Virtual Memory: Systems

Lecture 11-12, 9-19th May 2011.
Alexandre David

Credits to Randy Bryant & Dave O'Hallaron from Carnegie Mellon

Today

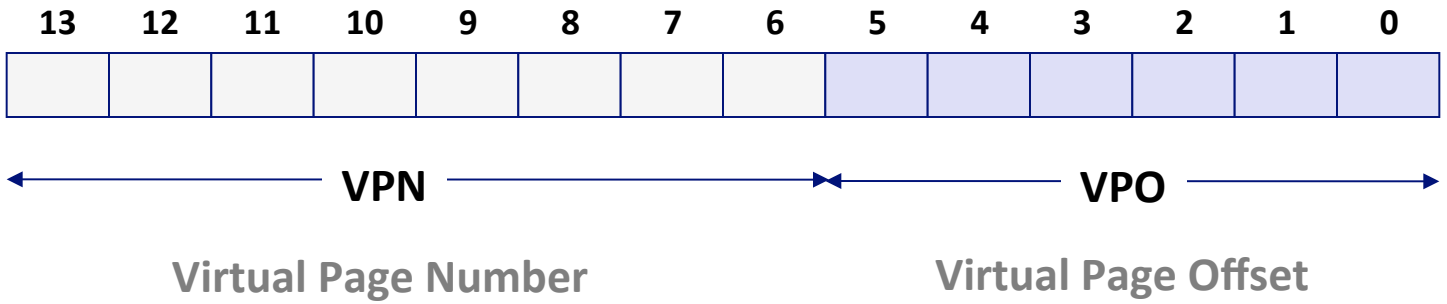
- **Simple memory system example**
- **Case study: Core i7/Linux memory system**
- **Memory mapping**

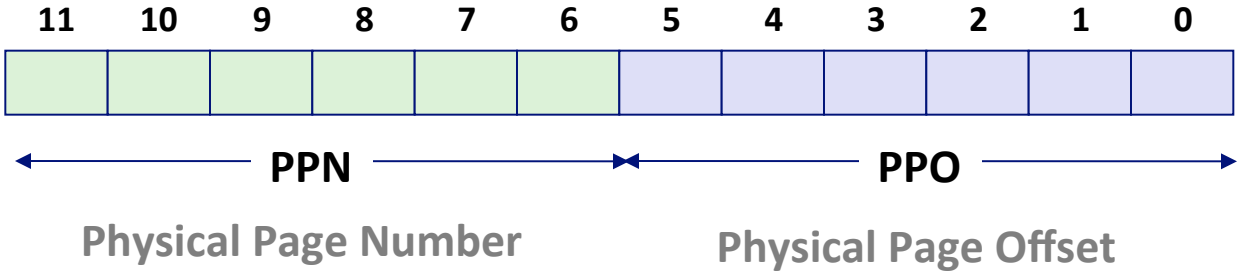
Review of Symbols

- **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)**
  - **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

Simple Memory System Example

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





Simple Memory System Page Table

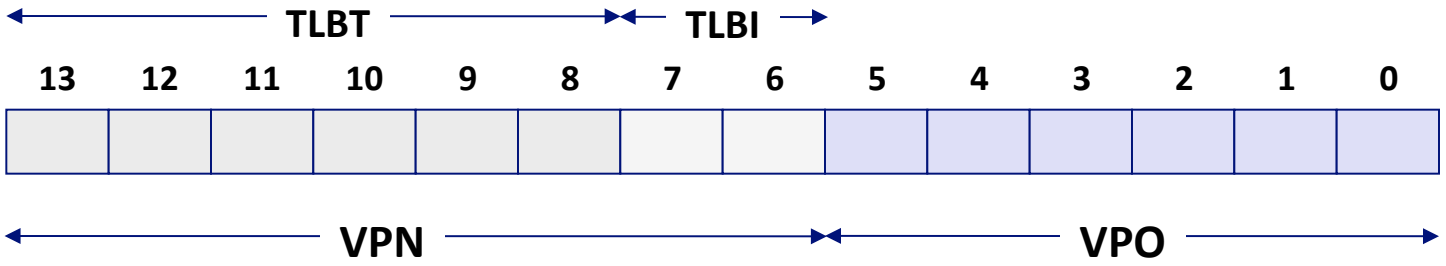
Only show first 16 entries (out of 256)

