CSC 252: Computer Organization
Spring 2023: Lecture 22

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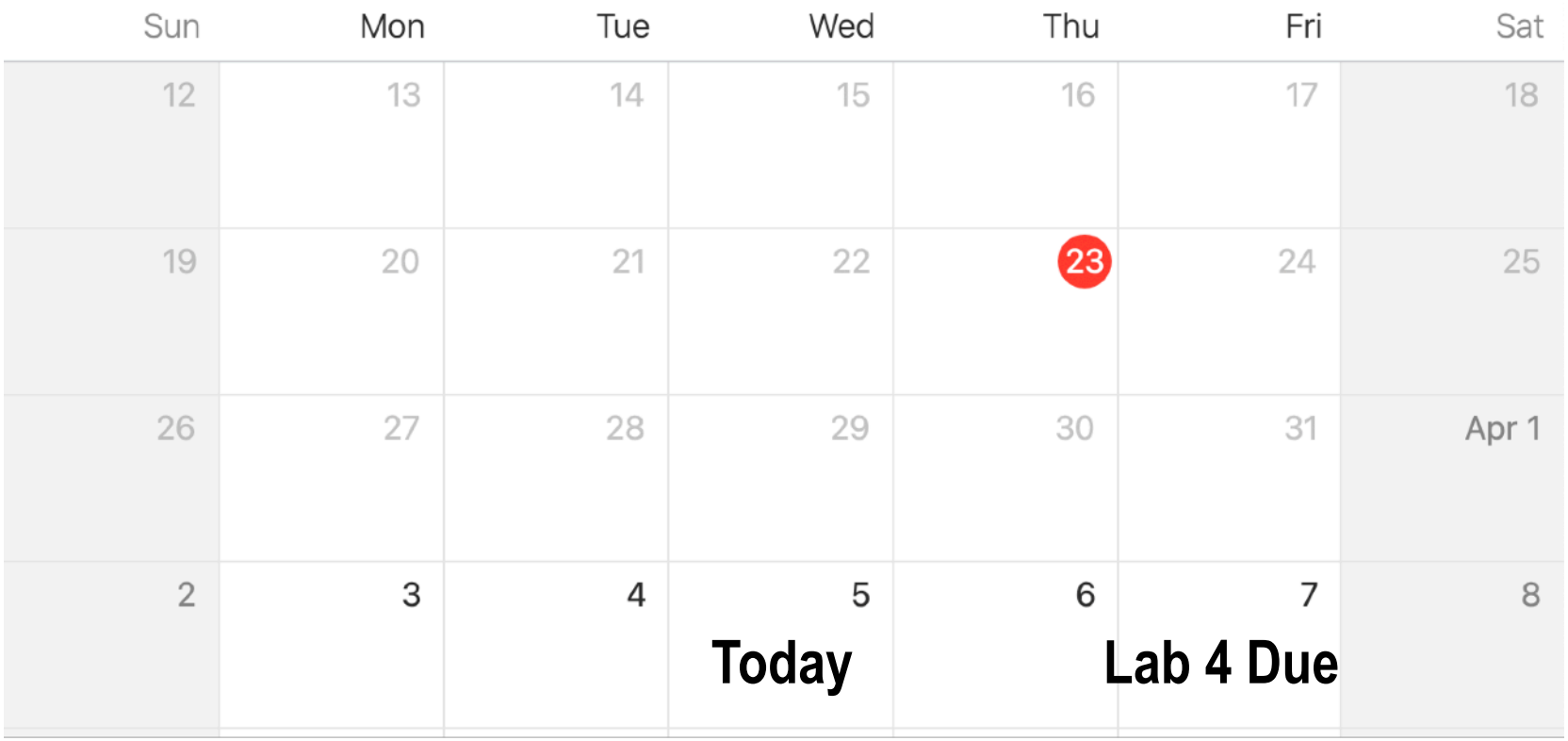
Department of Computer Science
University of Rochester

Announcements

- Cache problem set: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html Won't be graded.
- Mid-term solution posted: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html



Today

- Three Virtual Memory Optimizations
  - TLB
  - Virtually-indexed, physically-tagged cache
  - Page the page table (a.k.a., multi-level page table)
- Case-study: Intel Core i7/Linux example

Speeding up Address Translation

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- Problem: Every memory load/store requires two memory accesses: one for PTE, another for real
  - The PTE access is kind of an overhead
  - Can we speed it up?

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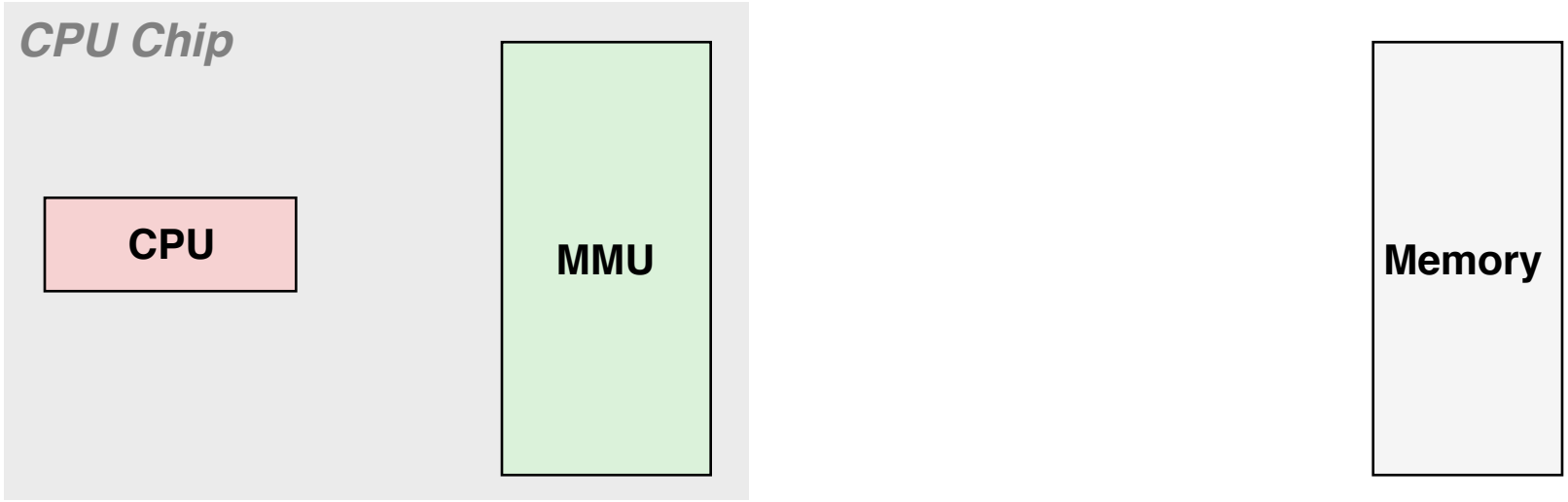
- Problem: Every memory load/store requires two memory accesses: one for PTE, another for real
  - The PTE access is kind of an overhead
  - Can we speed it up?
- Page table entries (PTEs) are already cached in L1 data cache like any other memory data. But:
  - PTEs may be evicted by other data references
  - PTE hit still requires a small L1 delay

Recall: Page Table is Cached



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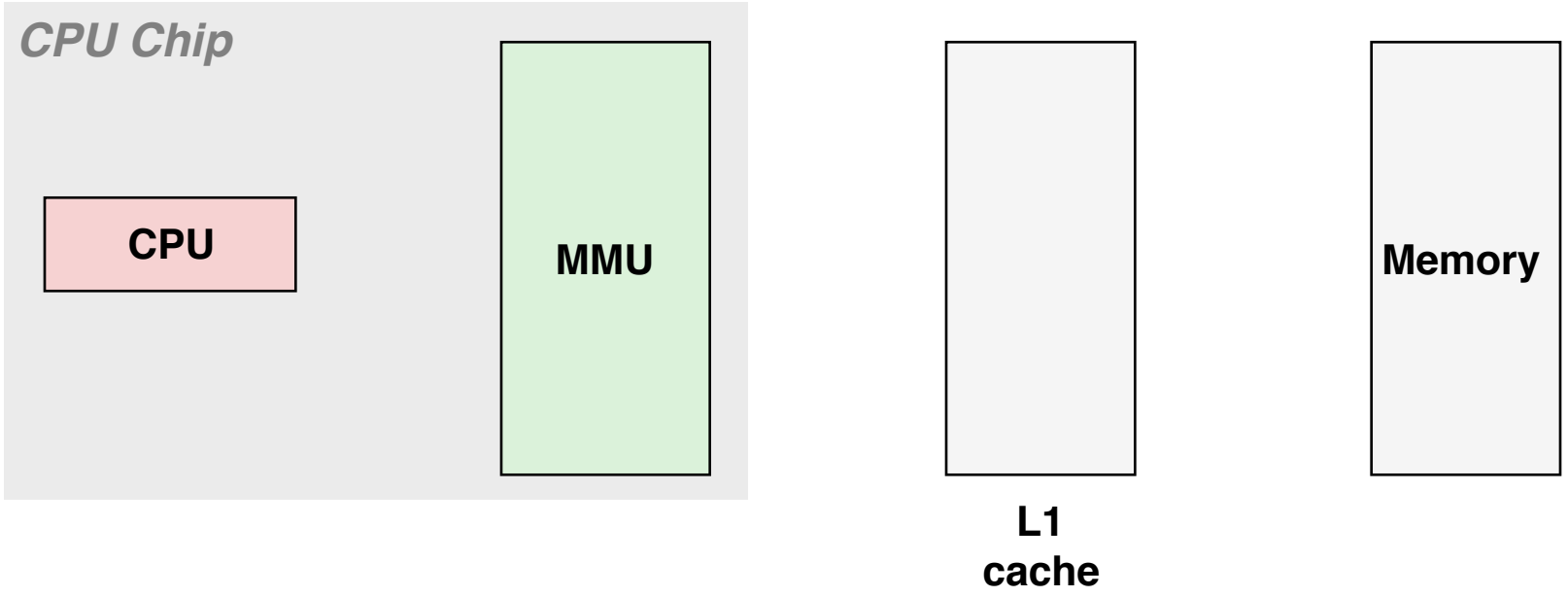

