Virtual Memory: Systems

15-213 / 18-213: Introduction to Computer Systems
17th Lecture, Mar. 22, 2012

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Today

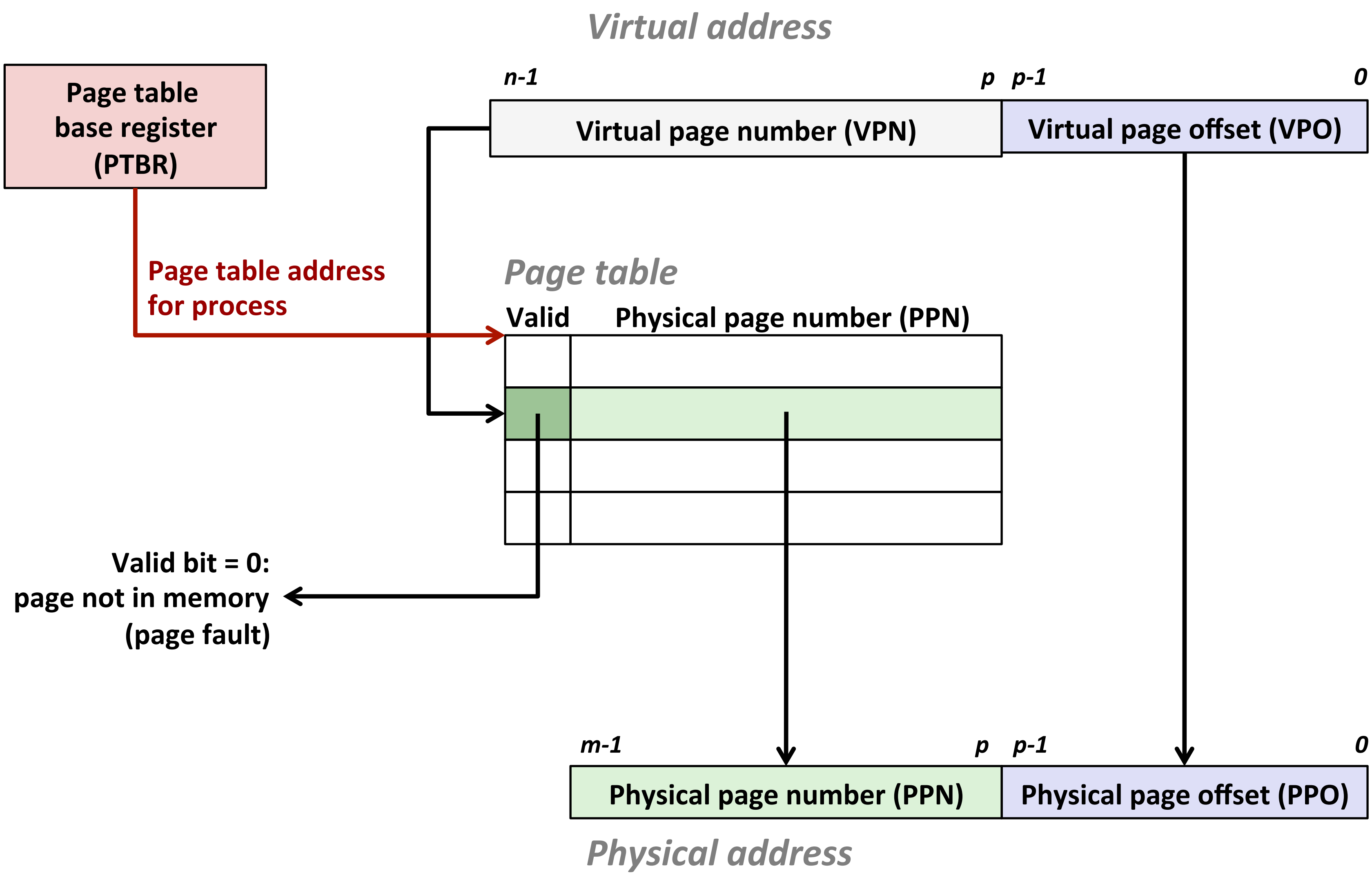
- **Virtual memory questions and answers**
- Simple memory system example
- Bonus: Case study: Core i7/Linux memory system
- Bonus: Memory mapping

Virtual memory reminder/review

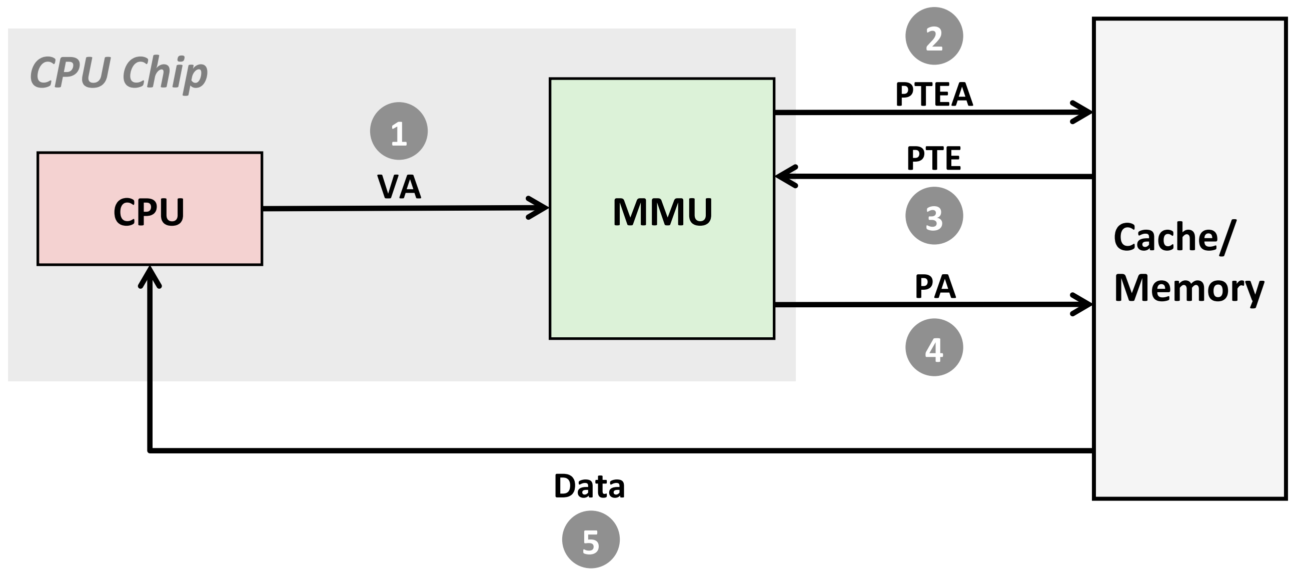
- **Programmer's view of virtual memory**
  - Each process has its own private linear address space
  - Cannot be corrupted by other processes

- **System view of virtual memory**
  - Uses memory efficiently by caching virtual memory pages
    - Efficient only because of locality
  - Simplifies memory management and programming
  - Simplifies protection by providing a convenient interpositioning point to check permissions

Recall: Address Translation With a Page Table



Recall: Address Translation: Page Hit



1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

4) MMU sends physical address to cache/memory

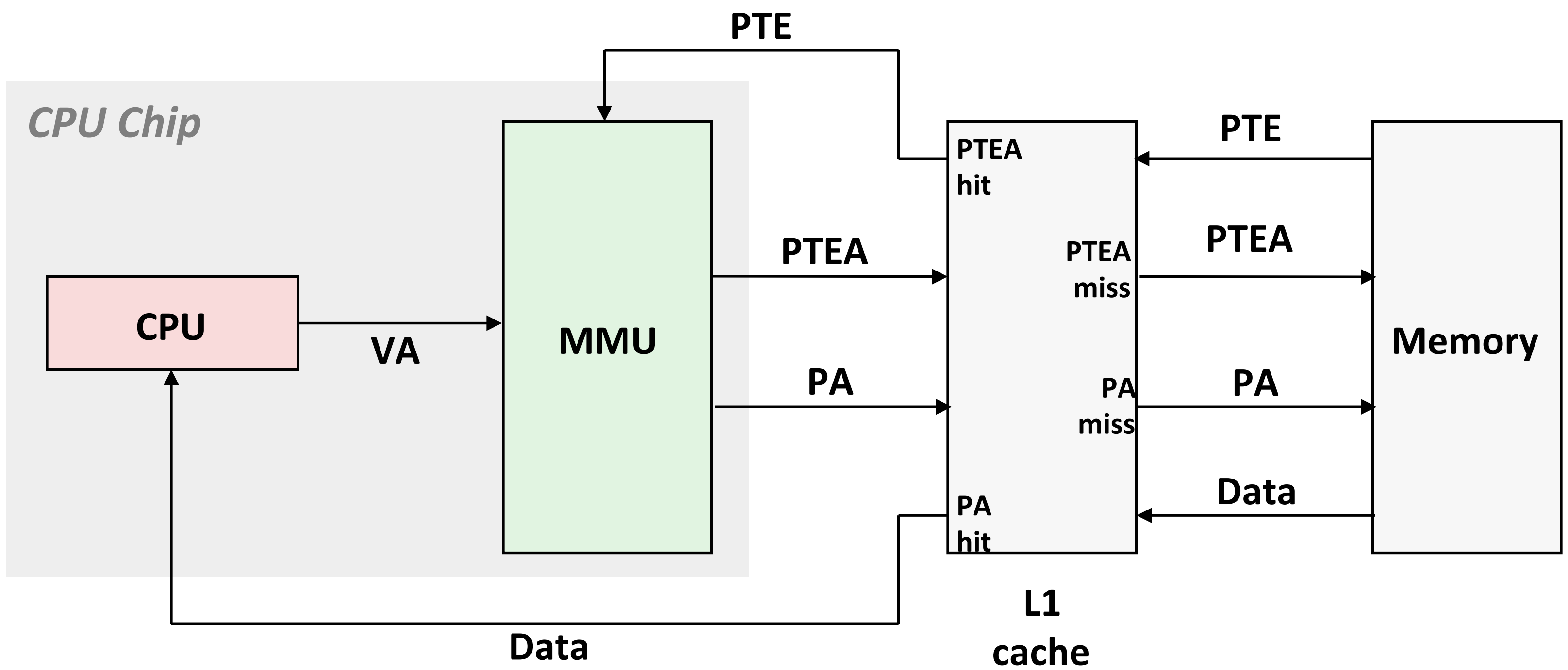
5) Cache/memory sends data word to processor