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

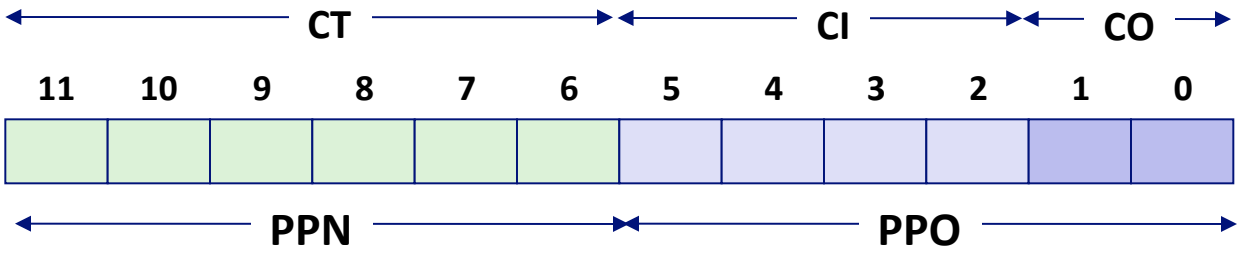
- 16 entries
- 4-way associative



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

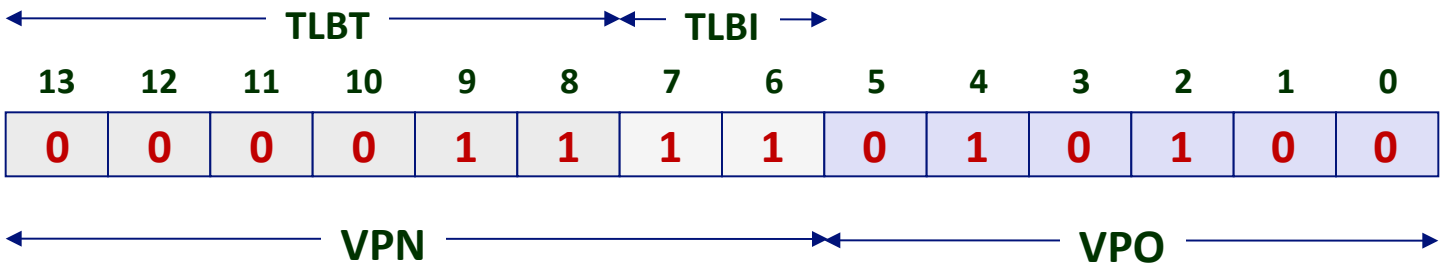


Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

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



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

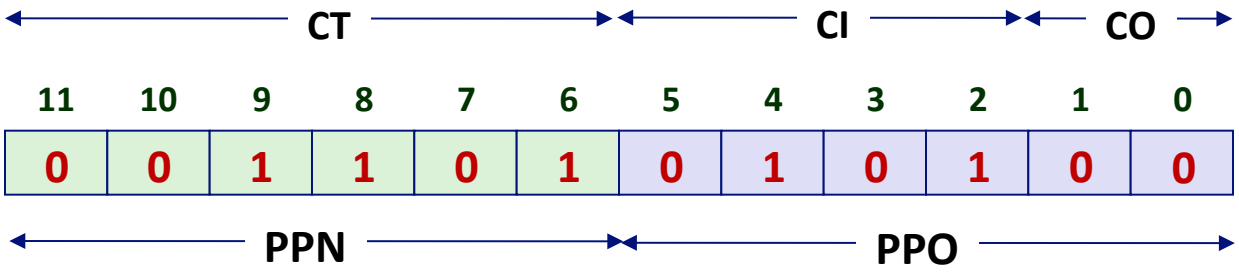
Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
0	03	–	0	09	0D	1	00	–	0	07	02	1
1	03	2D	1	02	–	0	04	–	0	0A	–	0
2	02	–	0	08	–	0	06	–	0	03	–	0
3	07	–	0	03	0D	1	0A	34	1	02	–	0

