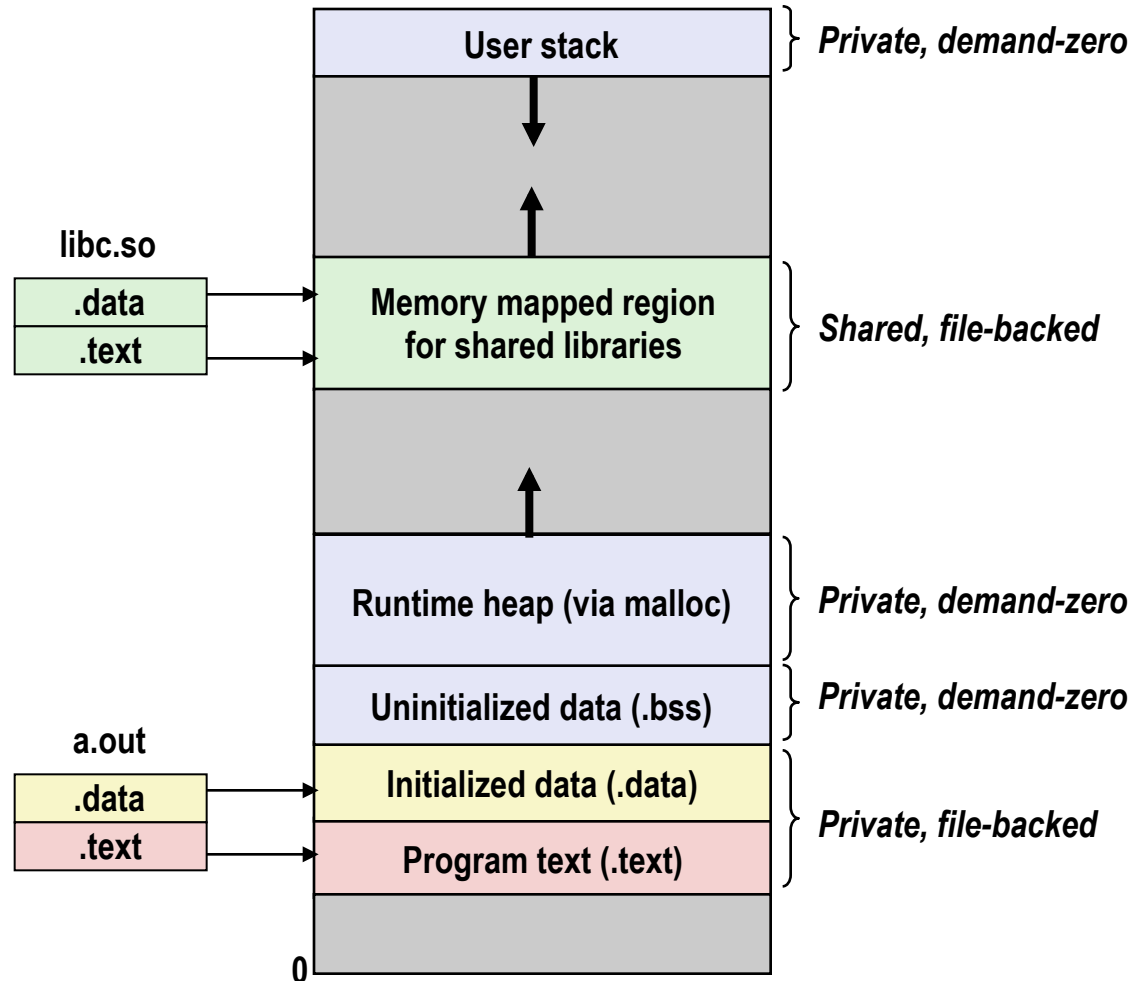


- Instruction writing to private page triggers protection fault.
- Handler creates new R/W page.
- Instruction restarts upon handler return.
- Copying deferred as long as possible!

# The `fork` Function Revisited

- VM and memory mapping explain how `fork` provides private address space for each process.
- To create virtual address for new new process
  - Create exact copies of current `mm_struct`, `vm_area_struct`, and page tables.
  - Flag each page in both processes as read-only
  - Flag each `vm_area_struct` in both processes as private COW
- On return, each process has exact copy of virtual memory
- Subsequent writes create new pages using COW mechanism.

# The `execve` Function Revisited



- To load and run a new program `a.out` in the current process using `execve`:
- Free `vm_area_struct`'s and page tables for old areas
- Create `vm_area_struct`'s and page tables for new areas
  - Programs and initialized data backed by object files.
  - `.bss` and stack backed by anonymous files.
- Set PC to entry point in `.text`
  - Linux will fault in code and data pages as needed.