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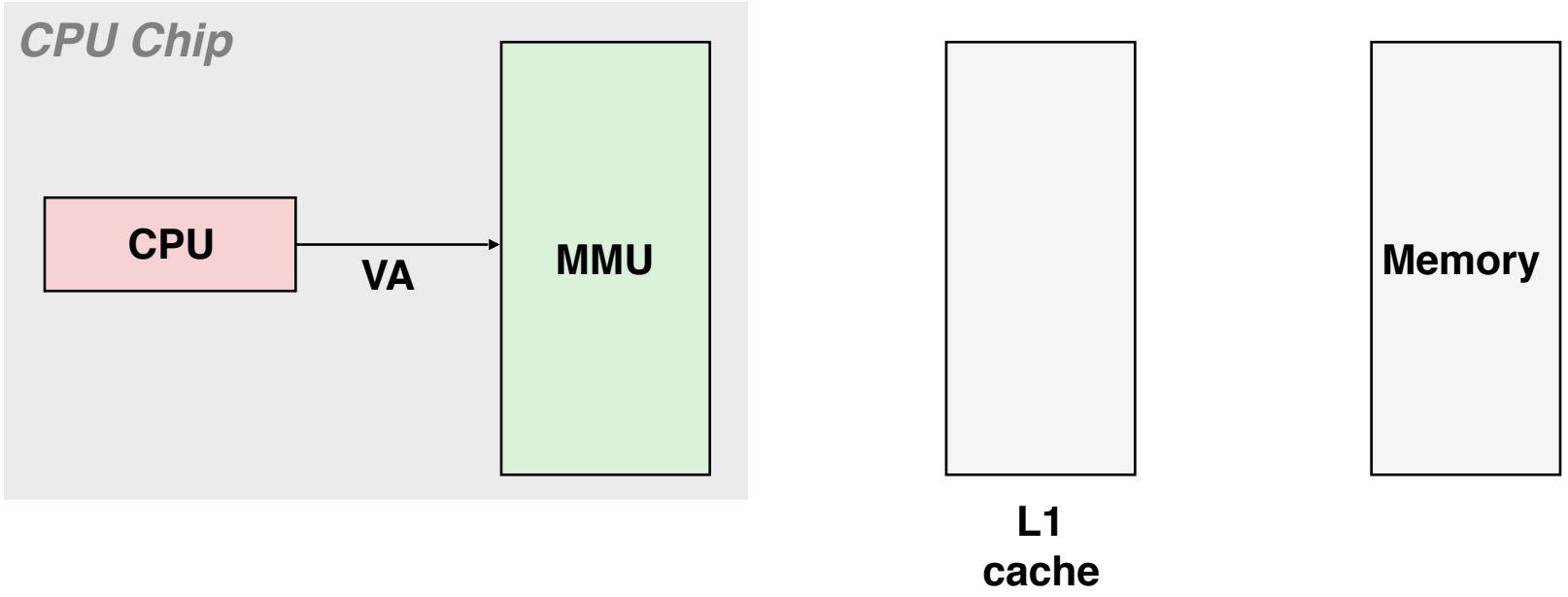

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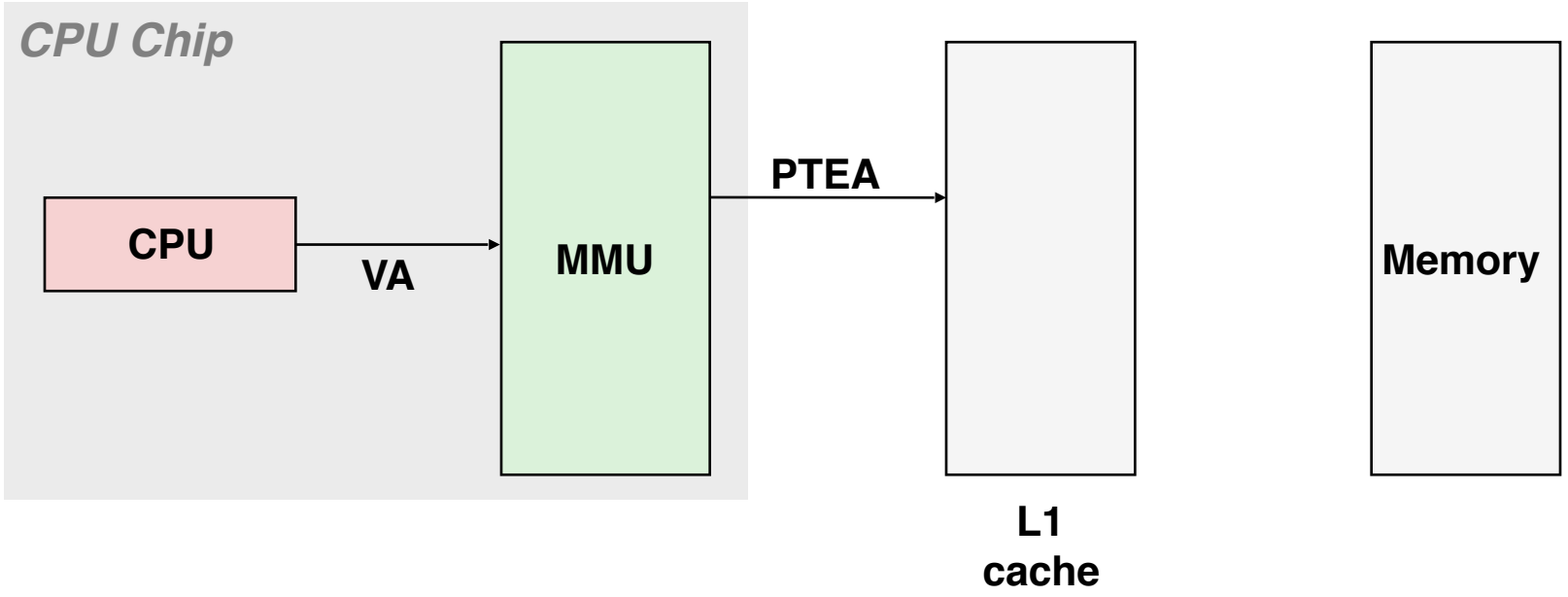

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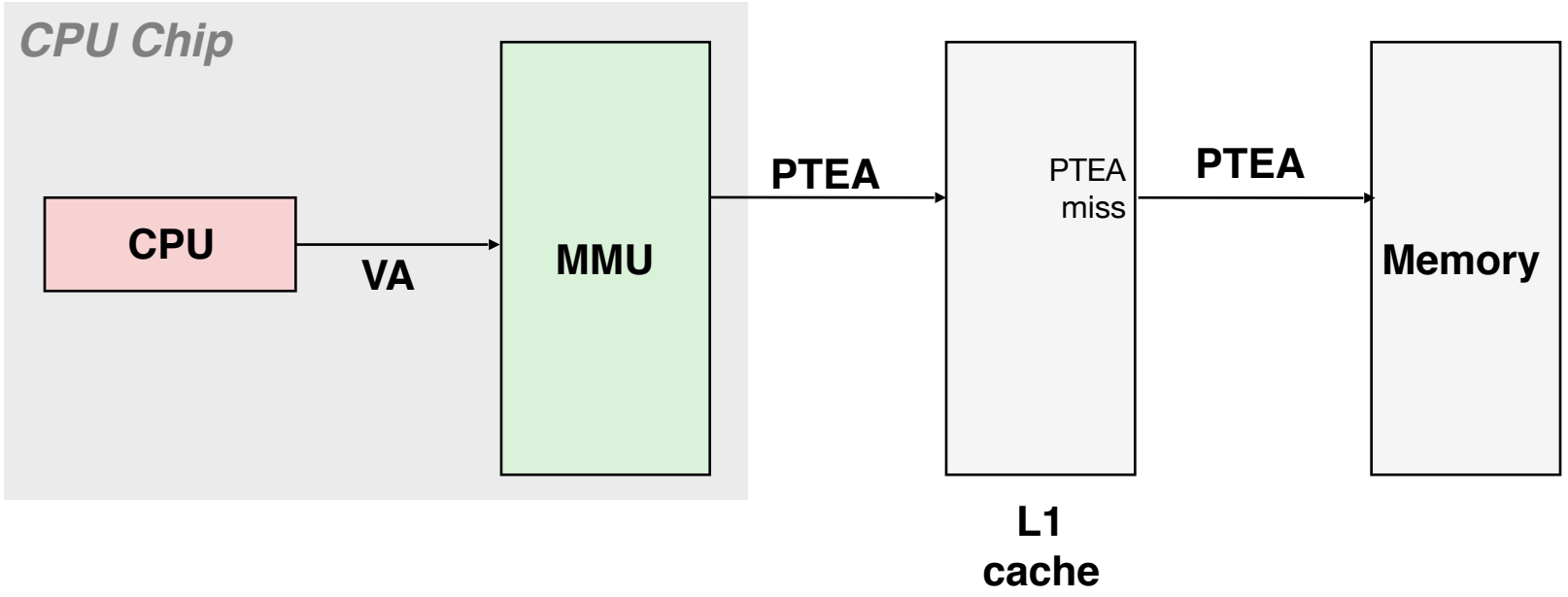

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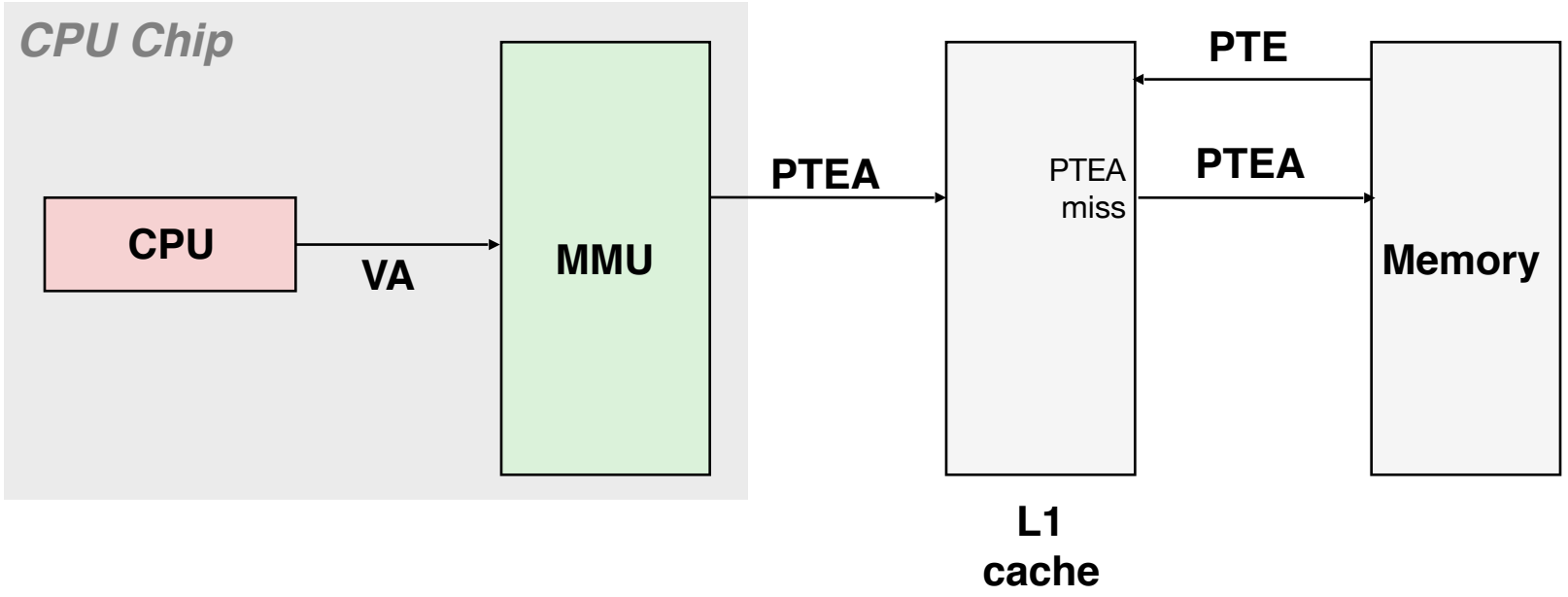