Address Translation Example #1

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	–	–	–	–

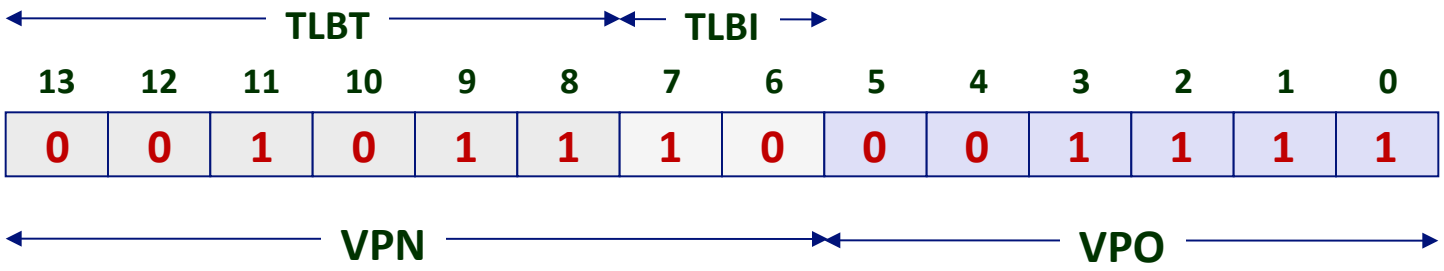
Physical Address



CO __0__ CI __0x5__ CT __0x0D__ Hit? __Y__ Byte: __0x36__

Address Translation Example #2

Virtual Address: 0x0B8F

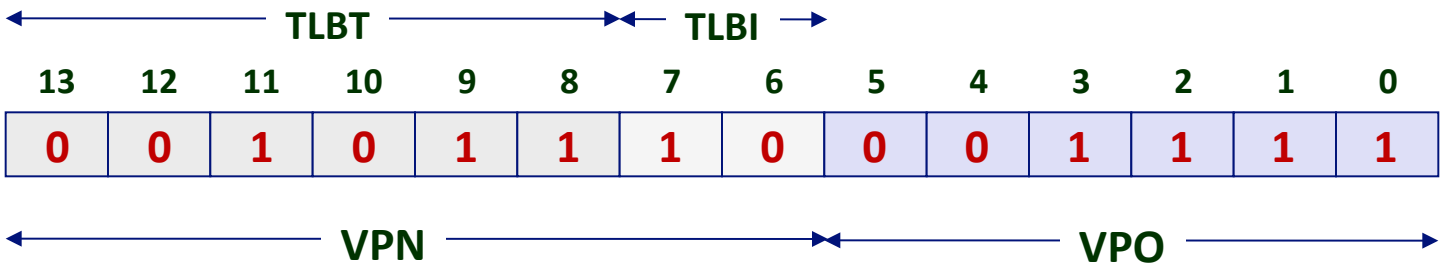


VPN 0x2E TLBI 2 TLBT 0x0B TLB Hit? N Page Fault? Y PPN: TBD

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

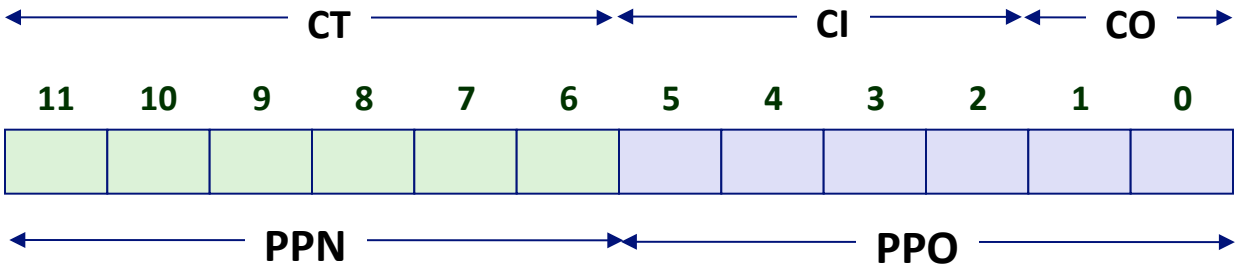
Address Translation Example #2