Question #1

- **Are the PTEs cached like other memory accesses?**

- **Yes (and no: see next question)**

Page tables in memory, like other data



VA: virtual address, PA: physical address, PTE: page table entry, PTEA = PTE address

Question #2

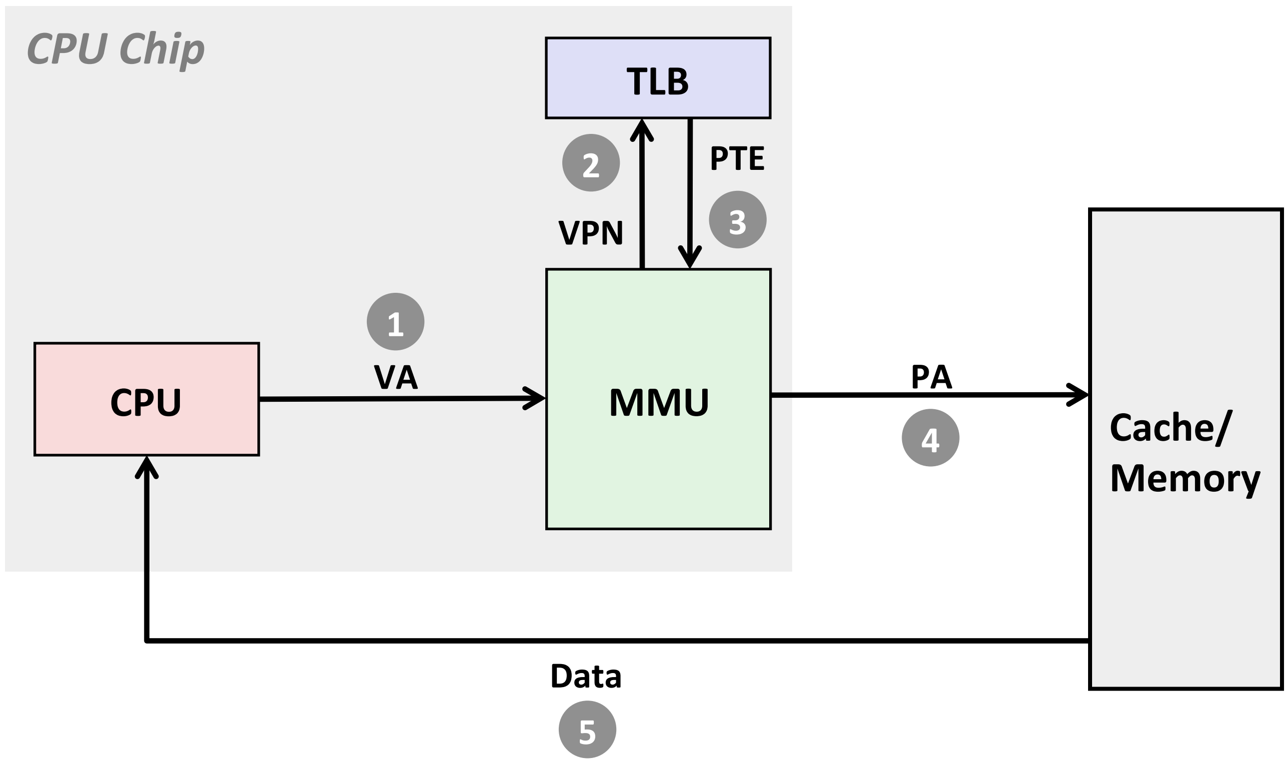
- Isn't it slow to have to go to memory twice every time?

- Yes, it would be… so, real MMUs don't

Speeding up Translation with a TLB

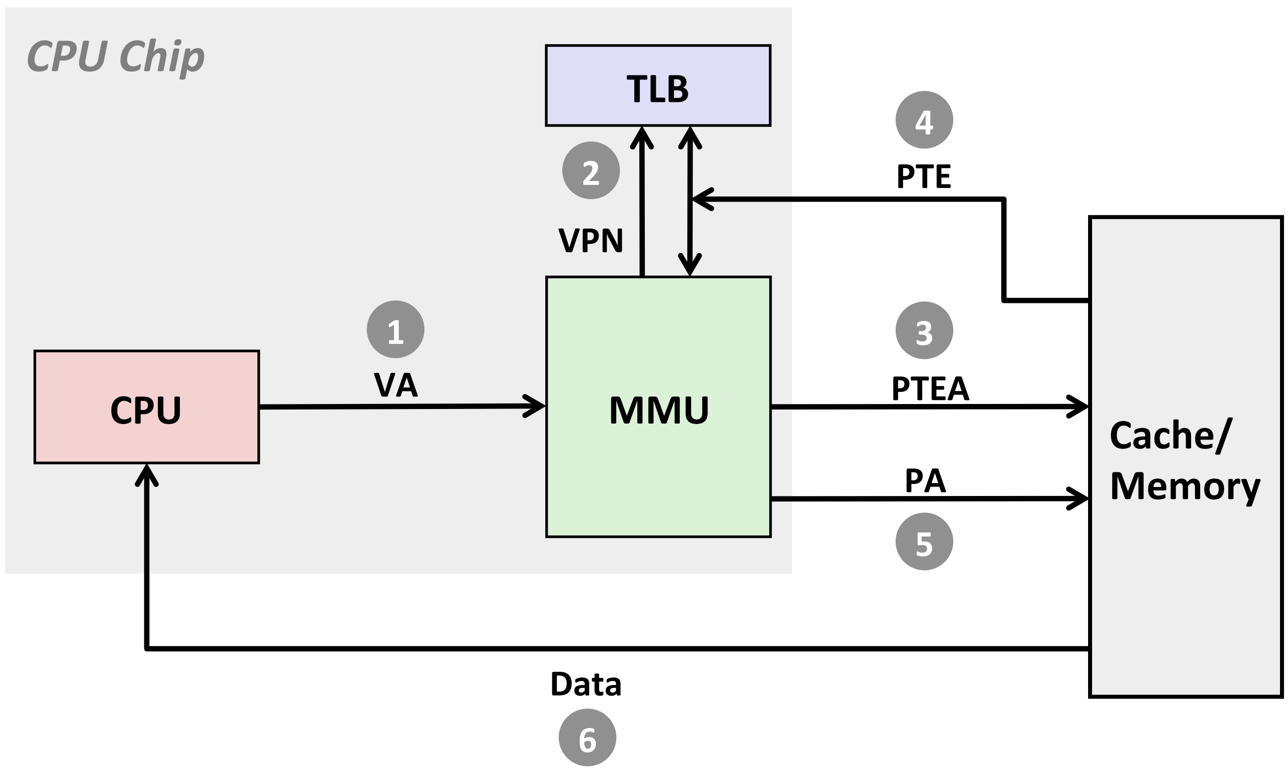
- **Page table entries (PTEs) are cached in L1 like any other memory word**
  - PTEs may be evicted by other data references
  - PTE hit still requires a small L1 delay
- **Solution: *Translation Lookaside Buffer* (TLB)**
  - Small, dedicated, super-fast hardware cache of PTEs in MMU
  - Contains complete page table entries for small number of pages

TLB Hit



A TLB hit eliminates a memory access

TLB Miss



A TLB miss incurs an additional memory access (the PTE)

Fortunately, TLB misses are rare. Why?

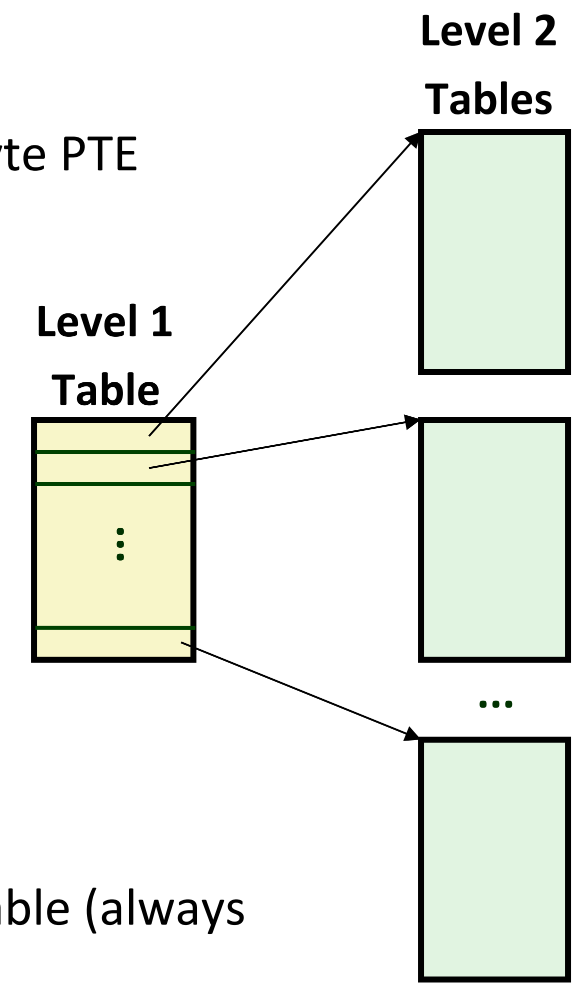
Question #3

- Isn't the page table huge? How can it be stored in RAM?