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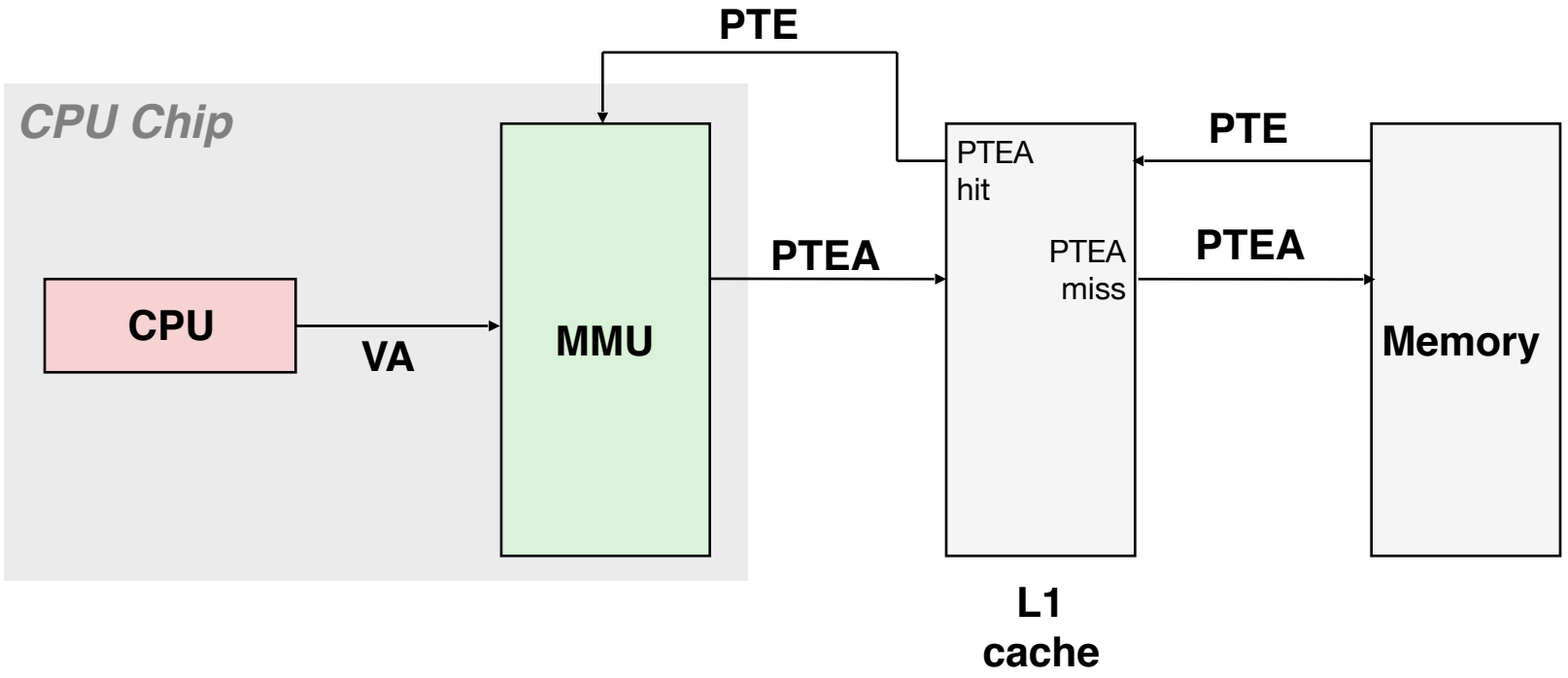

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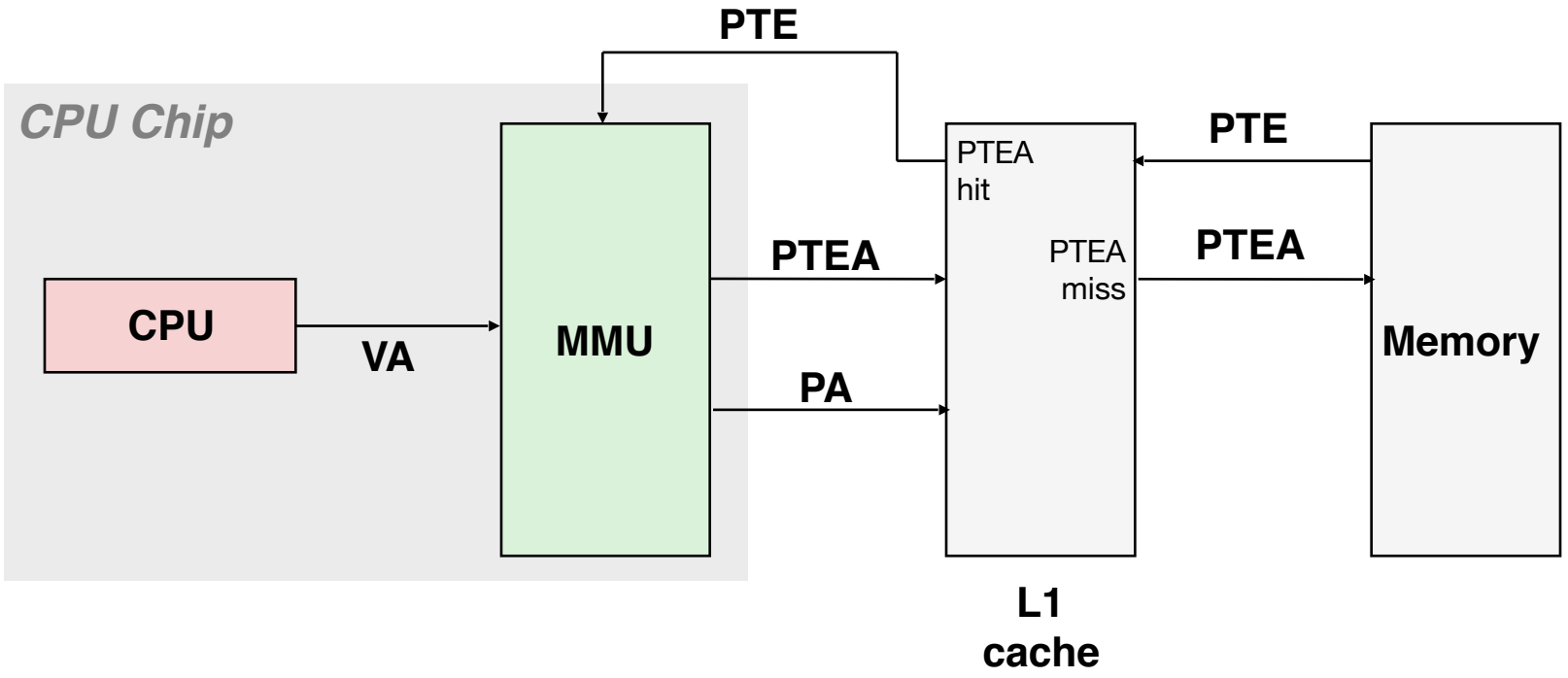

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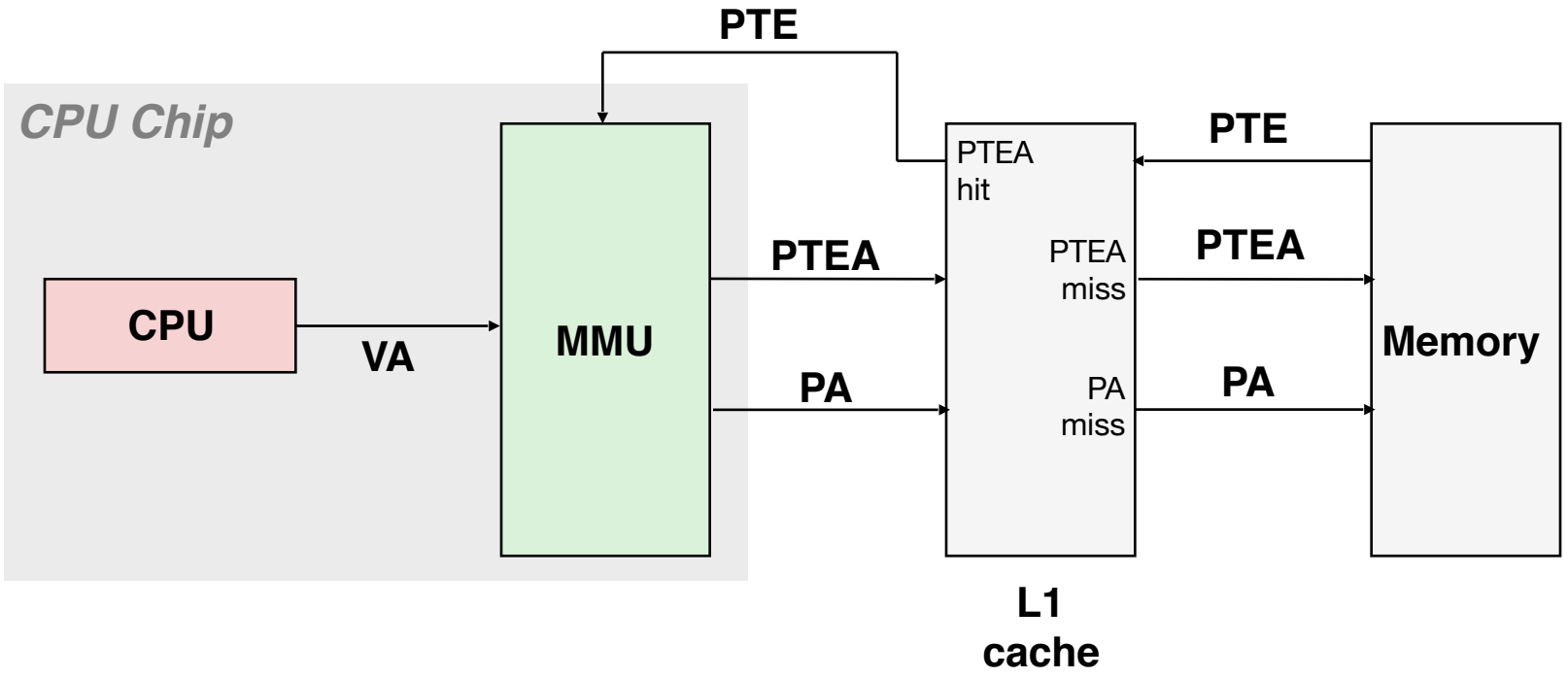