Virtual Address: 0x0B8F



VPN 0x2E TLBI 2 TLBT 0x0B TLB Hit? N Page Fault? Y PPN: TBD

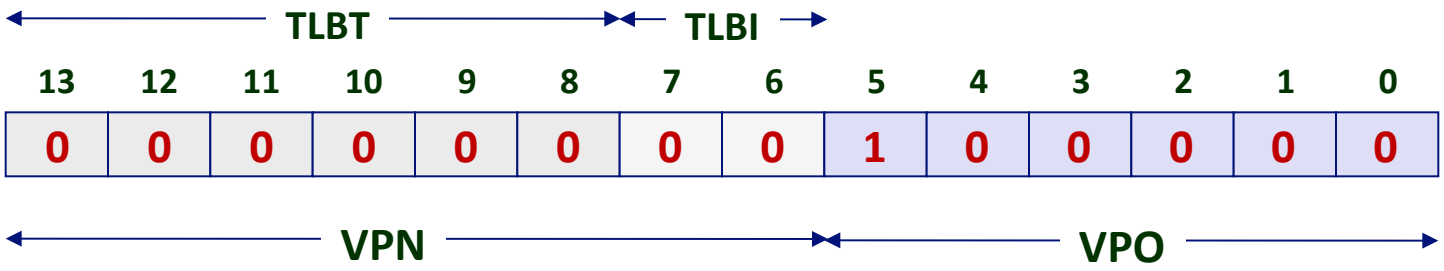
Physical Address



CO ___ CI___ CT ____ Hit? __ Byte: ____

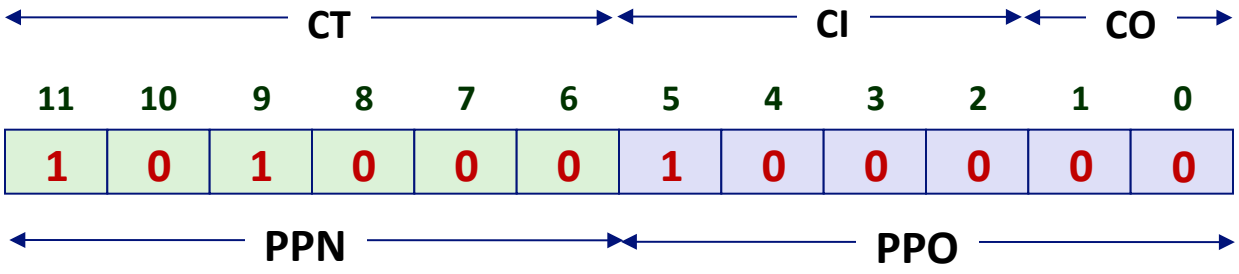
Address Translation Example #3

Virtual Address: 0x0020



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

Physical Address

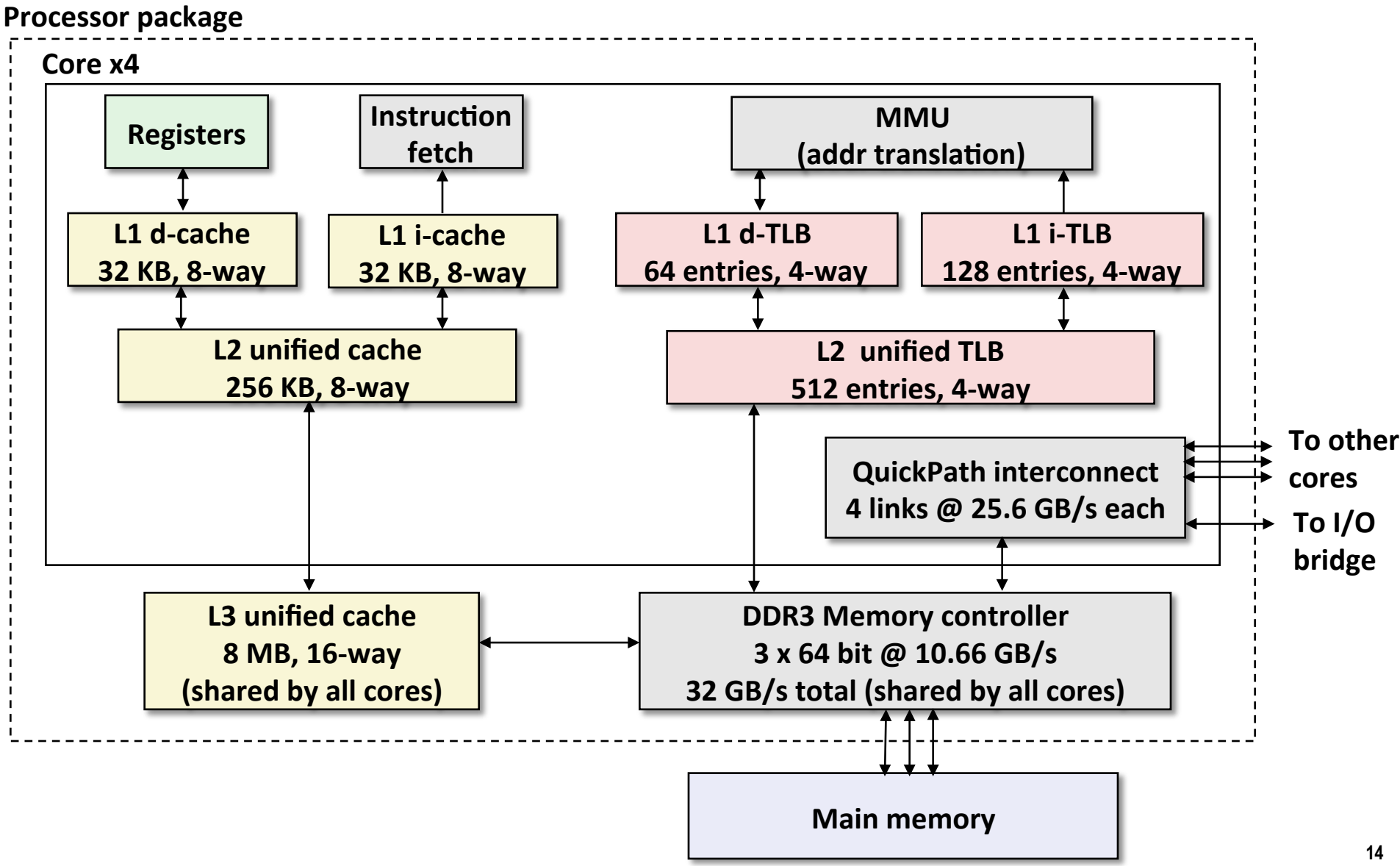


CO 0 CI 0x8 CT 0x28 Hit? N Byte: Mem

Today

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