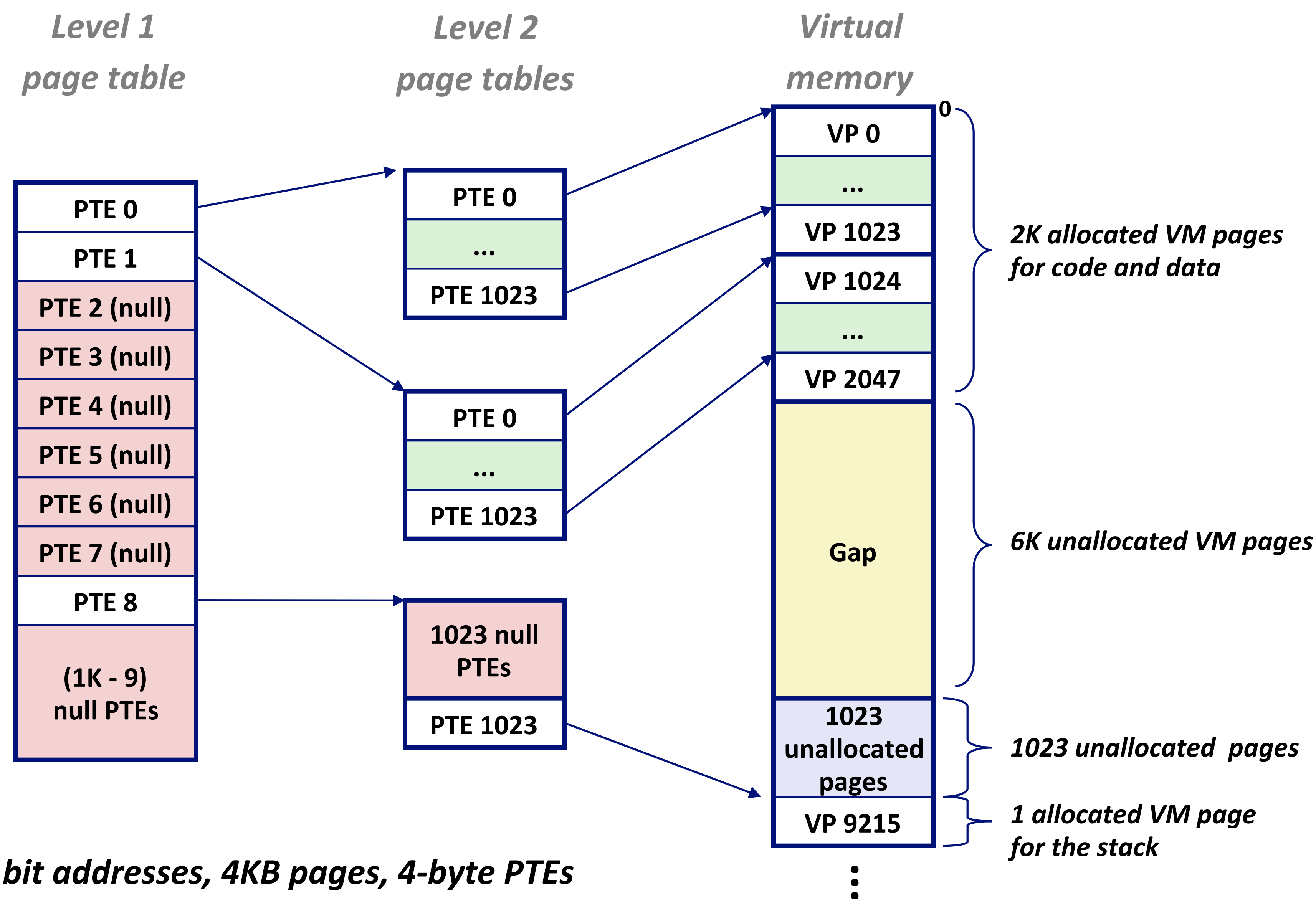
- Yes, it would be… so, real page tables aren't simple arrays

Multi-Level Page Tables

- **Suppose:**
  - 4KB (2^{12}) page size, 64-bit address space, 8-byte PTE
- **Problem:**
  - Would need a 32,000 TB page table!
    - $2^{64} * 2^{-12} * 2^{3} = 2^{55}$ bytes
- **Common solution:**
  - Multi-level page tables
  - Example: 2-level page table
    - Level 1 table: each PTE points to a page table (always memory resident)
    - Level 2 table: each PTE points to a page (paged in and out like any other data)

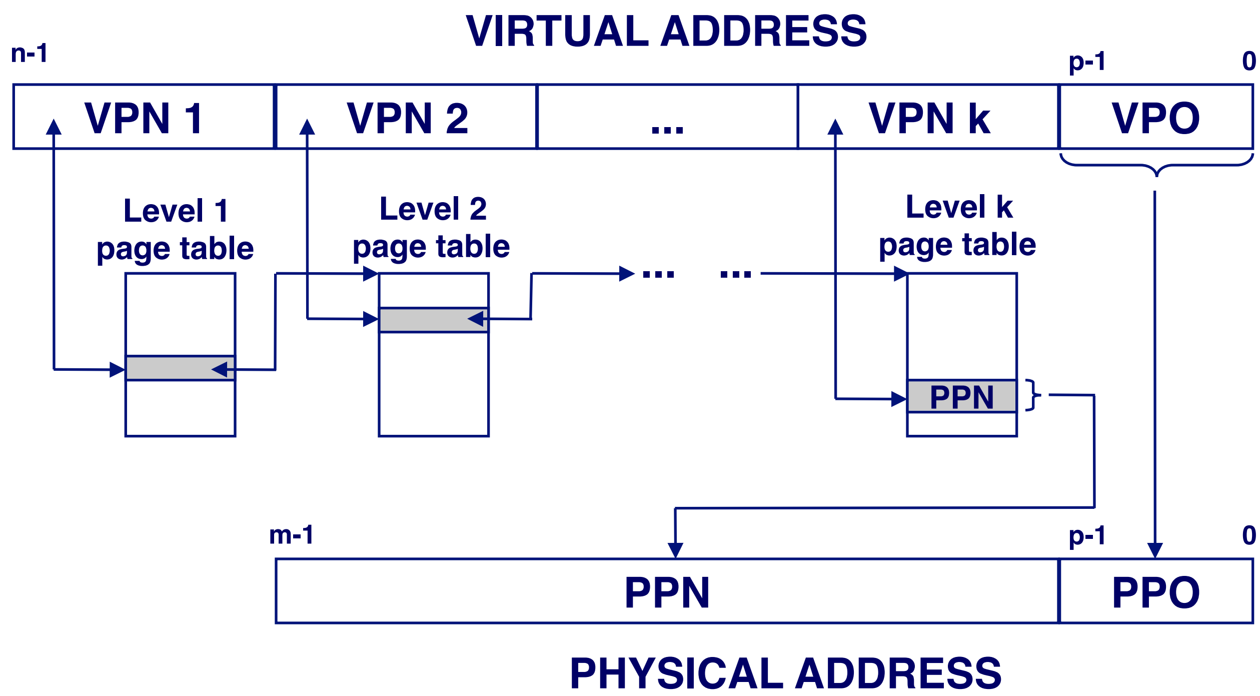


A Two-Level Page Table Hierarchy



32 bit addresses, 4KB pages, 4-byte PTEs

Translating with a k-level Page Table

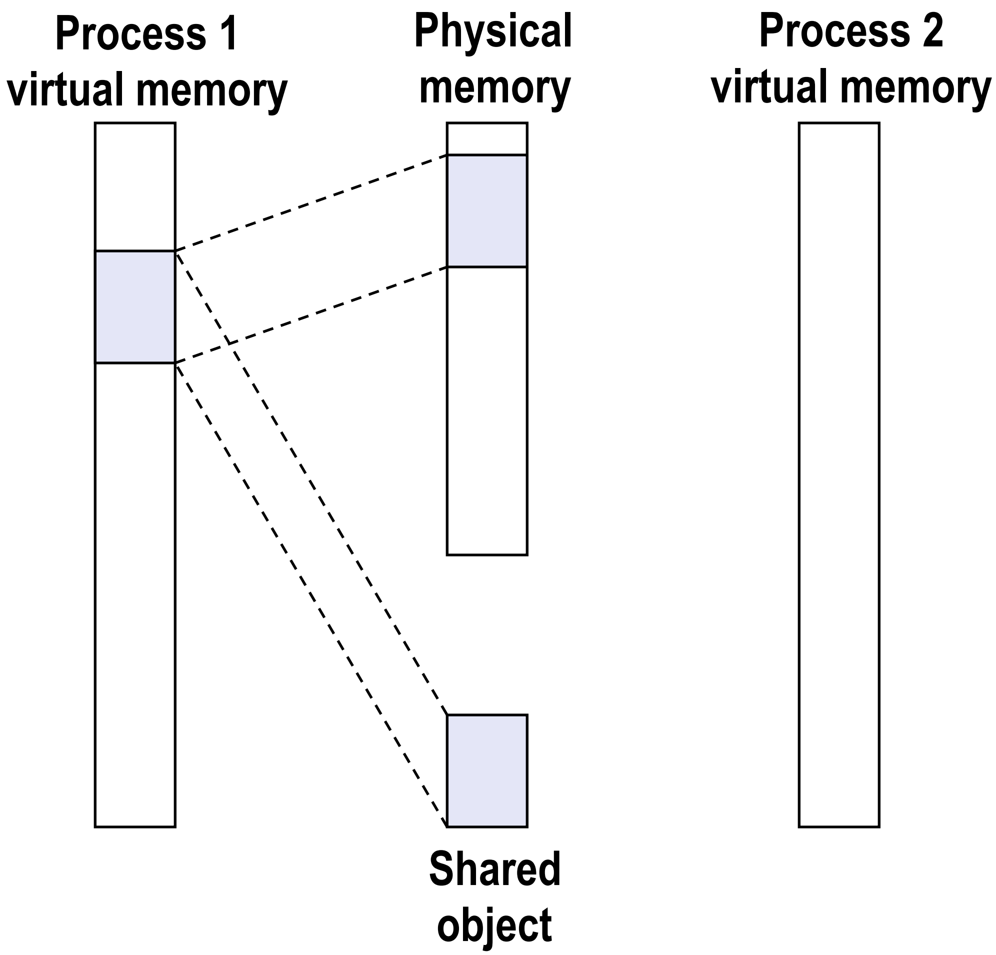


Question #4

- Shouldn't fork() be really slow, since the child needs a copy of the parent's address space?