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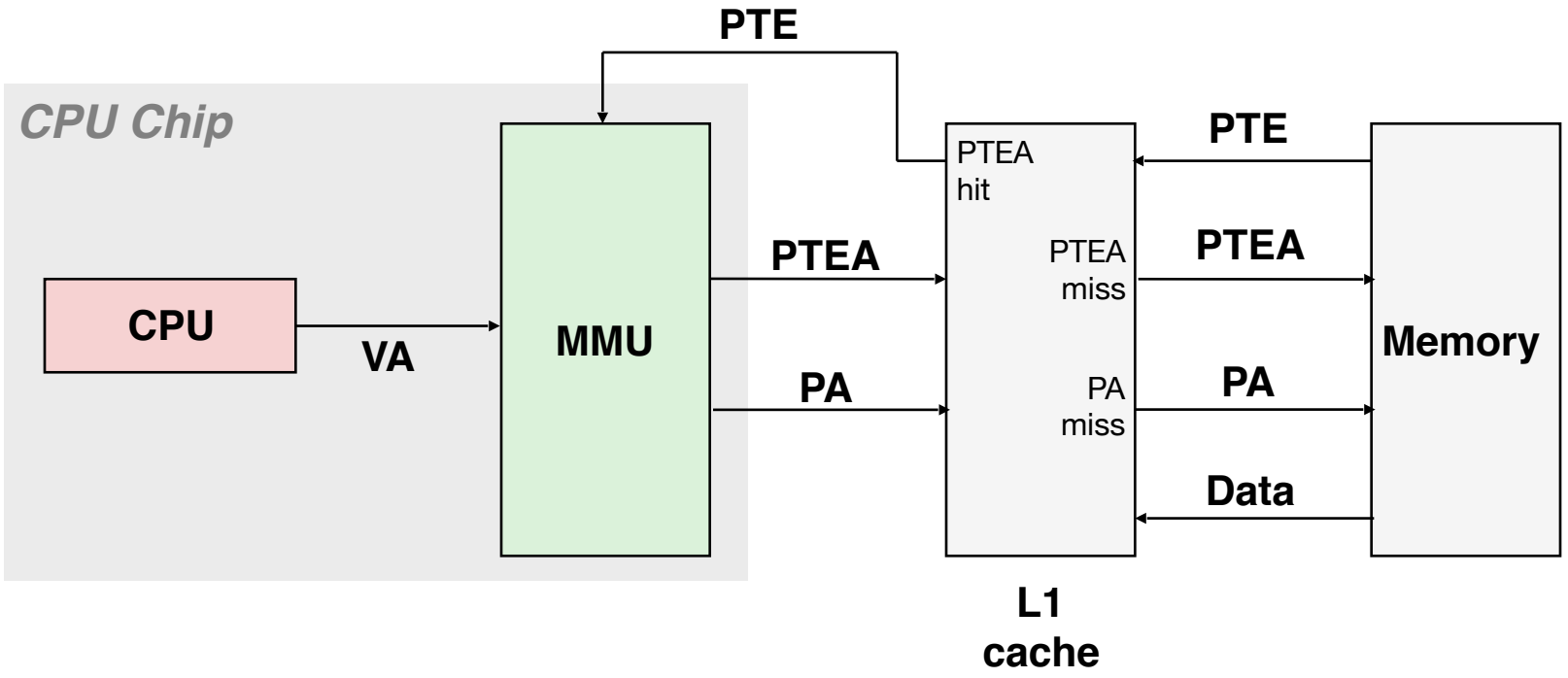

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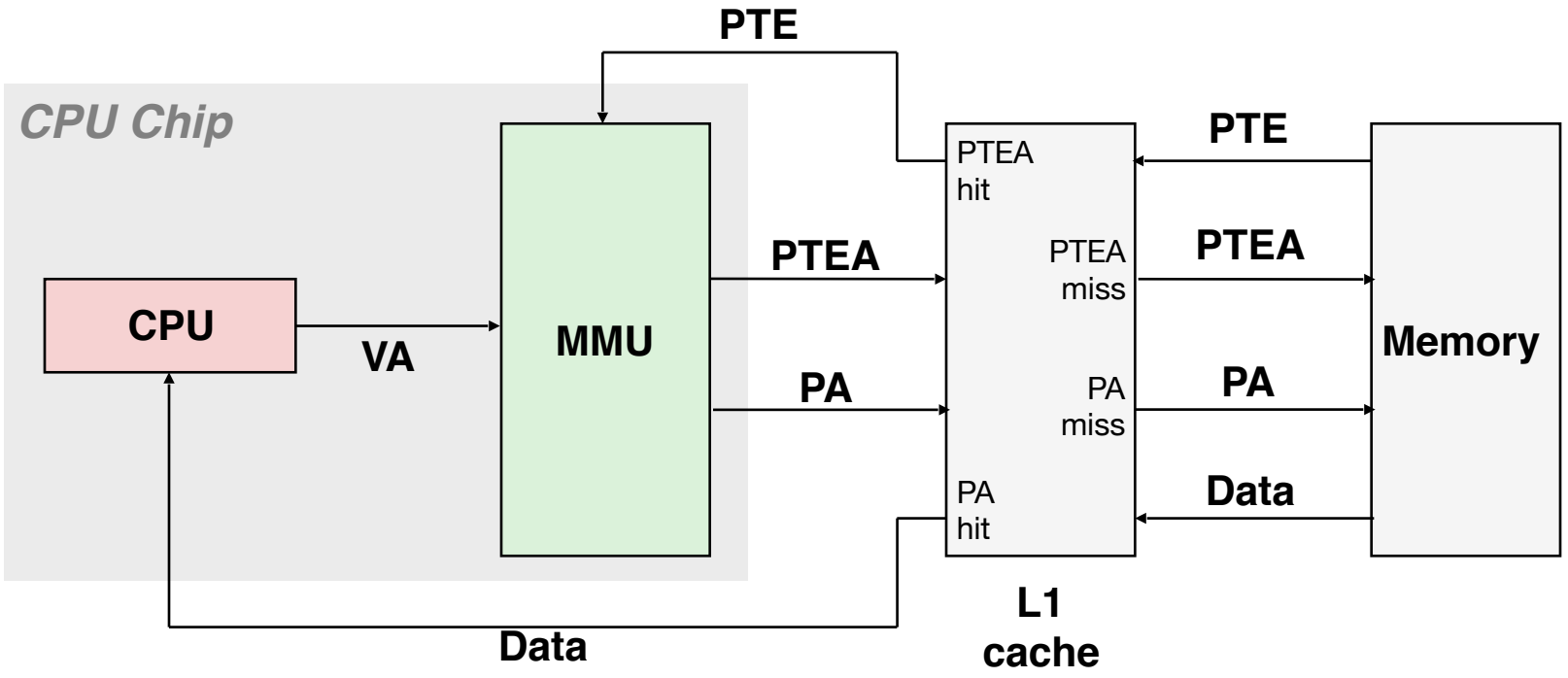

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Speeding up Translation with a TLB

- Solution: *Translation Lookaside Buffer* (TLB)
  - Think of it as a dedicated cache for page table
  - Small set-associative hardware cache in MMU
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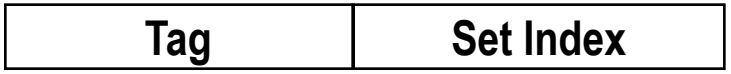

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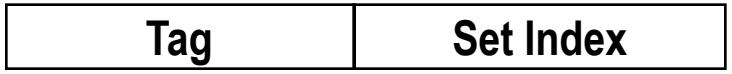