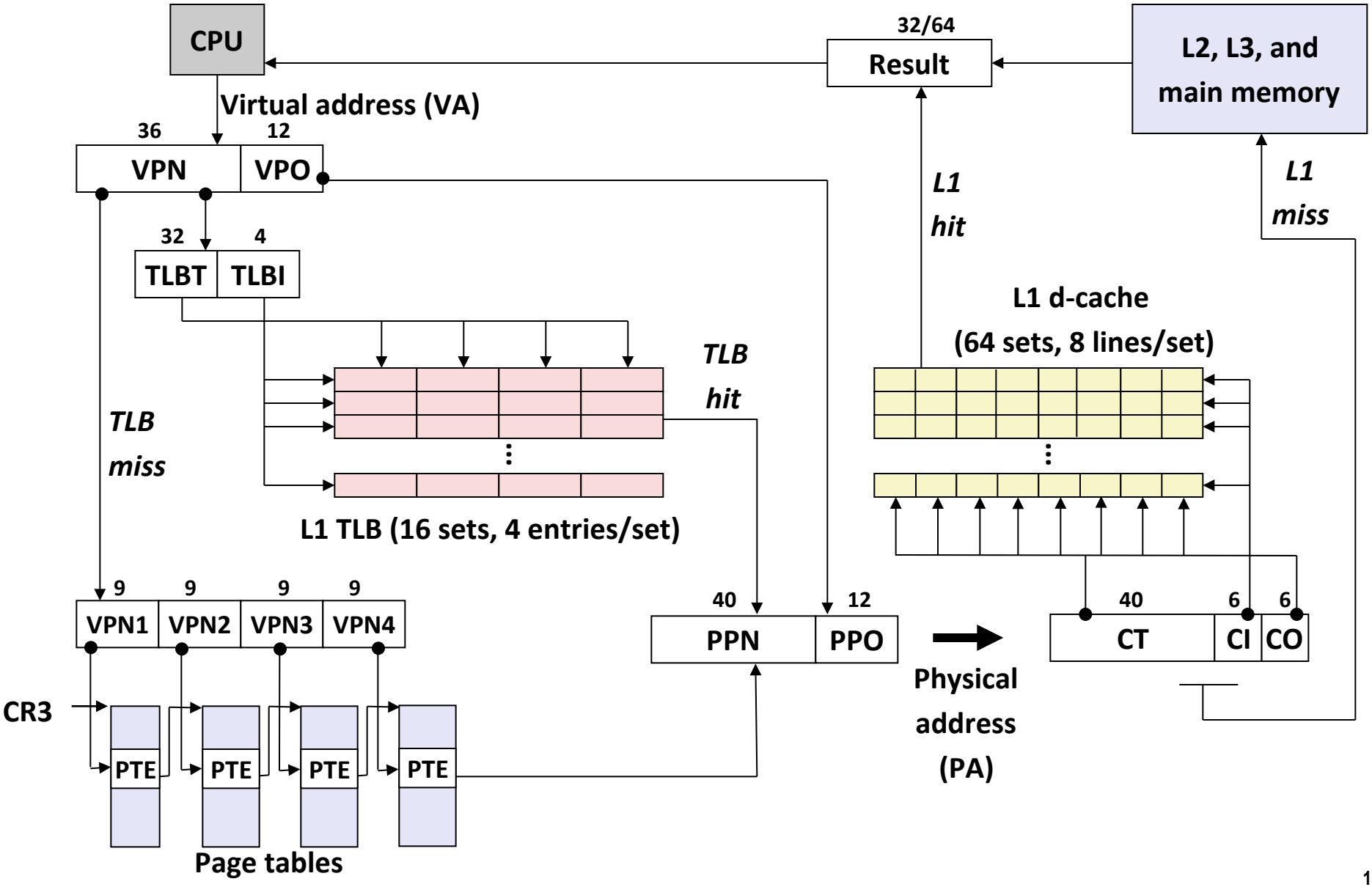
Intel Core i7 Memory System



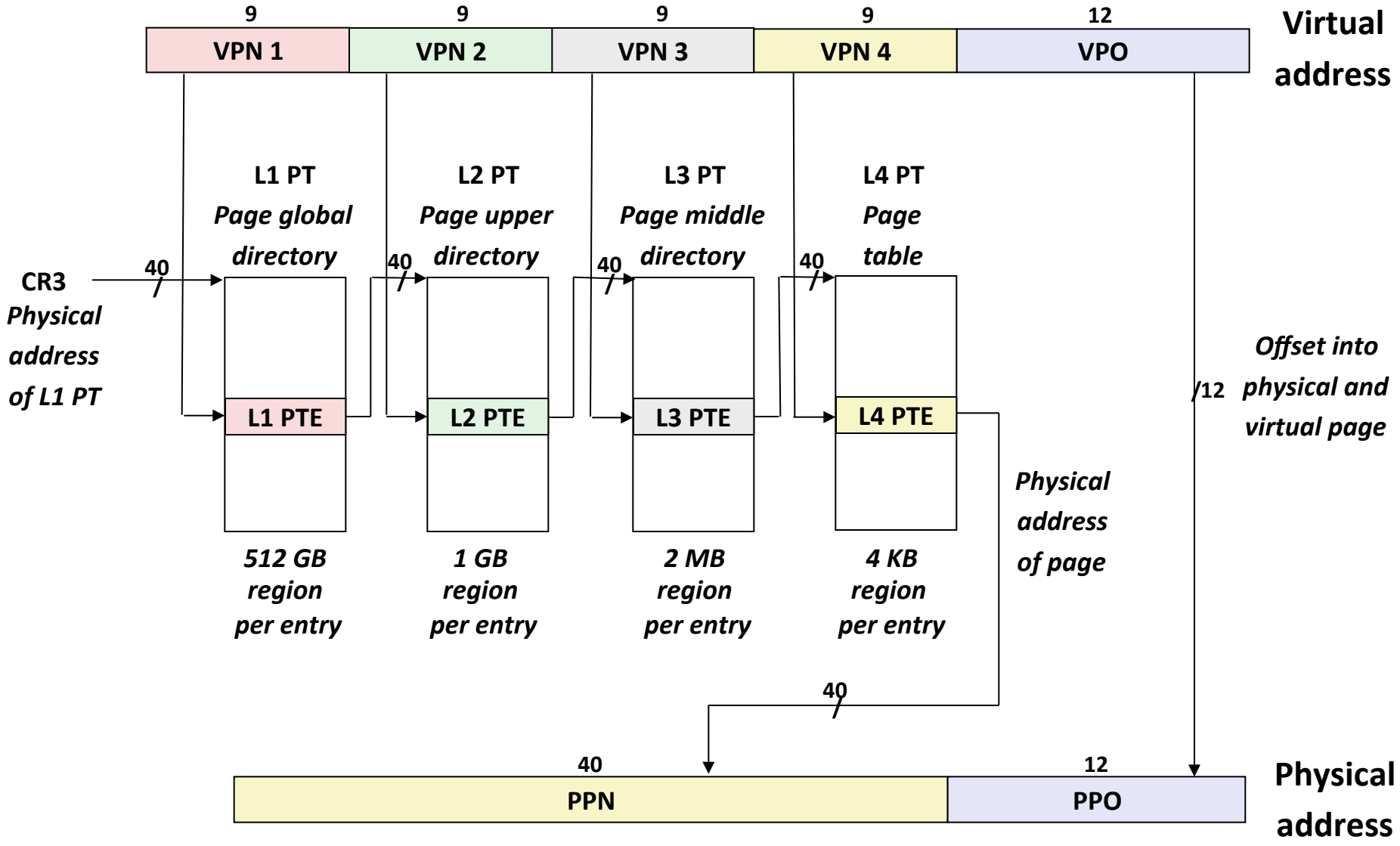
Review of Symbols

- **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

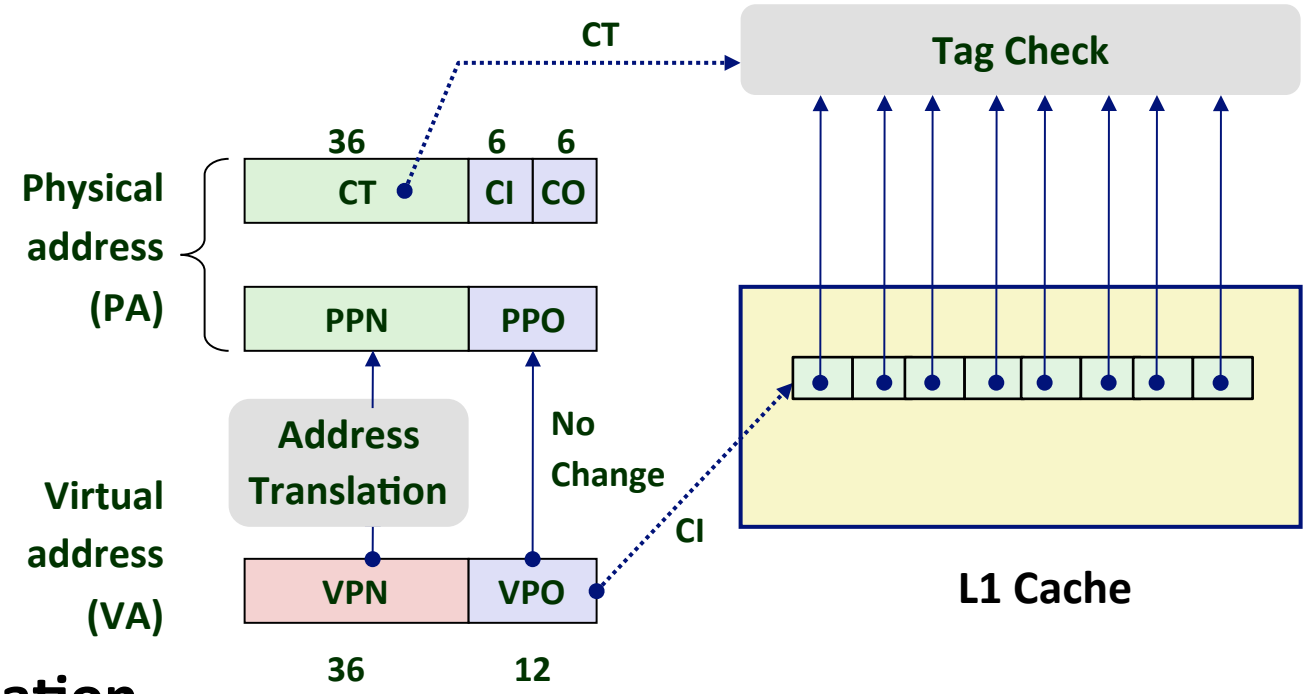
End-to-end Core i7 Address Translation



Core i7 Page Table Translation

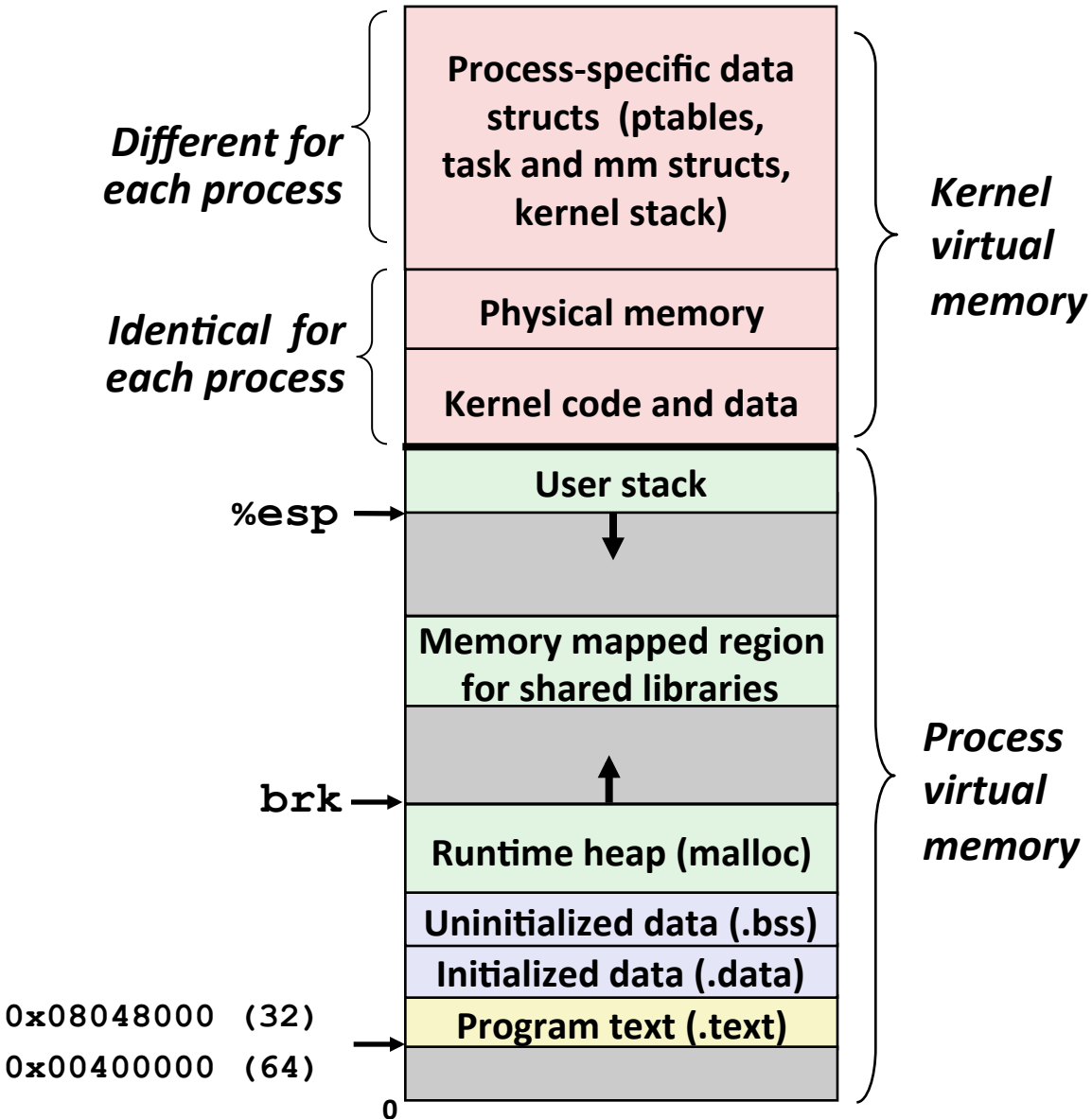


Cute Trick for Speeding Up L1 Access

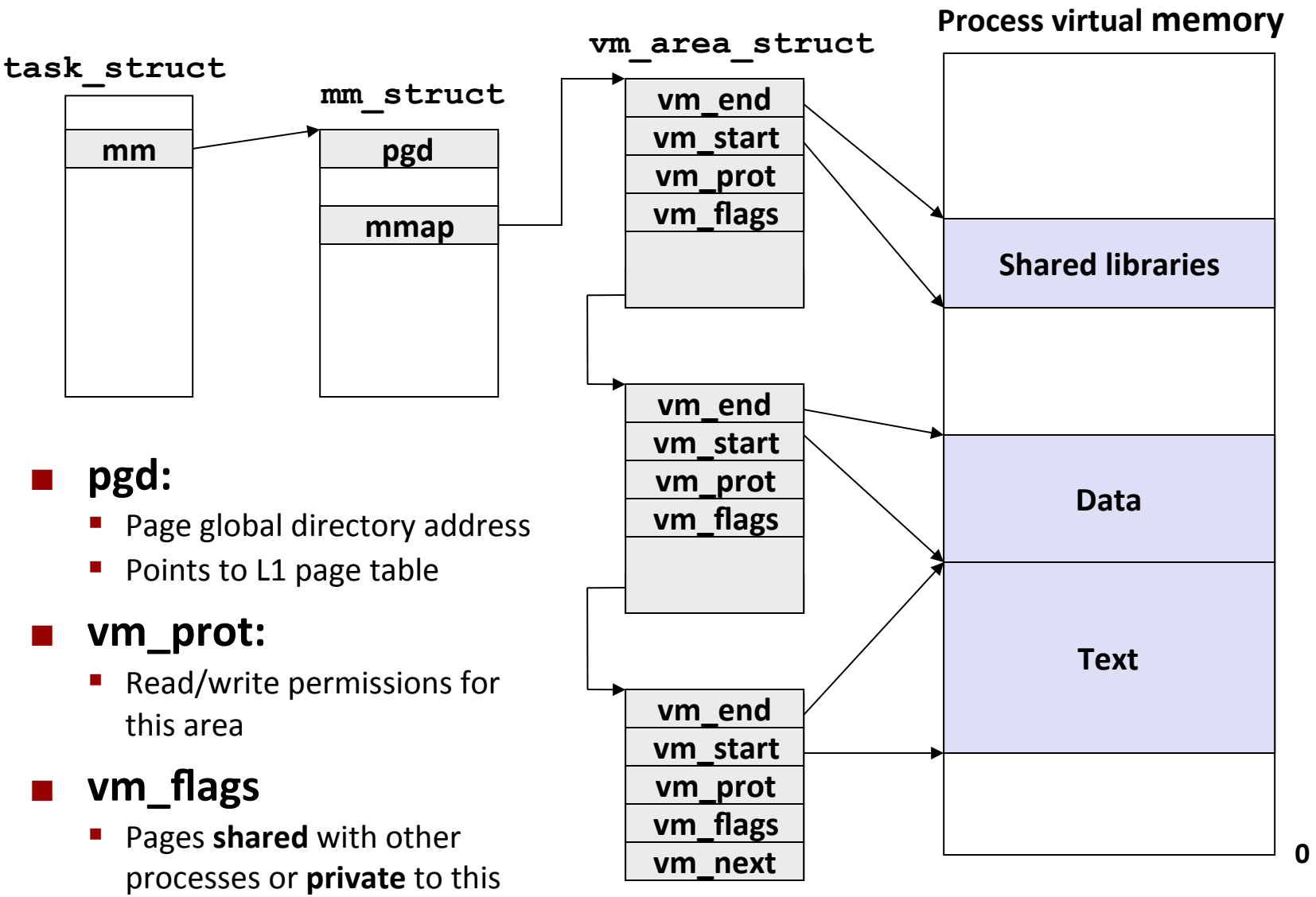


- **Observation**
  - Bits that determine CI identical in virtual and physical address