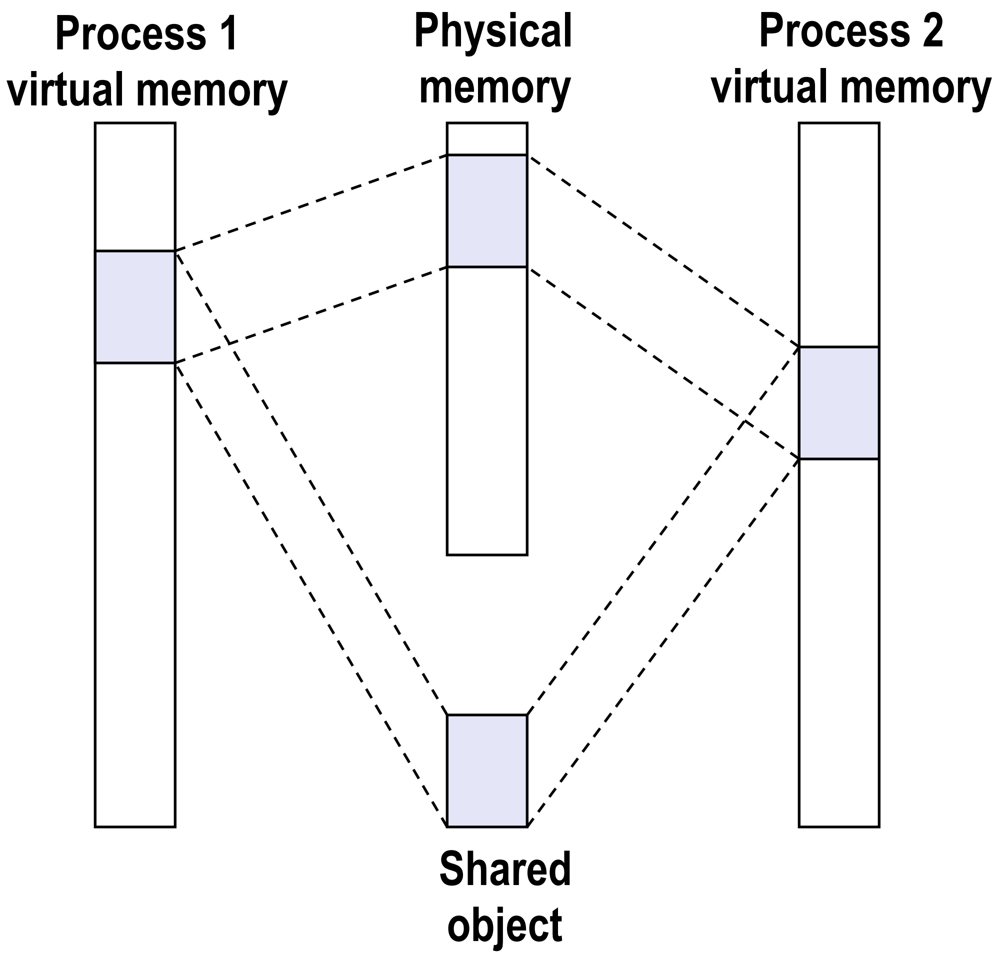
- Yes, it would be… so, fork() doesn't really work that way

Sharing Revisited: Shared Objects



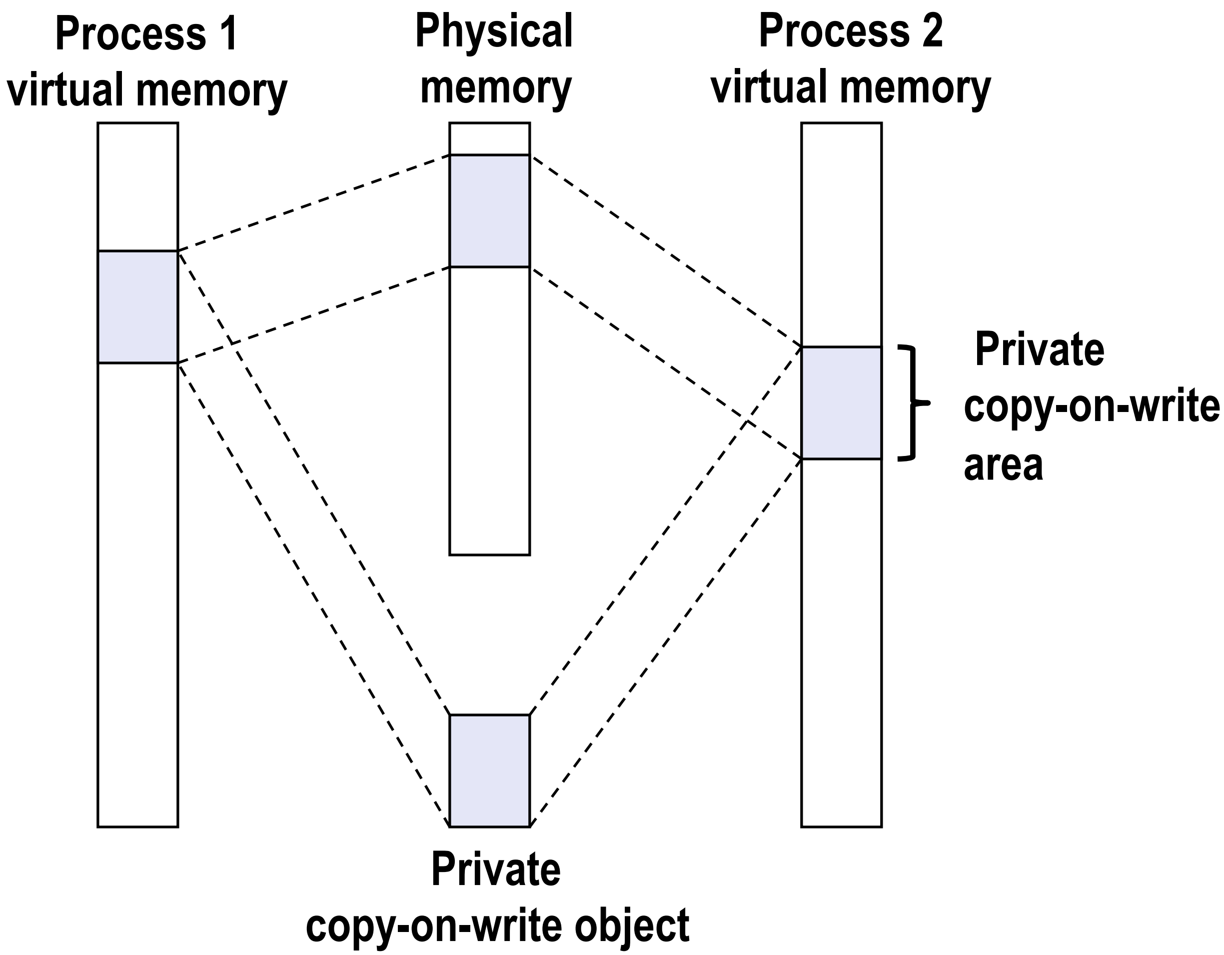
- Process 1 maps the shared object.

Sharing Revisited: Shared Objects



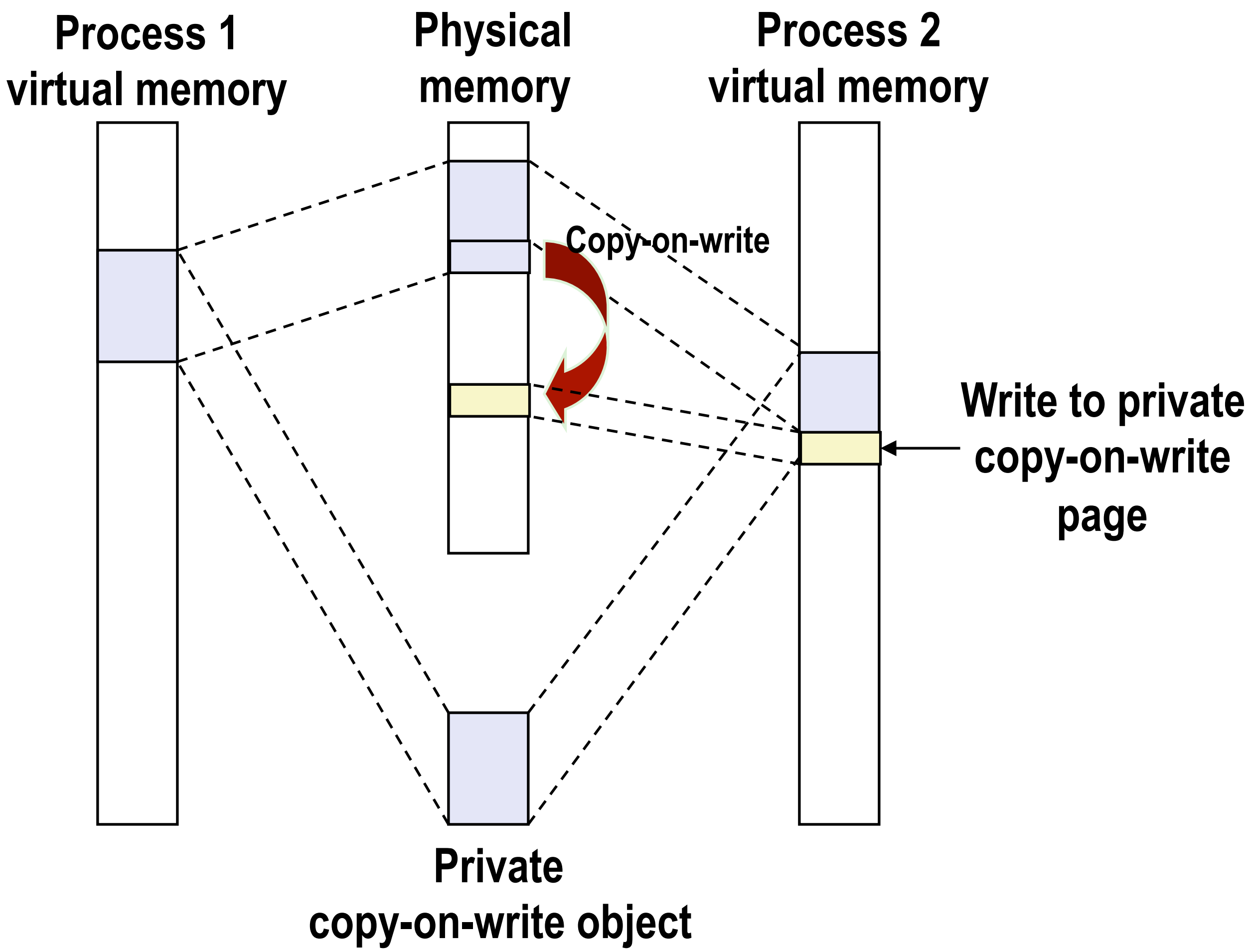
- Process 2 maps the shared object.
- Notice how the virtual addresses can be different.

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

- **`fork` provides private address space for each process**
- **To create virtual address for new process**
  - Create exact copies of parent page tables
  - Flag each page in both processes (parent and child) as read-only
  - Flag writeable areas in both processes as private COW
- **On return, each process has exact copy of virtual memory**
- **Subsequent writes create new physical pages using COW mechanism**
- **Perfect approach for common case of fork() followed by exec()**
  - Why?