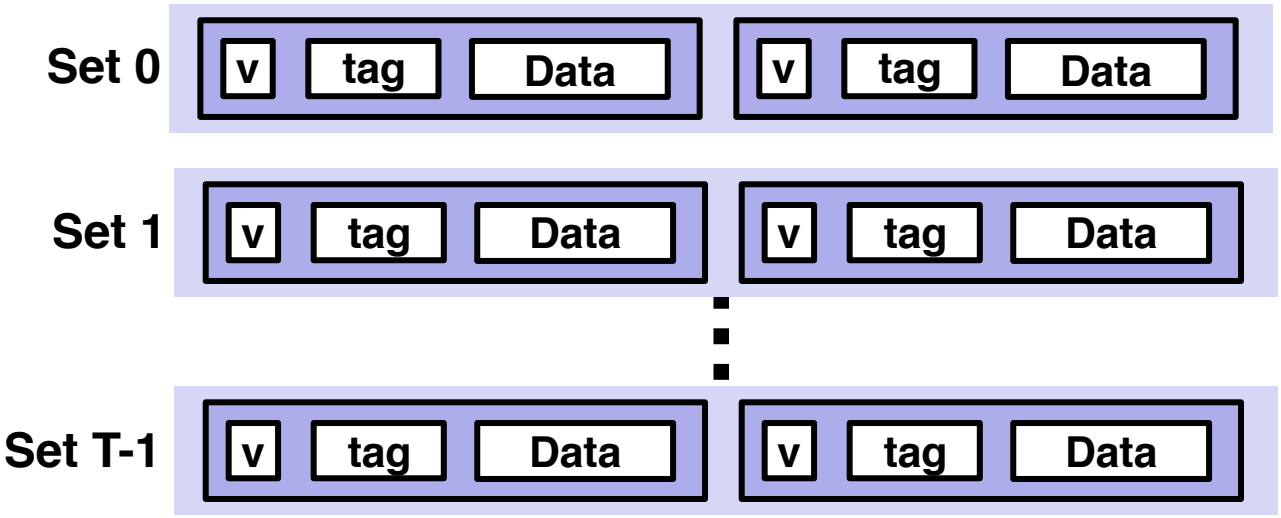

A Conventional Data Cache

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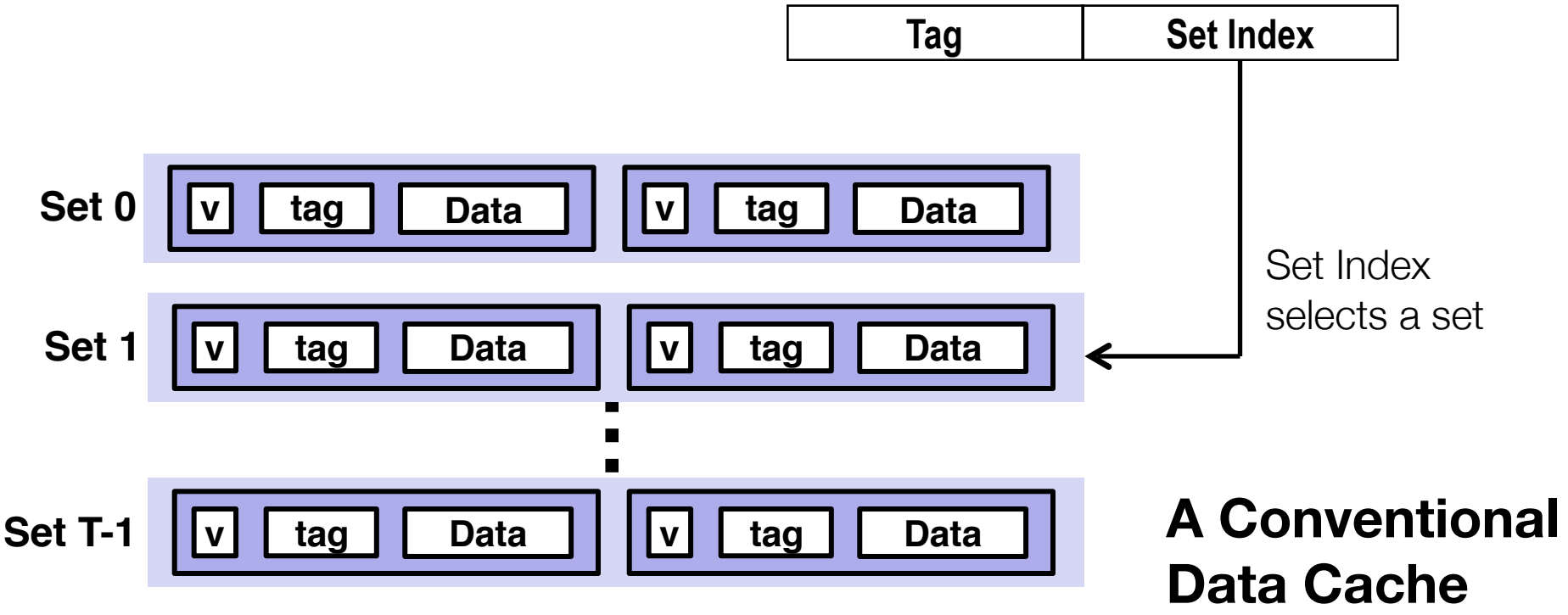

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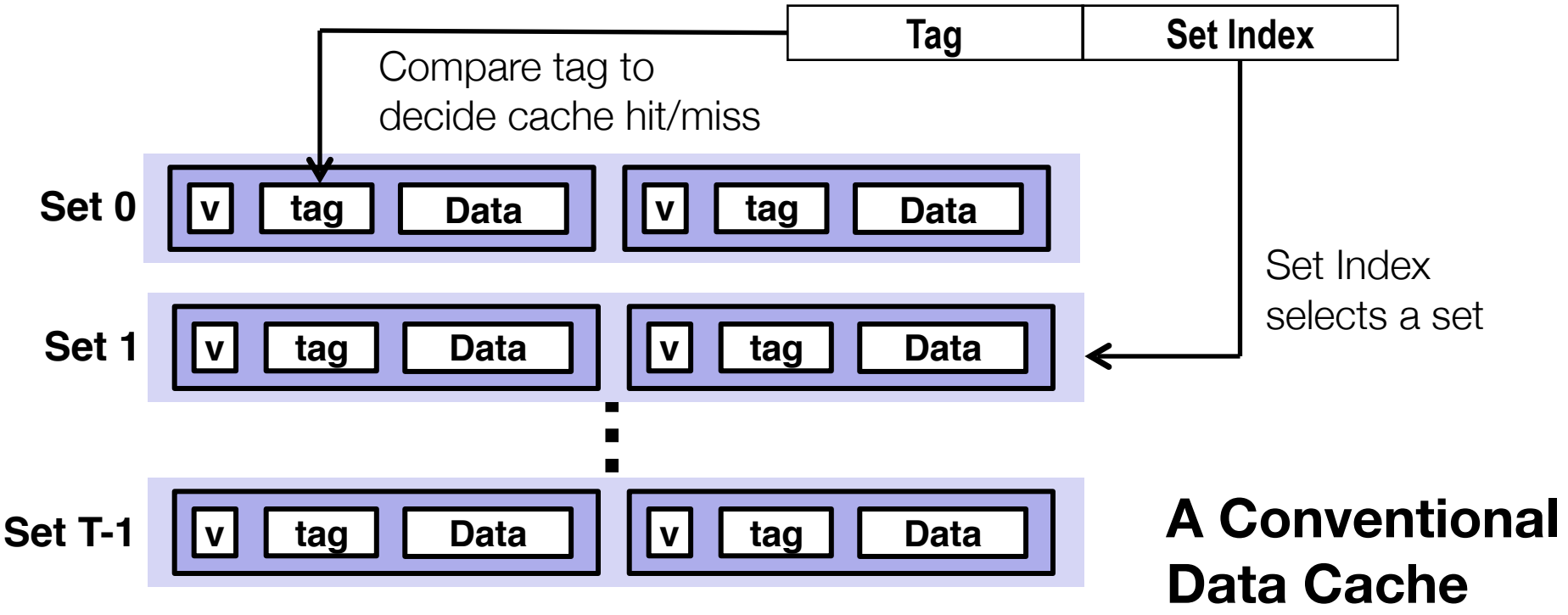
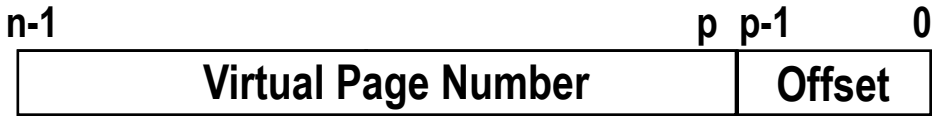
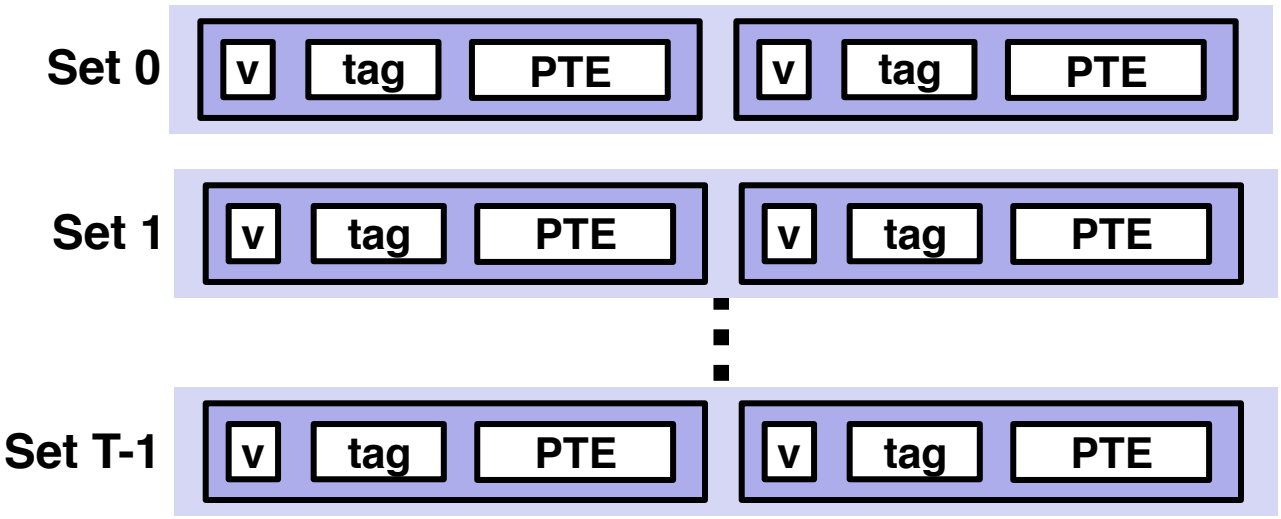


Accessing the TLB

- MMU uses the Virtual Page Number portion of the virtual address to access the TLB:





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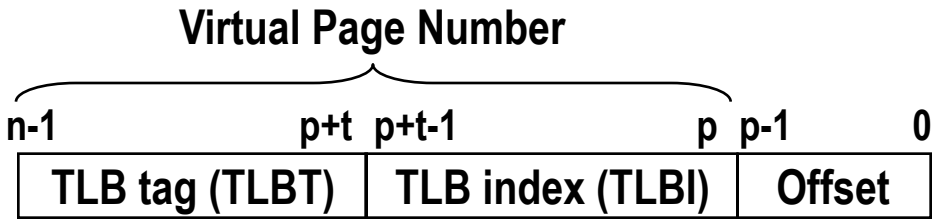