  - Can index into cache while address translation taking place
  - Generally we hit in TLB, so PPN bits (CT bits) available next
  - "Virtually indexed, physically tagged"
  - Cache carefully sized to make this possible

Virtual Memory of a Linux Process

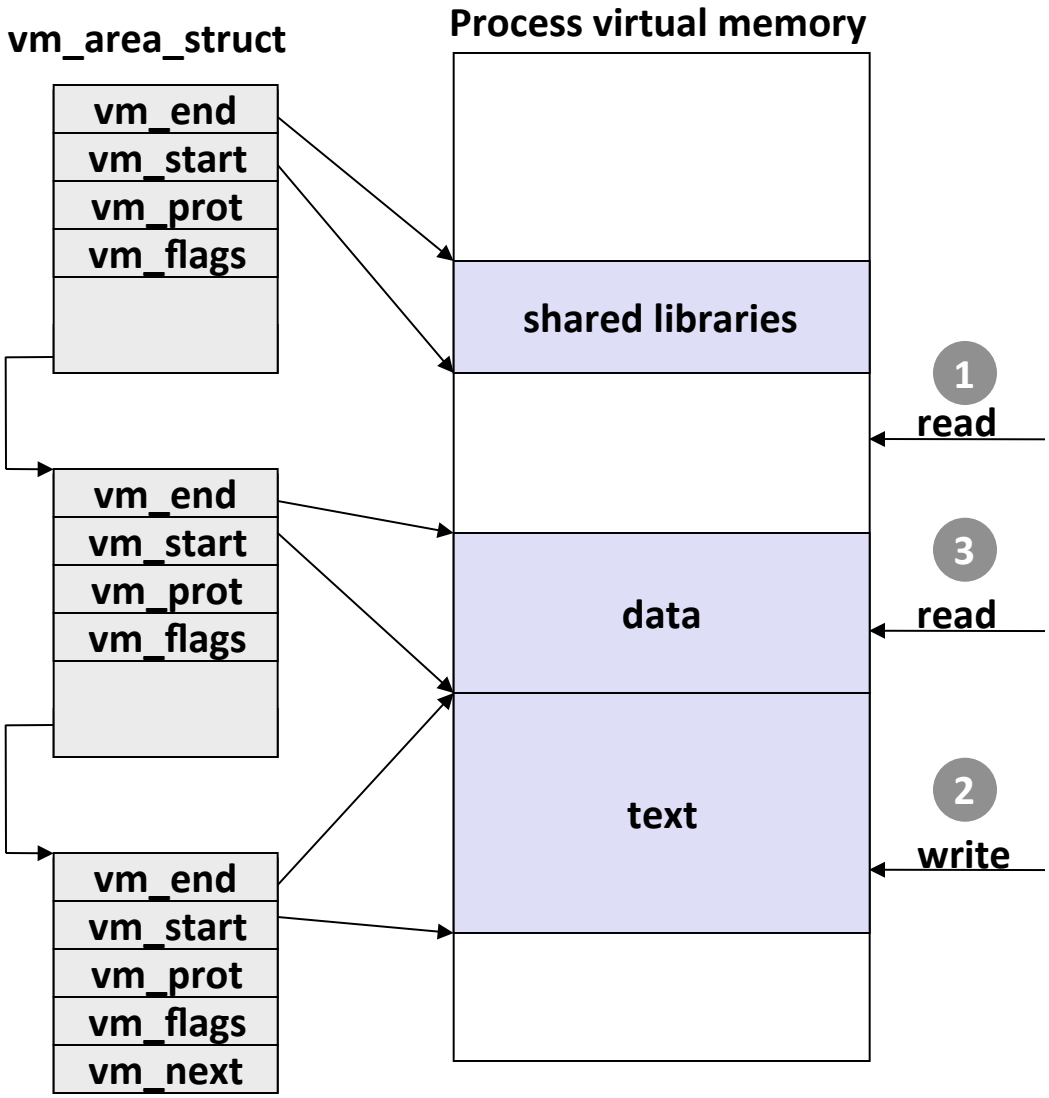


Linux Organizes VM as Collection of "Areas"



- **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

- Simple memory system example
- Case study: Core i7/Linux memory system
- **Memory mapping – *self-read summary***