Today

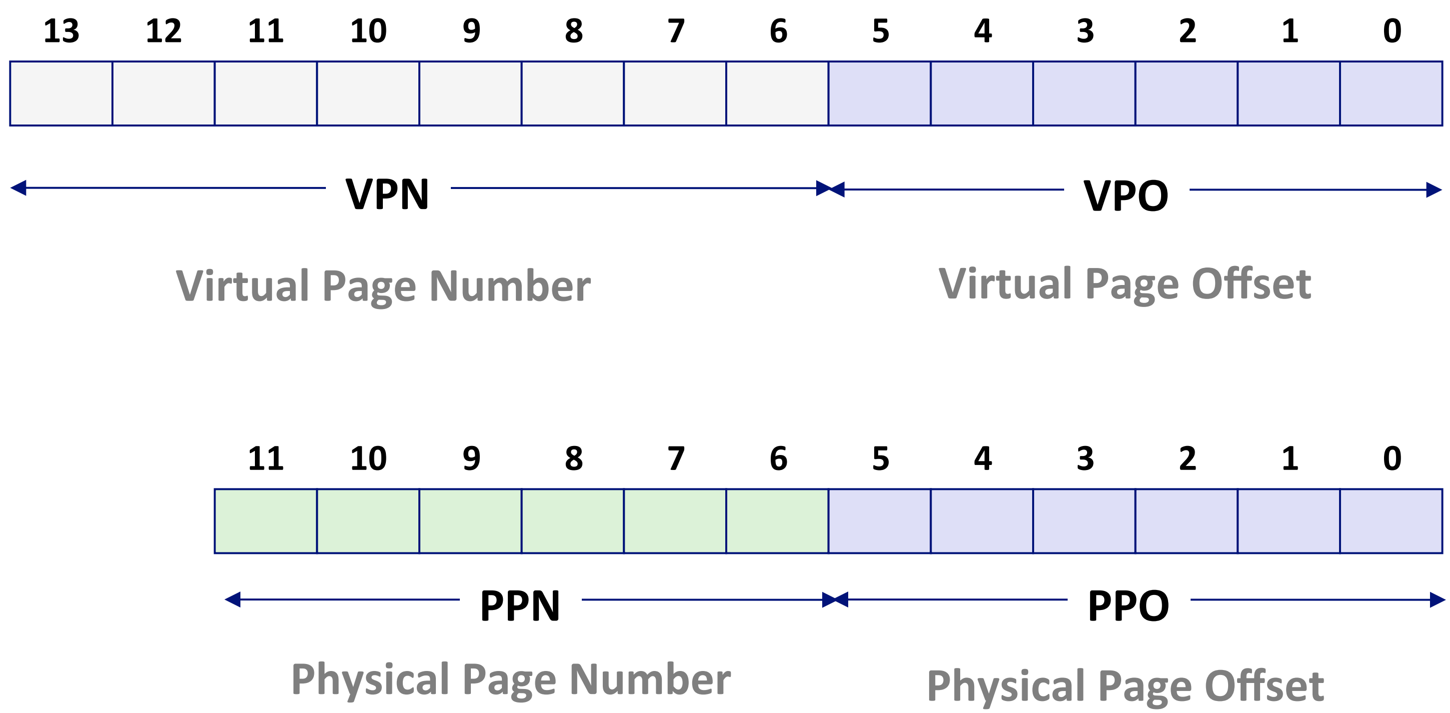
- Virtual memory questions and answers
- **Simple memory system example**
- Bonus: Case study: Core i7/Linux memory system
- Bonus: Memory mapping

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

Simple Memory System Example

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



Simple Memory System Page Table

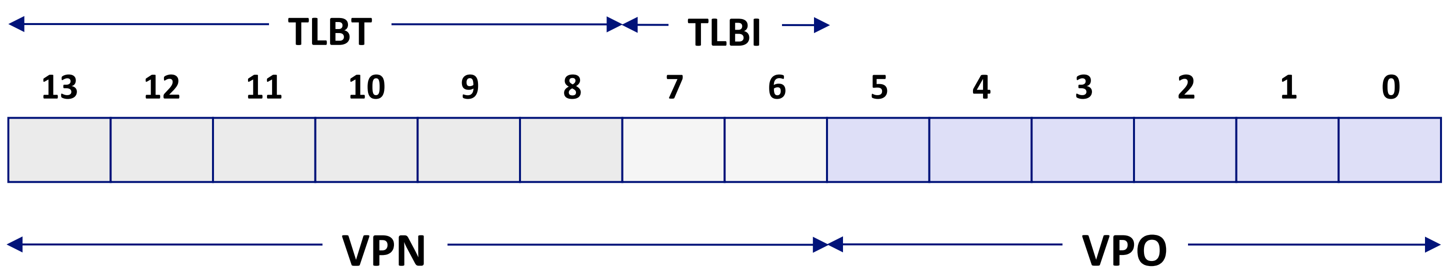
Only show first 16 entries (out of 256)

VPN	PPN	Valid
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

Simple Memory System TLB

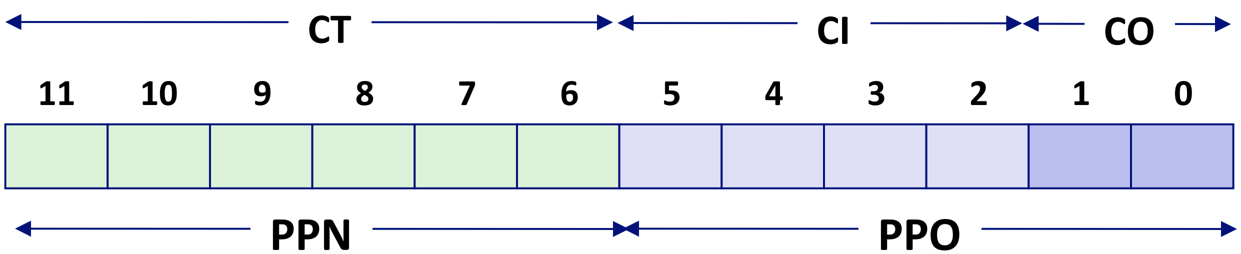
- 16 entries
- 4-way associative



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

Simple Memory System Cache

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



Idx	*Tag*	*Valid*	*B0*	*B1*	*B2*	*B3*
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

Idx	*Tag*	*Valid*	*B0*	*B1*	*B2*	*B3*
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	–	–	–	–

Address Translation Example #1

Virtual Address: 0x03D4

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

VPN | VPO

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

Physical Address

CT | CI | CO

11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0

PPN | PPO

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

Address Translation Example #2

Virtual Address: 0x01CF

TLBT: bits 13–8 | TLBI: bits 7–6

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	1	1	1	0	0	1	1	1	1

VPN: bits 13–6 | VPO: bits 5–0

VPN **0x7** TLBI **0x3** TLBT **0x1** TLB Hit? **N** Page Fault? **Y** PPN: **TBD**

Physical Address

CT: bits 11–6 | CI: bits 5–2 | CO: bits 1–0

11	10	9	8	7	6	5	4	3	2	1	0

PPN: bits 11–6 | PPO: bits 5–0

CO ___ CI___ CT _____ Hit? __ Byte: _____

Address Translation Example #3

Virtual Address: 0x0020

TLBT (bits 13–6) | TLBI (bits 7–6)

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0

VPN (bits 13–6) | VPO (bits 5–0)

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

Physical Address

CT (bits 11–6) | CI (bits 5–2) | CO (bits 1–0)

11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	0	0	0	1	0	0	0	0	0

PPN (bits 11–6) | PPO (bits 5–0)

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

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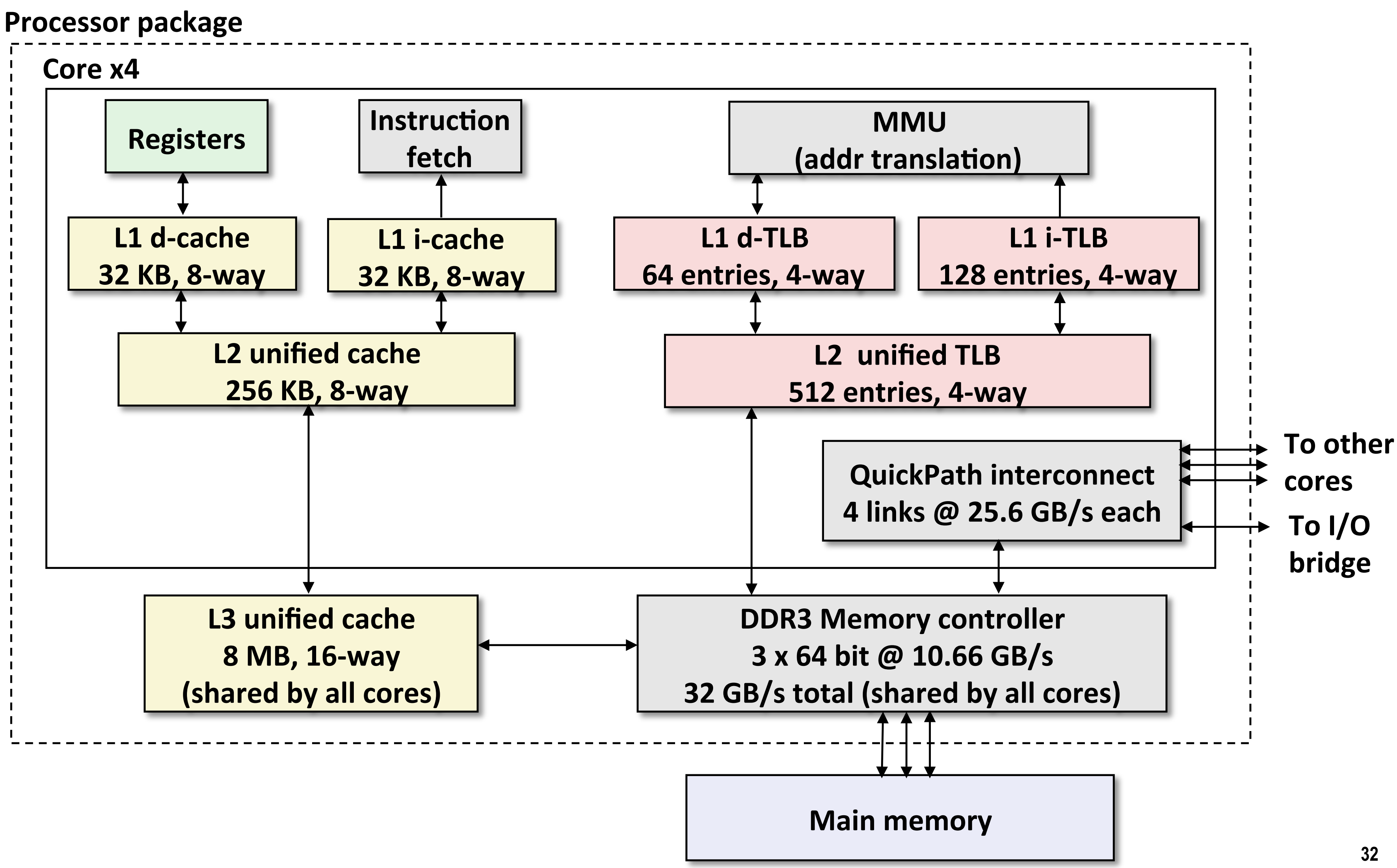
Intel Core i7 Memory System