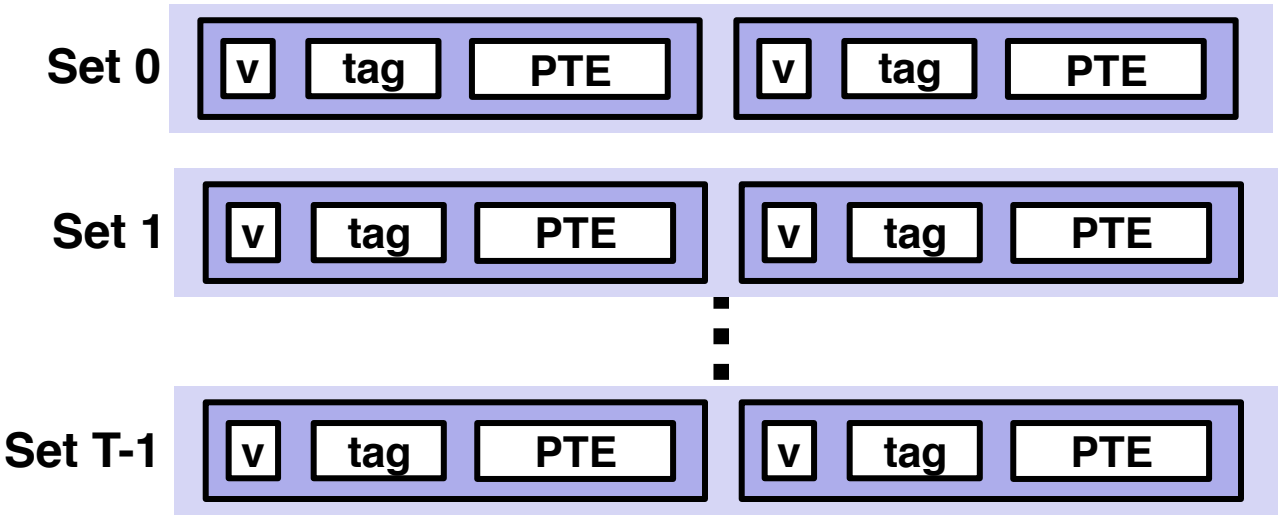

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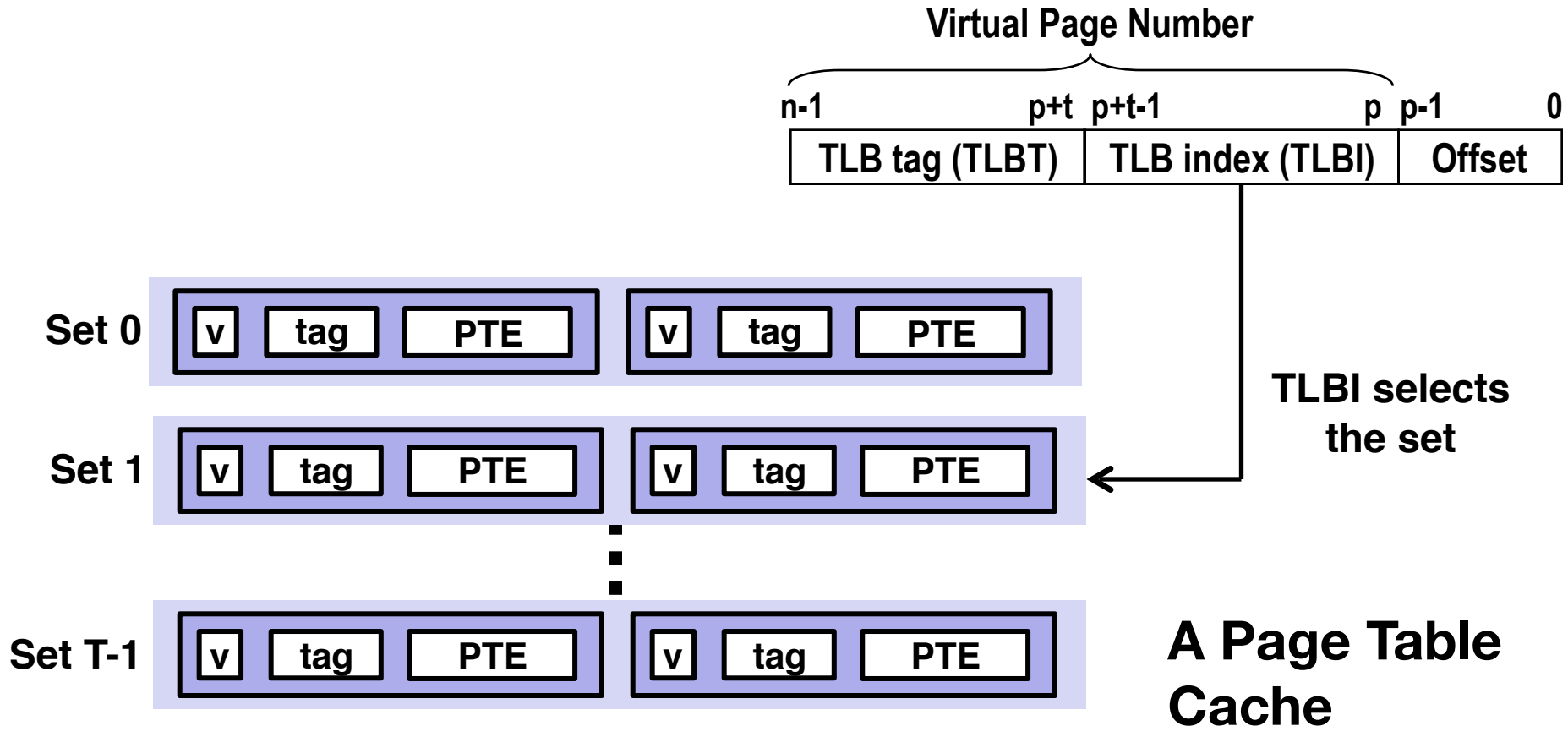

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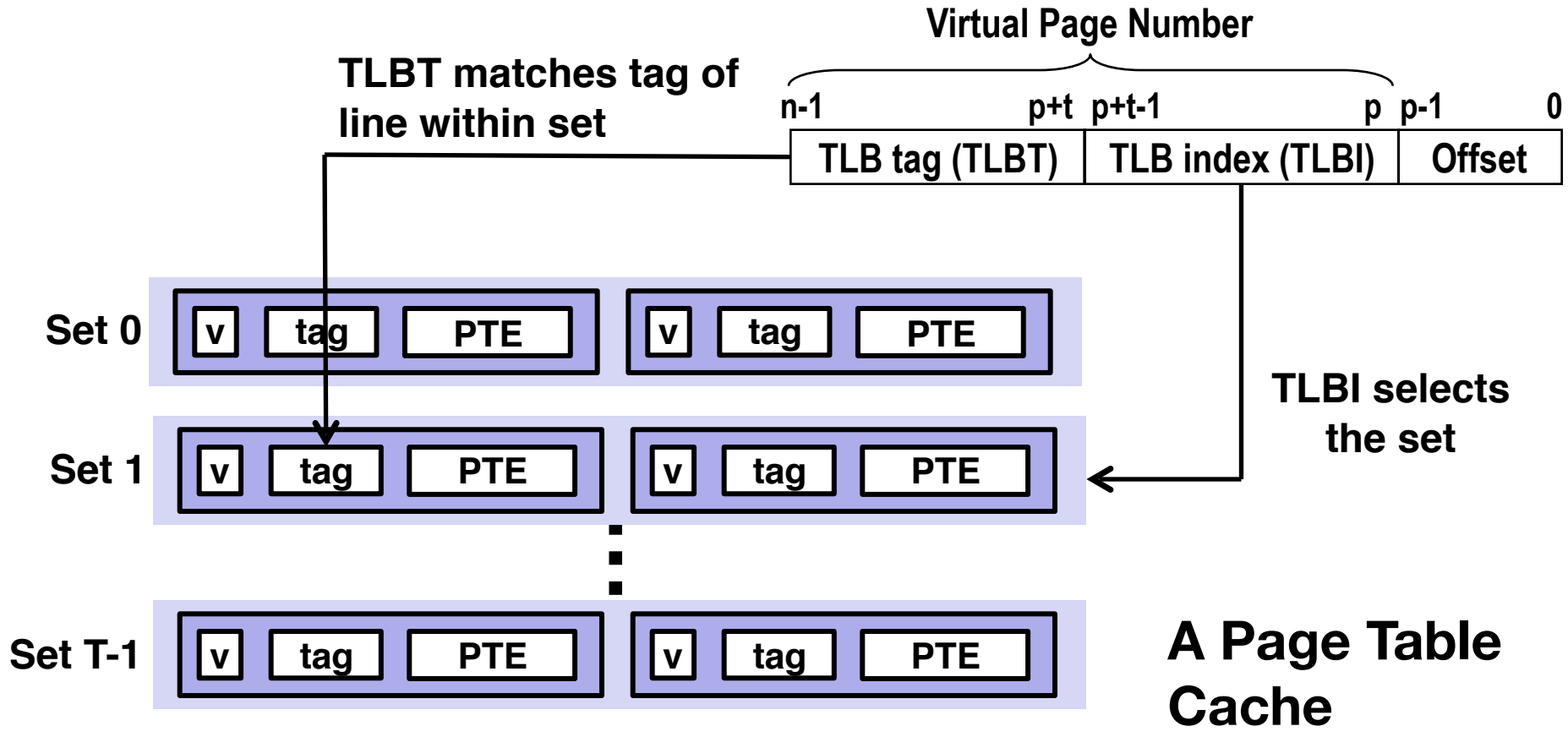
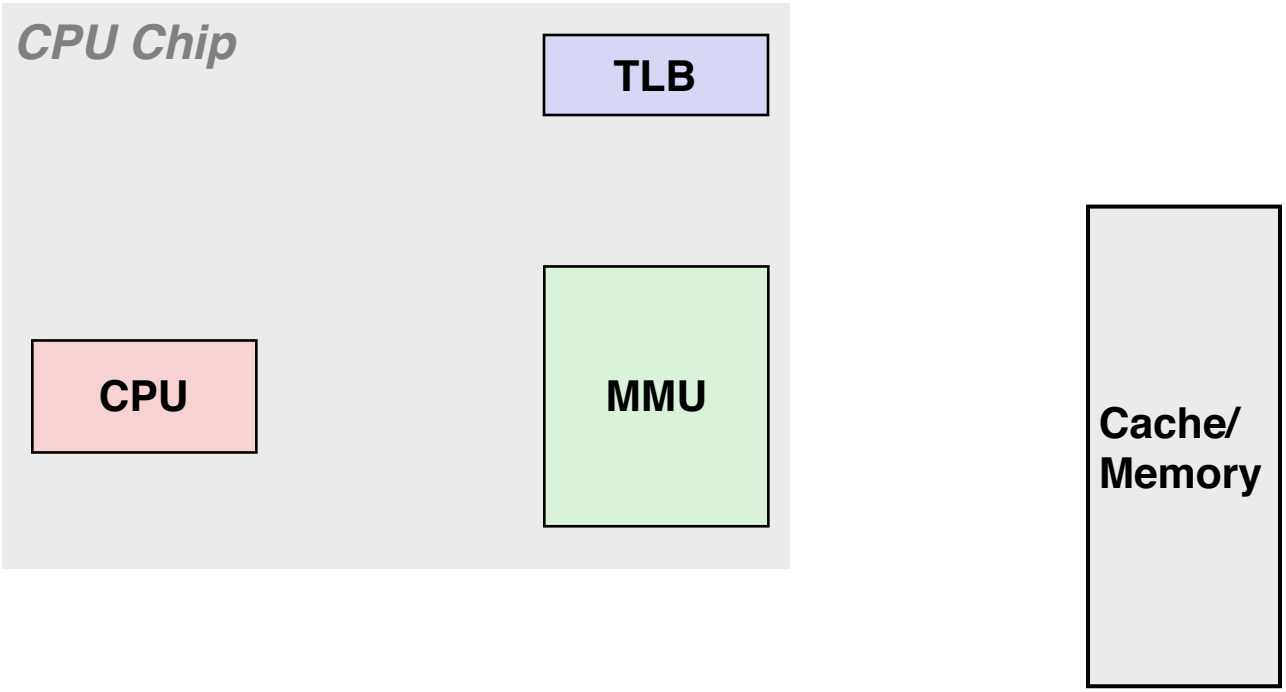