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

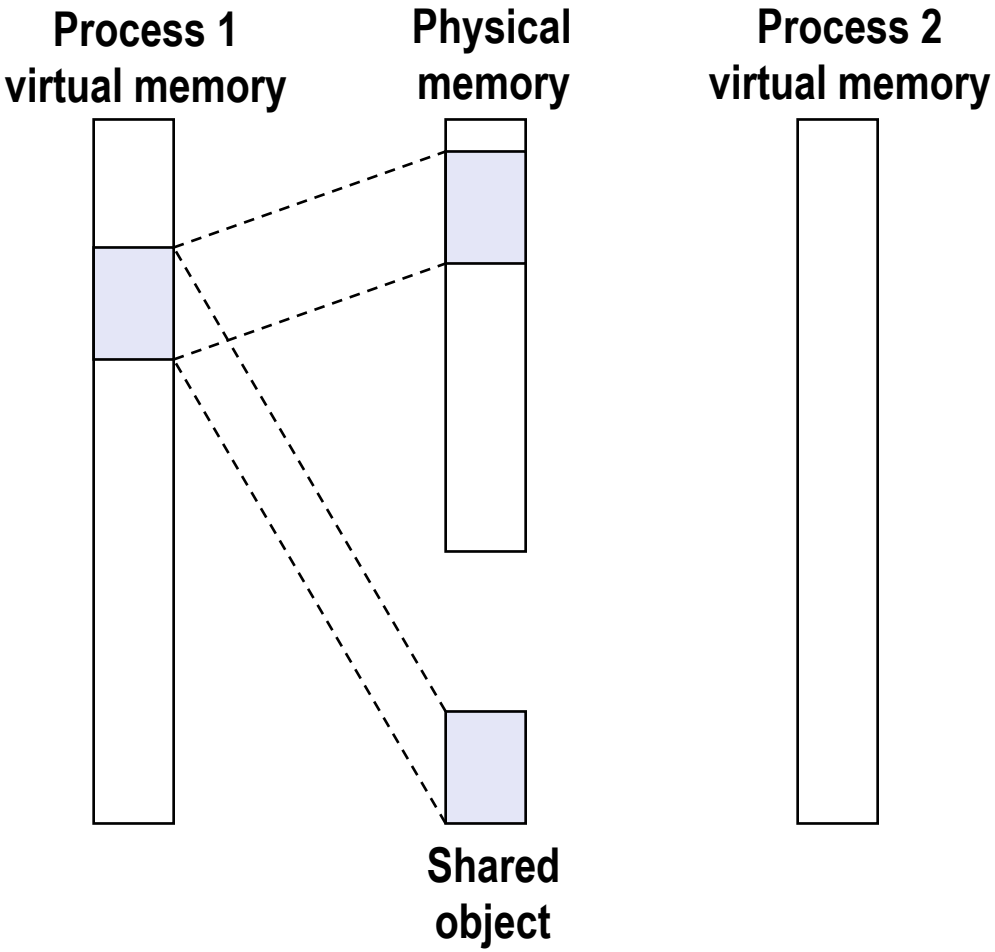
- **Dirty pages are copied back and forth between memory and a special *swap file*.**

Demand paging

- ***Key point:*** **no virtual pages are copied into physical memory until they are referenced!**
  - Known as ***demand paging***

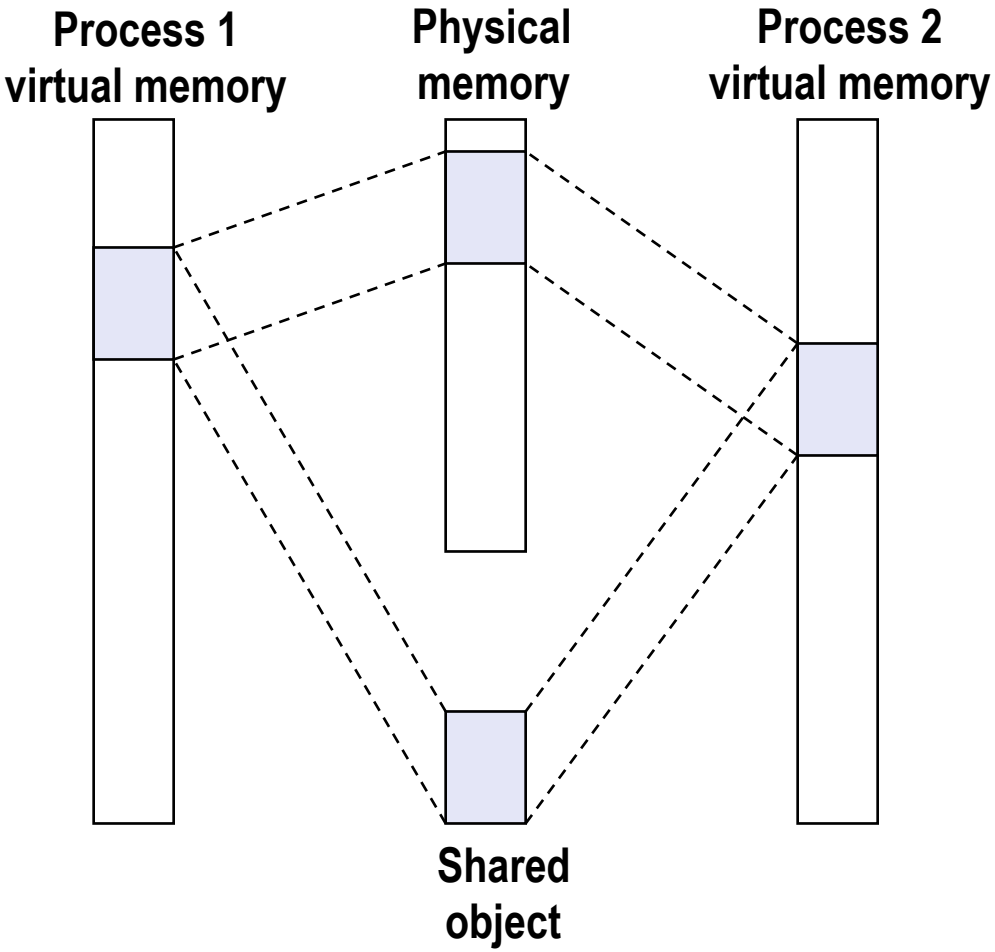
- **Crucial for time and space efficiency**