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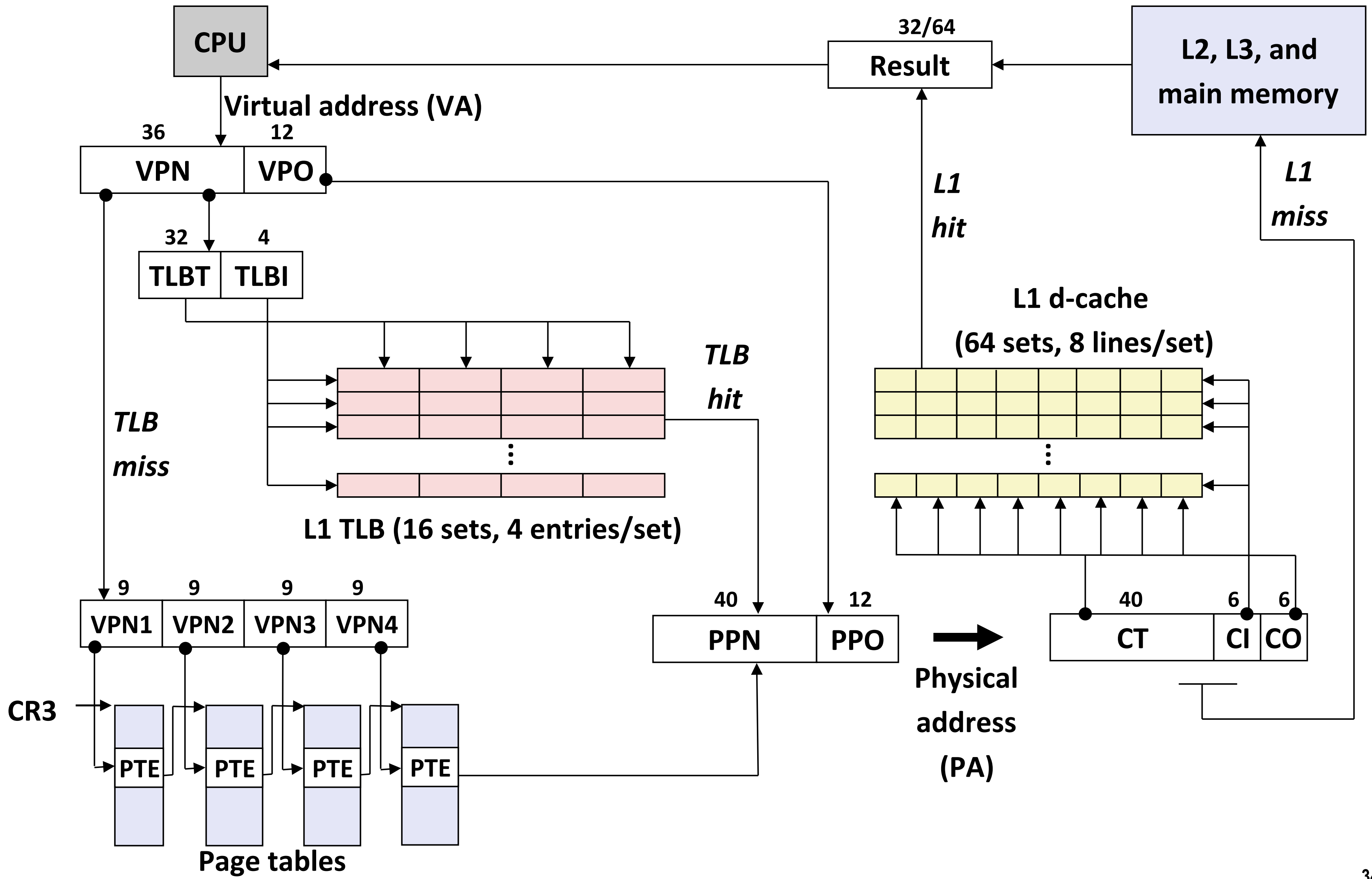
End-to-end Core i7 Address Translation



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)

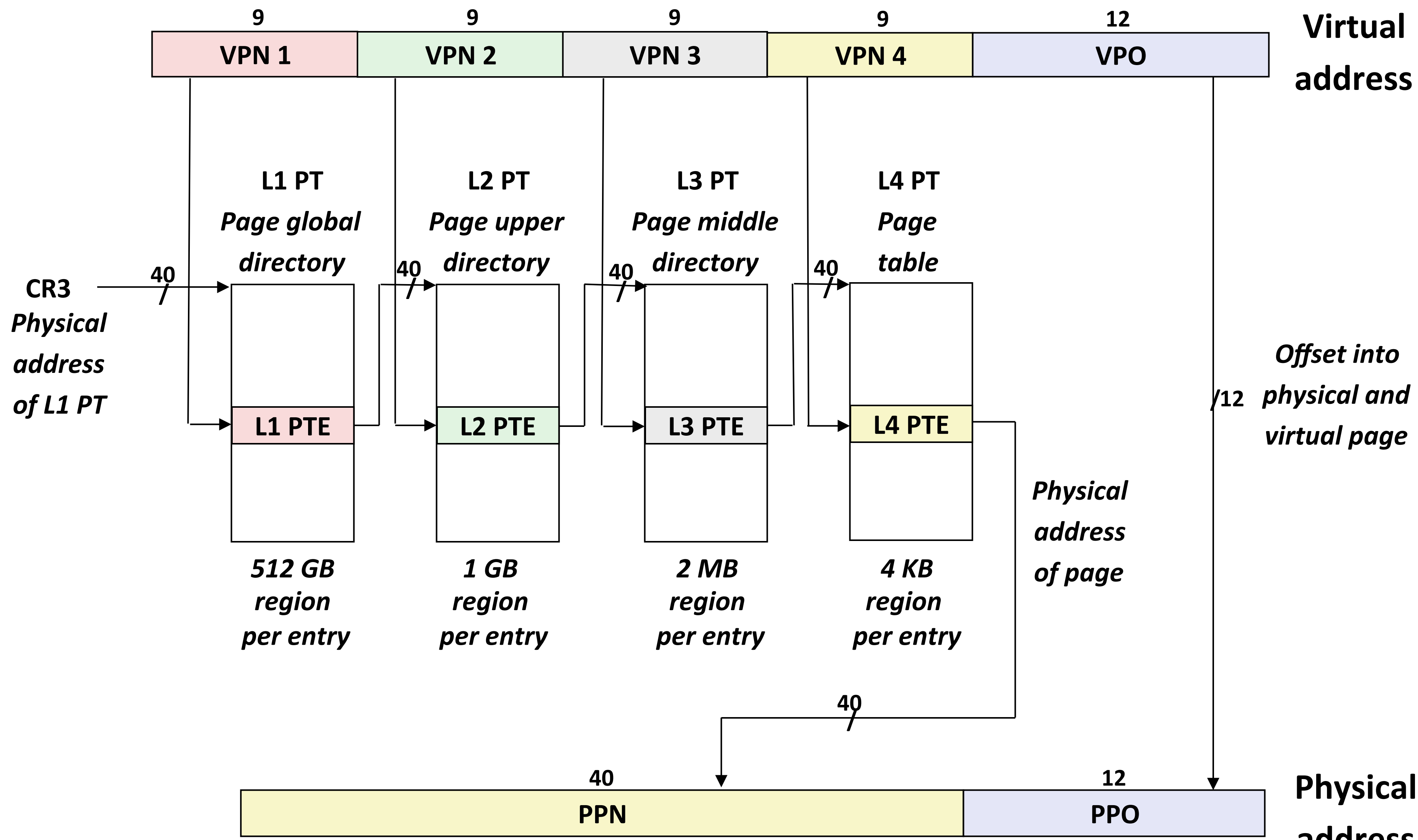
A: Reference bit (set by MMU on reads and writes, cleared by software)

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

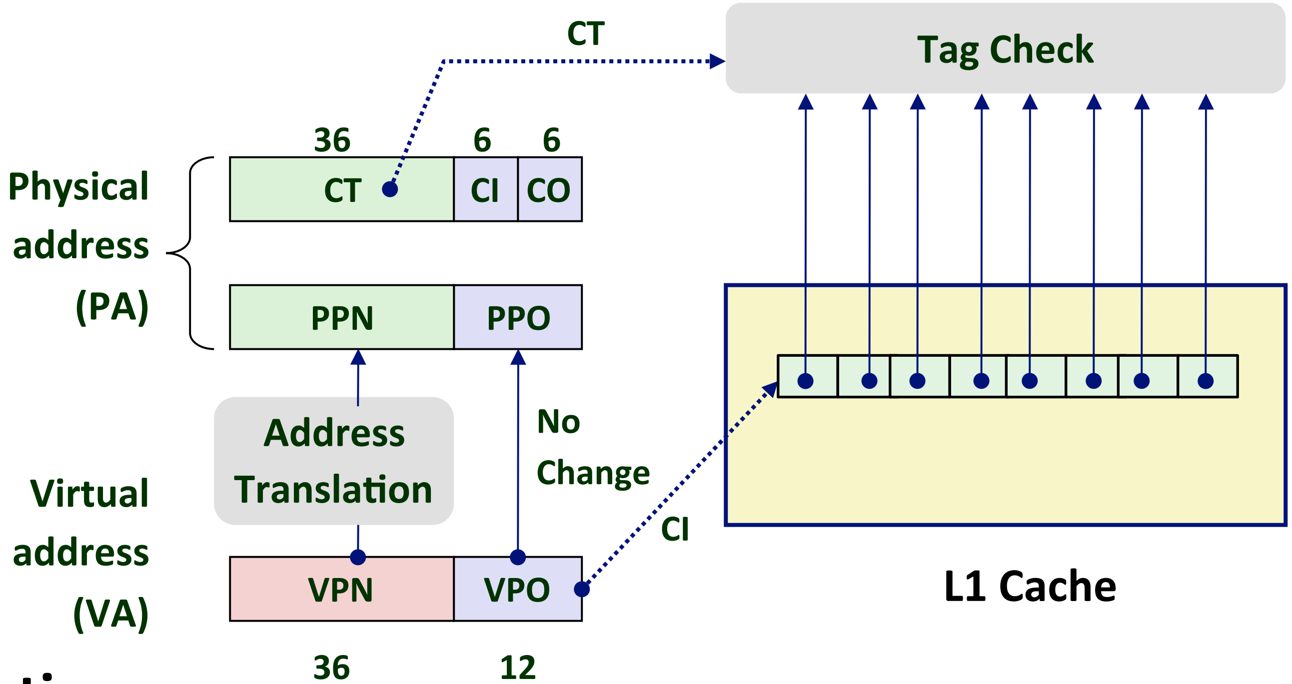
G: Global page (don't evict from TLB on task switch)