TLB Hit



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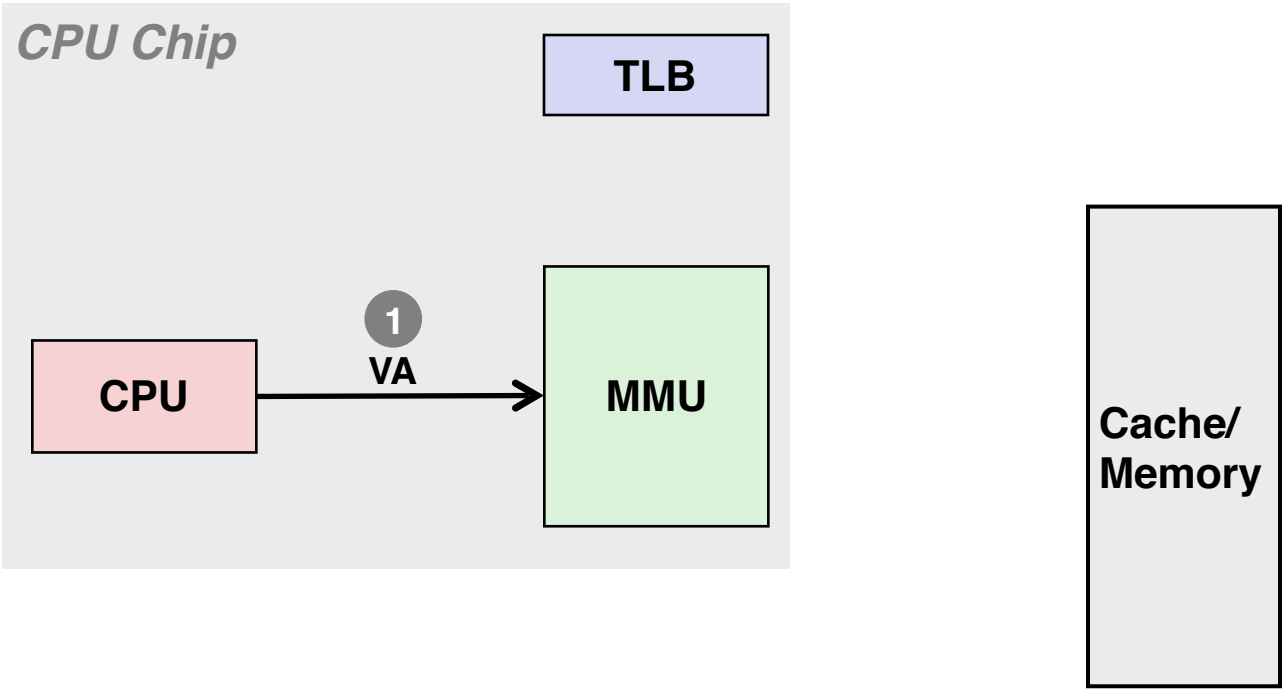

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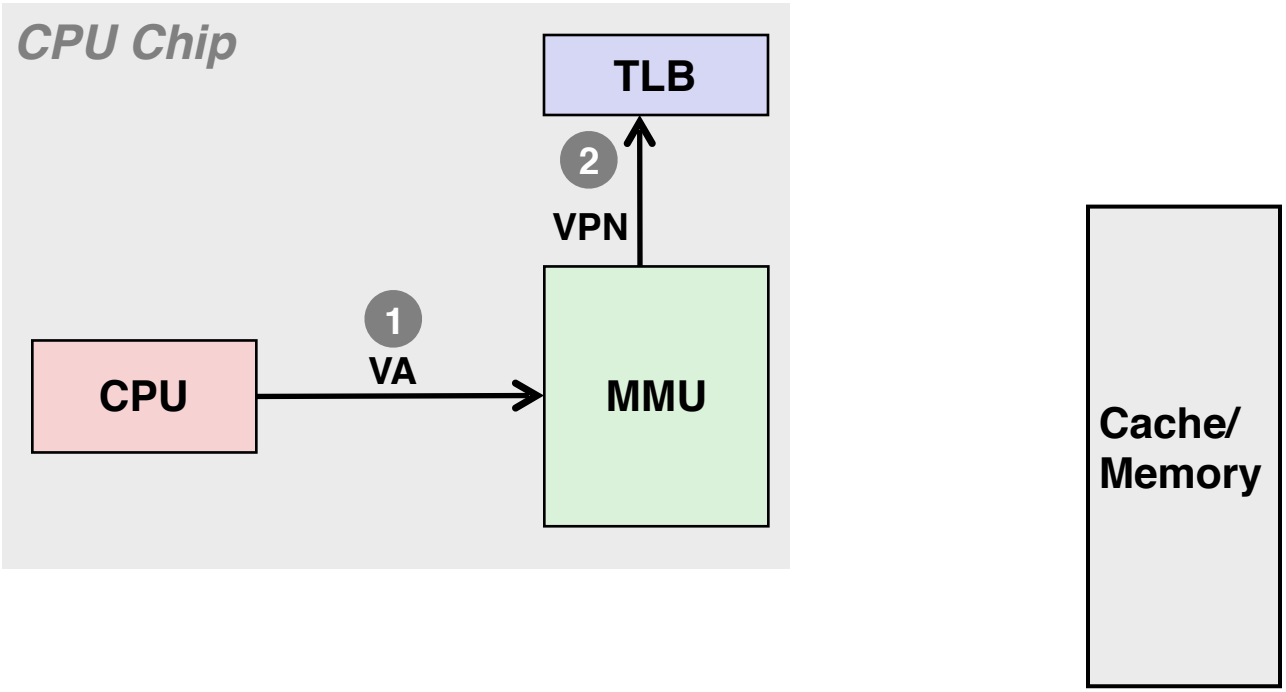

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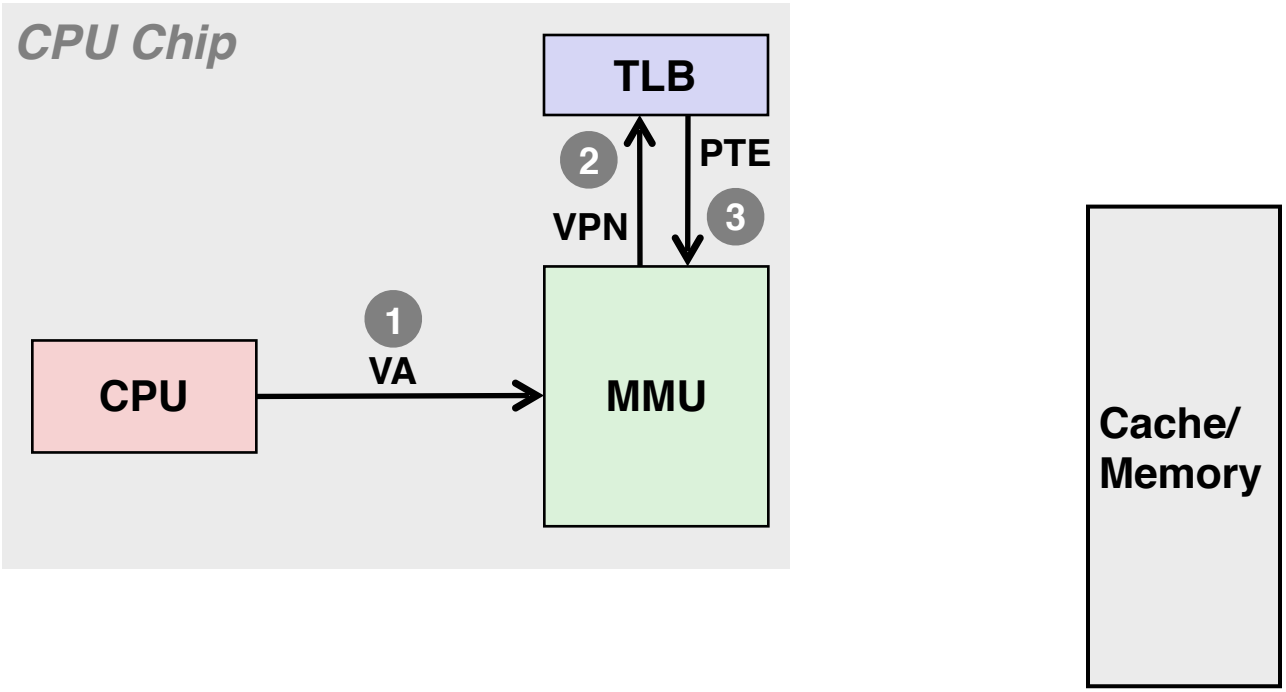

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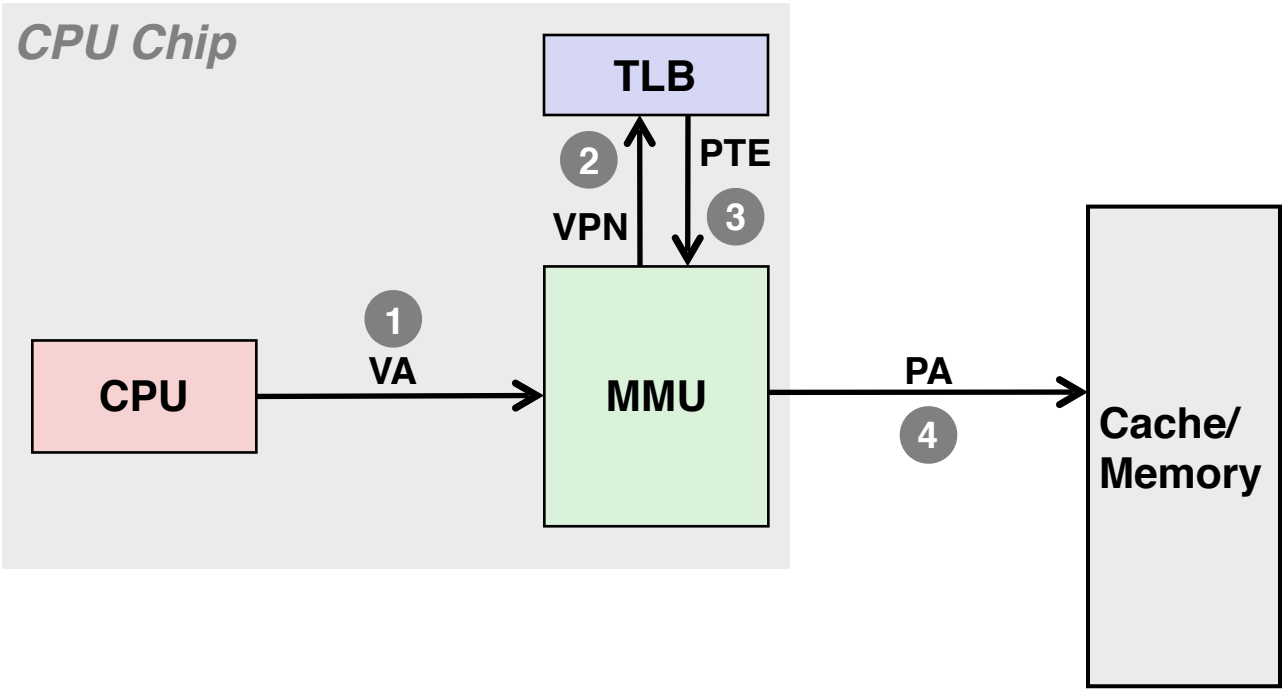