Sharing Revisited: Shared Objects



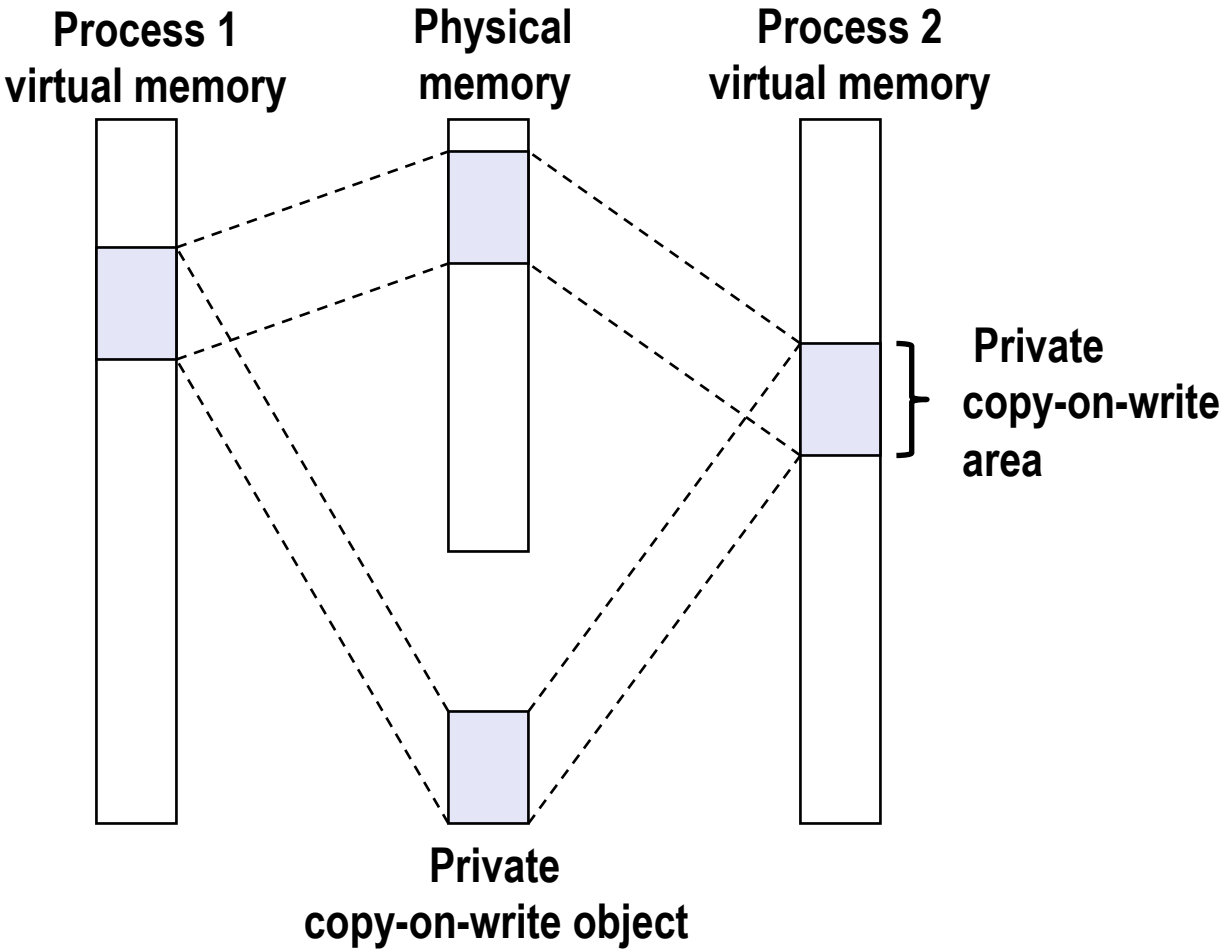
- Process 1 maps the shared object.

Sharing Revisited: Shared Objects



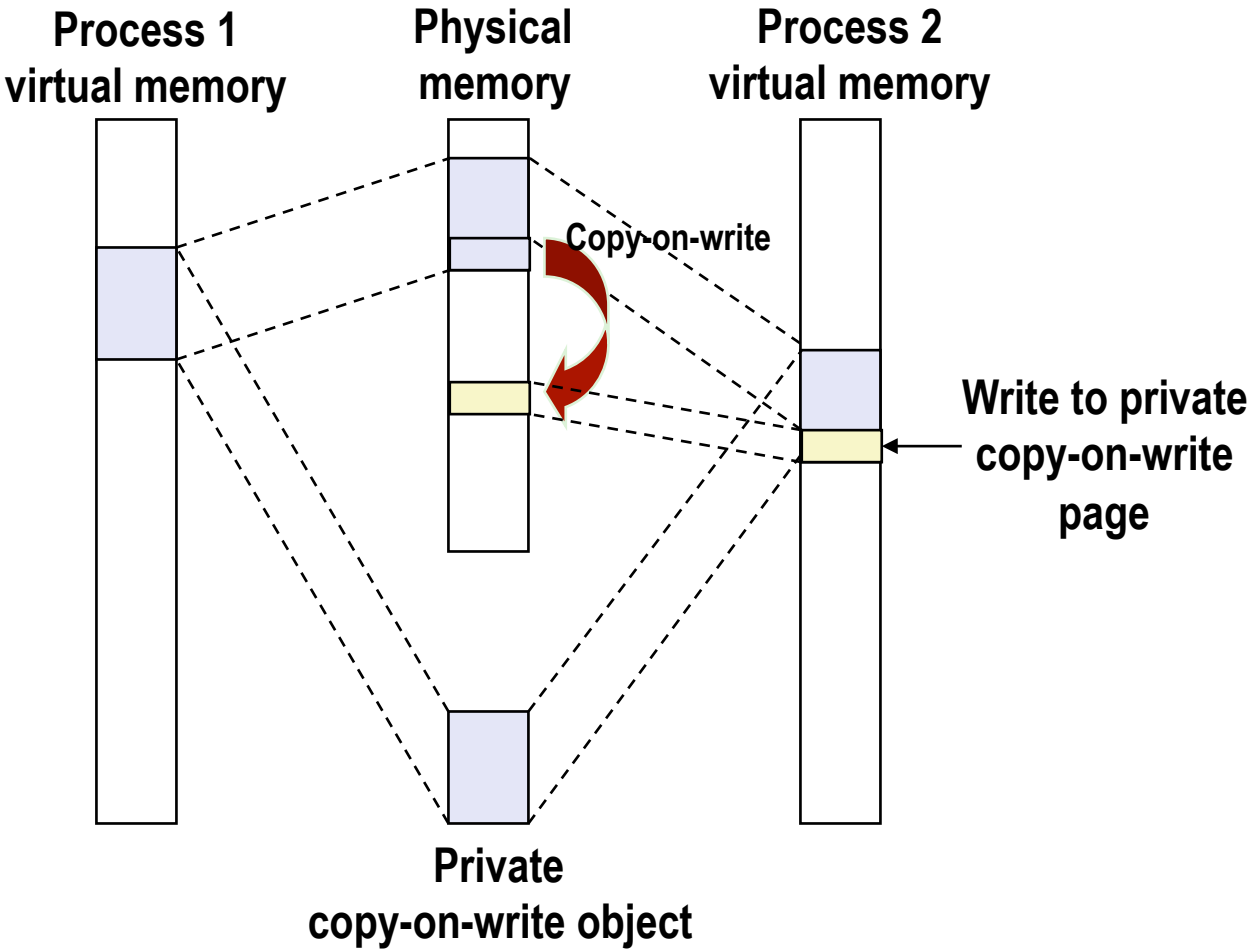
- Process 2 maps the shared object.
- Notice how the virtual addresses can be different.

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.**