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

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- **Bonus: 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**

User-Level Memory Mapping

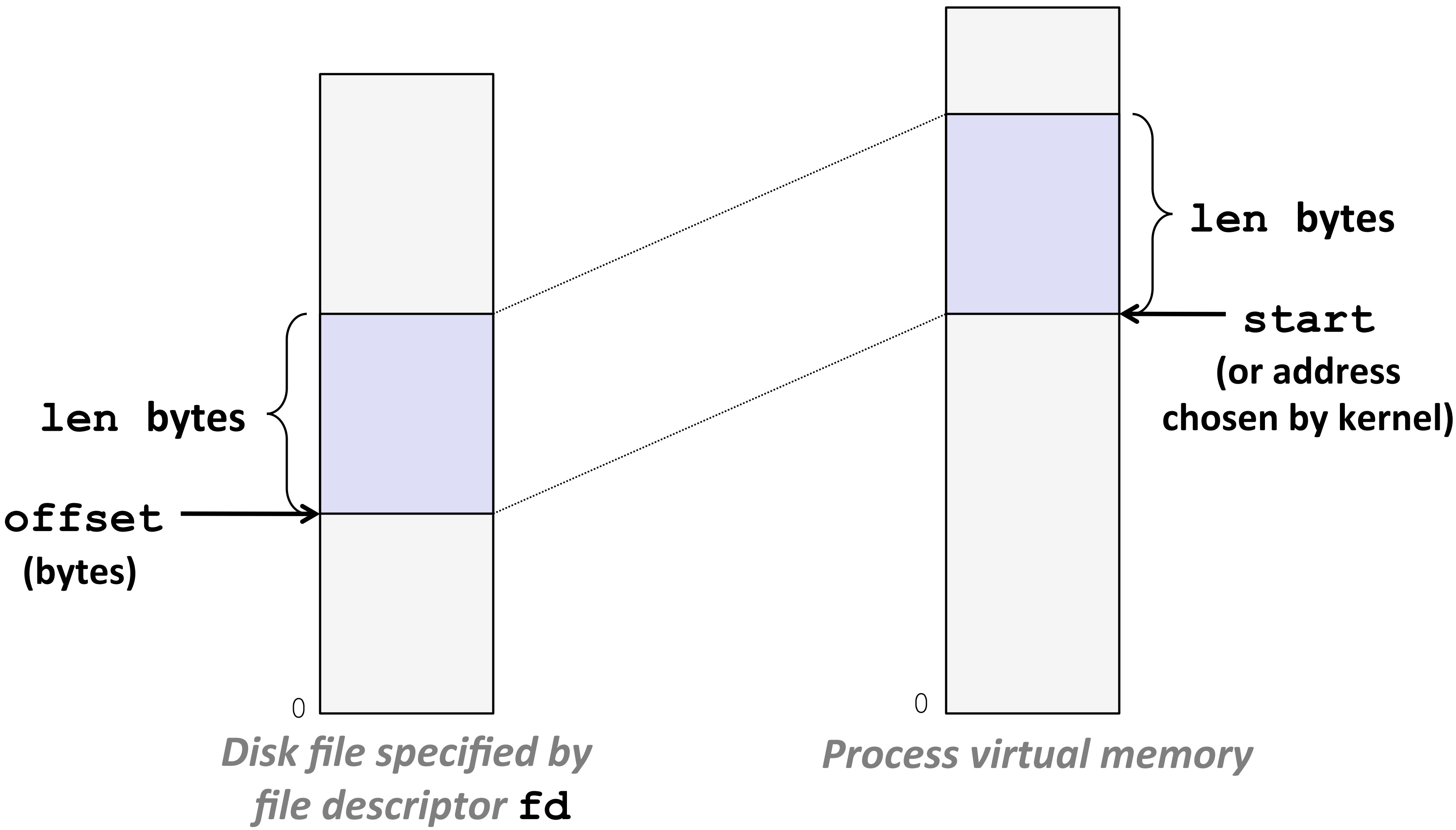
```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```

- **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)
```