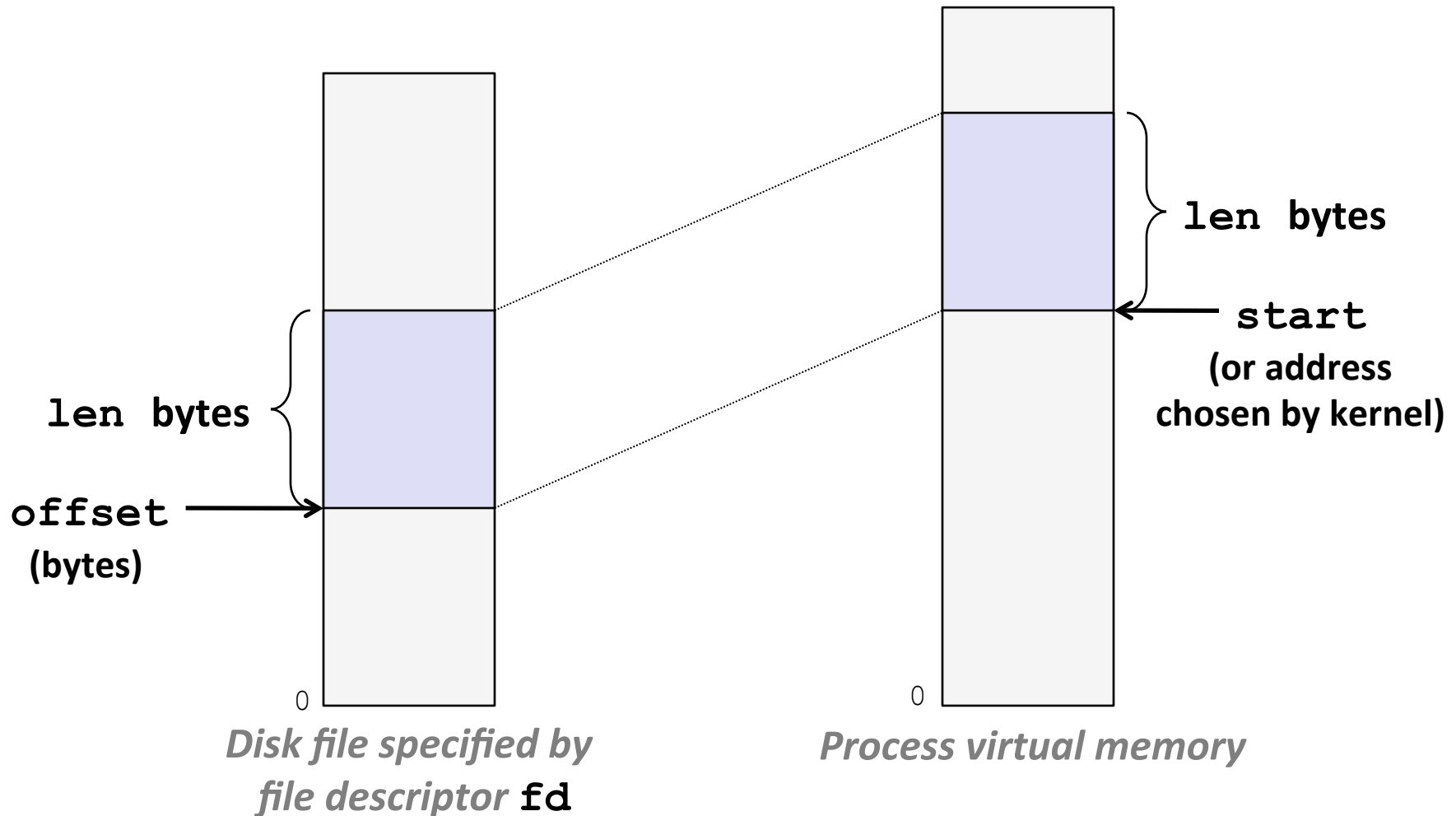
# User-Level Memory Mapping

```
void *mmap(void *start, int len,  
           int prot, int flags, int fd, int offset)
```

- **Map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start`**
  - **`start`**: may be 0 for “pick an address”
  - **`prot`**: `PROT_READ`, `PROT_WRITE`, ...
  - **`flags`**: `MAP_ANON`, `MAP_PRIVATE`, `MAP_SHARED`, ...
  
- **Return a pointer to start of mapped area (may not be `start`)**

# User-Level Memory Mapping

```
void *mmap(void *start, int len,  
           int prot, int flags, int fd, int offset)
```





# Using mmap to Copy Files

- Copying without transferring data to user space .

```
#include "csapp.h"

/*
 * mmapcopy - uses mmap to copy
 *            file fd to stdout
 */
void mmapcopy(int fd, int size)
{
    /* Ptr to mem-mapped VM area */
    char *bufp;

    bufp = Mmap(NULL, size,
                PROT_READ,
                MAP_PRIVATE, fd, 0);
    Write(1, bufp, size);
    return;
}
```

```
/* mmapcopy driver */
int main(int argc, char **argv)
{
    struct stat stat;
    int fd;

    /* Check for required cmdline arg */
    if (argc != 2) {
        printf("usage: %s <filename>\n",
              argv[0]);
        exit(0);
    }

    /* Copy the input arg to stdout */
    fd = Open(argv[1], O_RDONLY, 0);
    Fstat(fd, &stat);
    mmapcopy(fd, stat.st_size);
    exit(0);
}
```