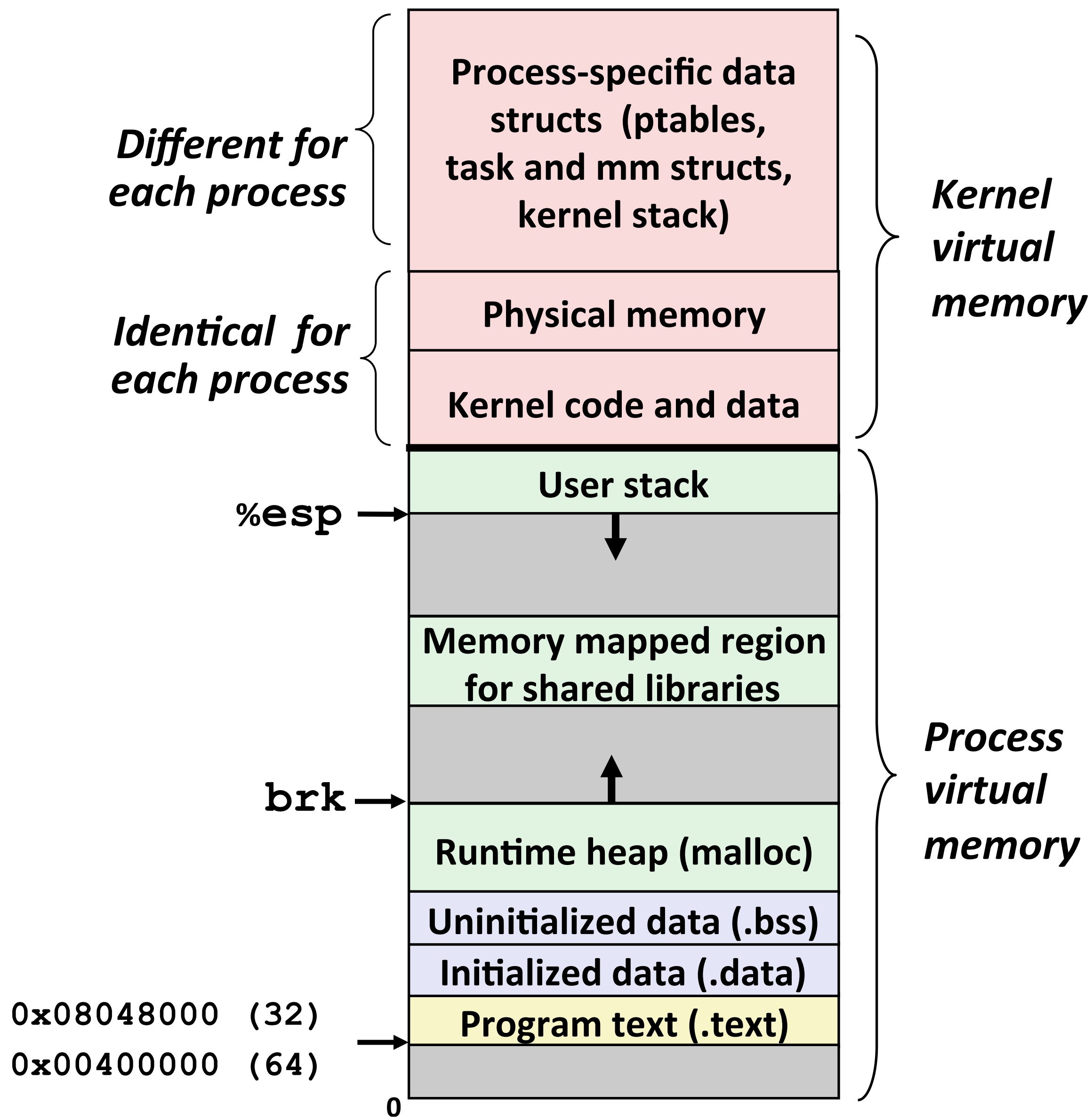
Using mmap to Copy Files

- **Copying without transferring data to user space .**

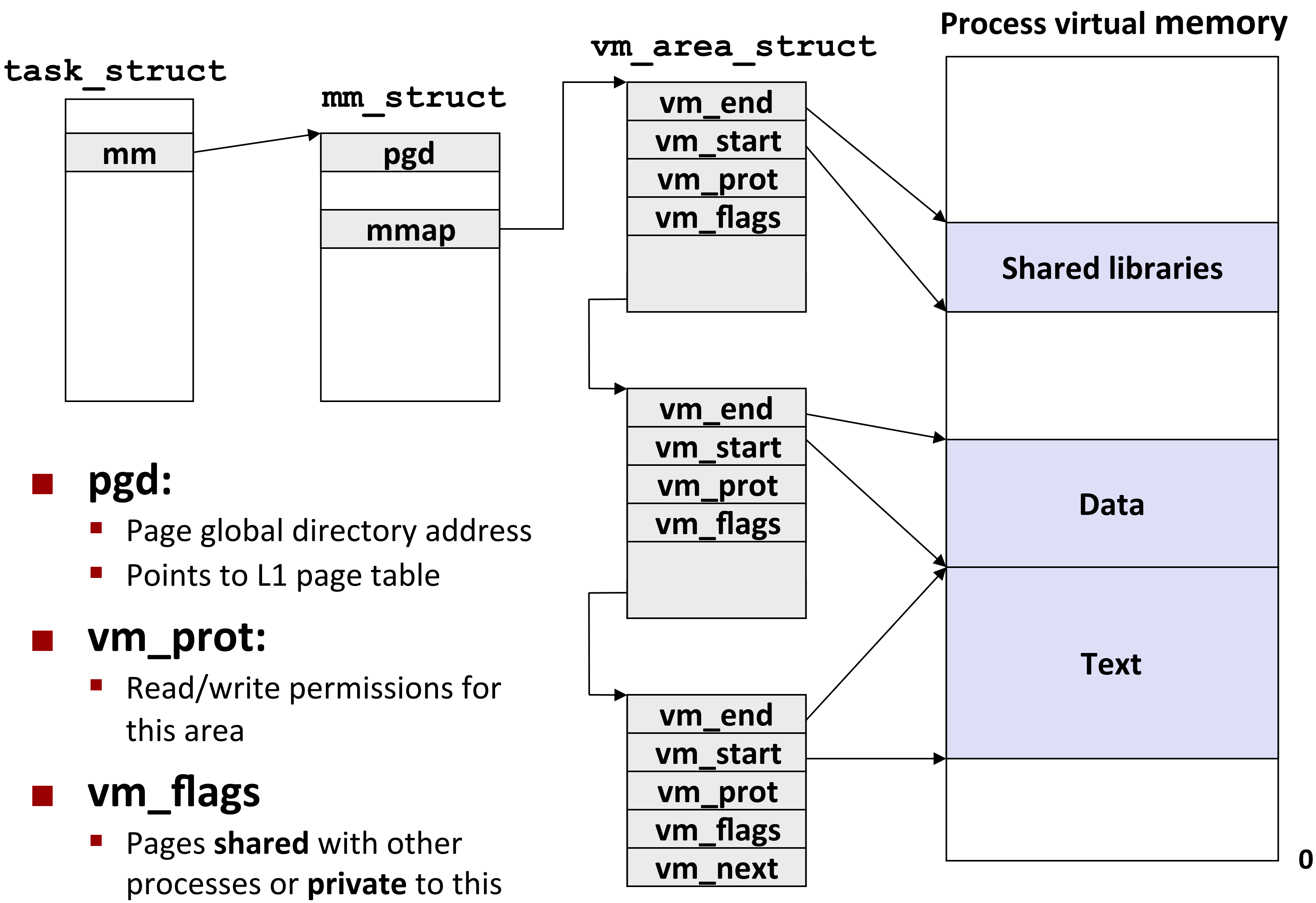
```
#include "csapp.h"

/*
 * 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);
}
```

Virtual Memory of a Linux Process

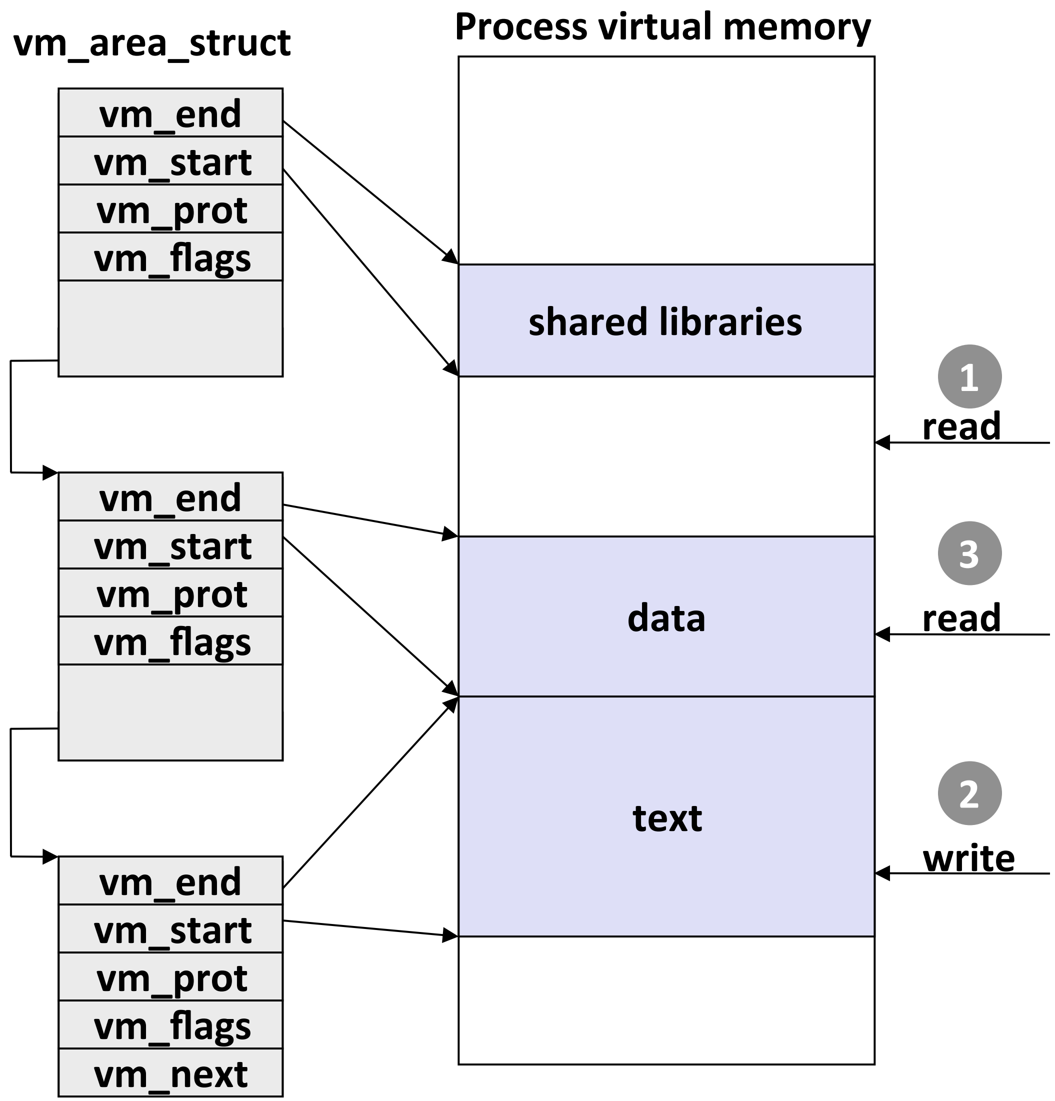


Linux Organizes VM as Collection of "Areas"



- **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

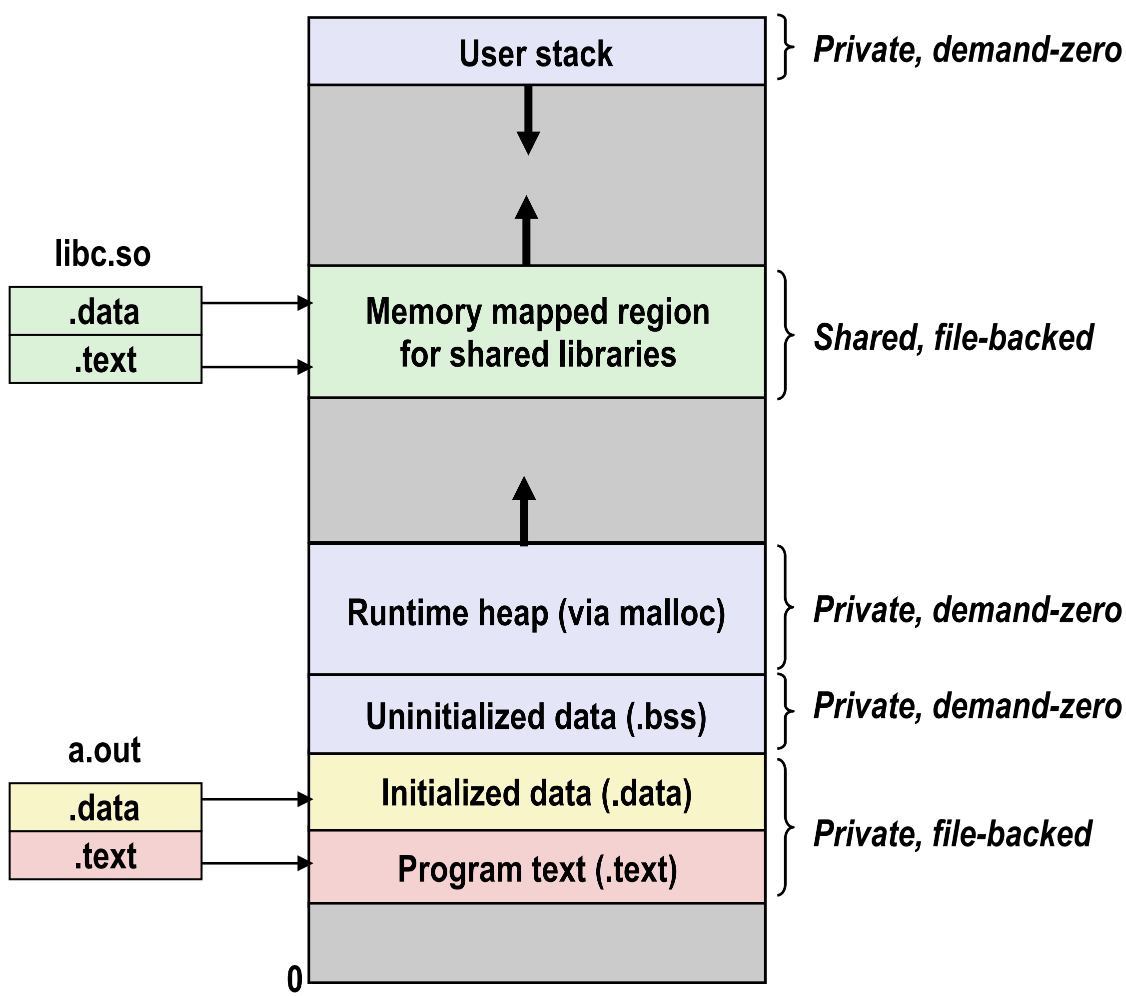


Segmentation fault:
accessing a non-existing page

Normal page fault

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

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.