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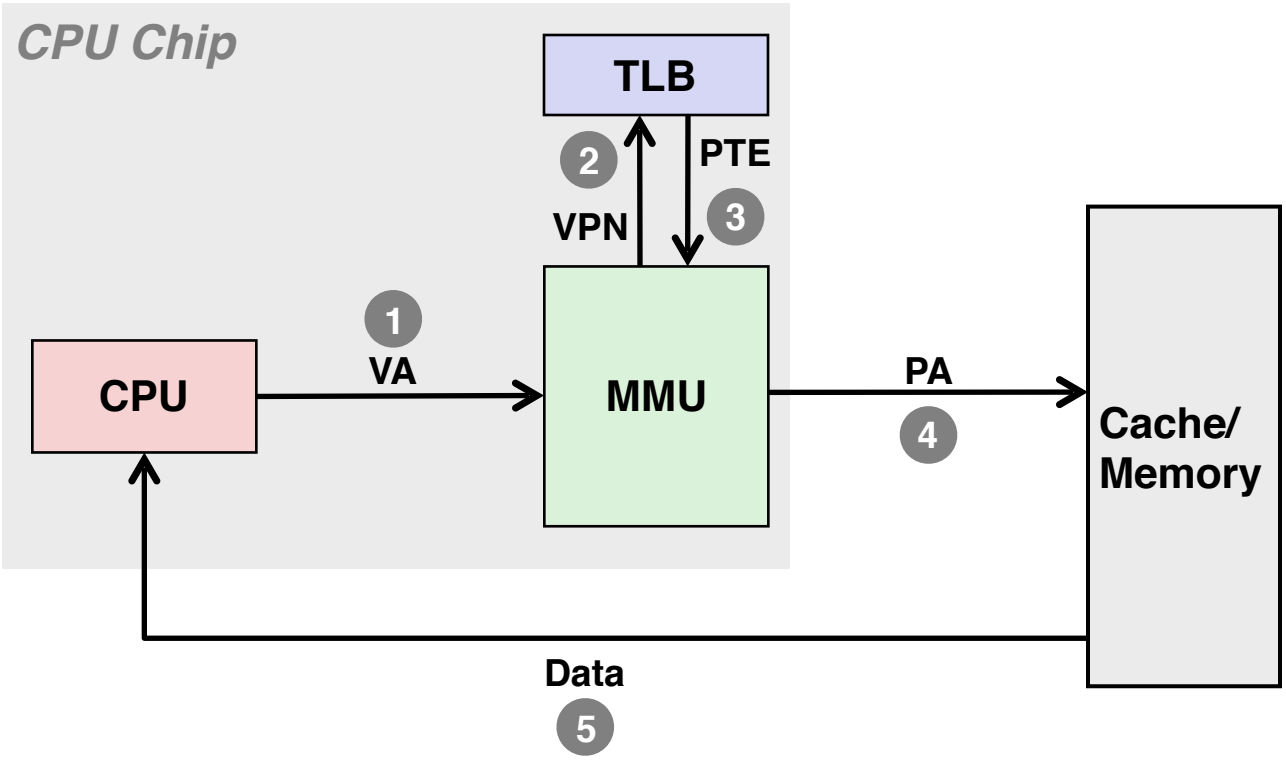

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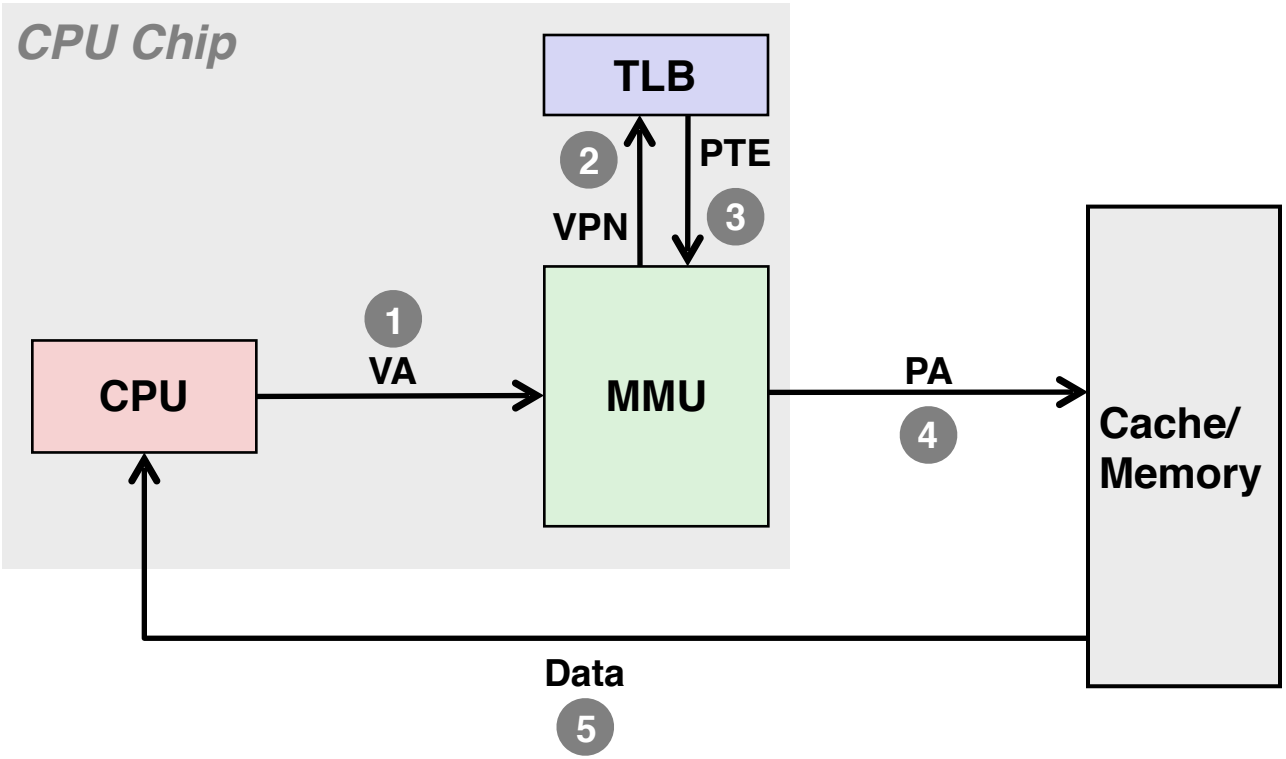
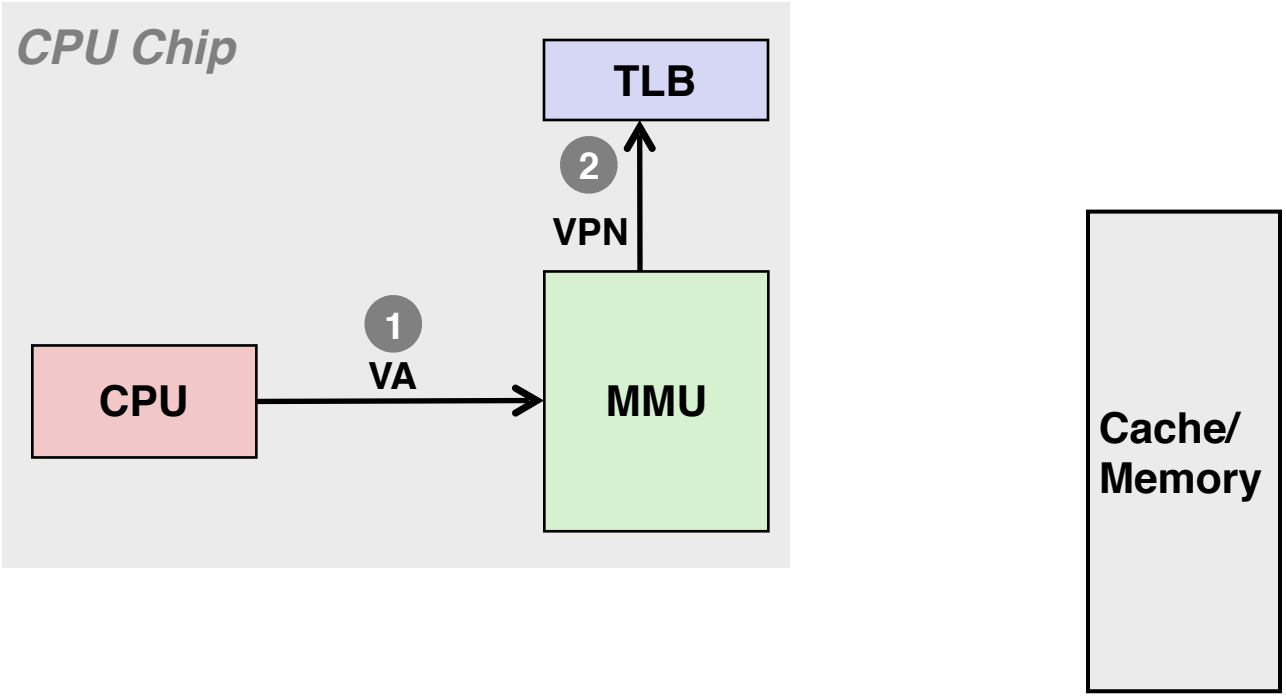


A TLB hit eliminates a memory access

TLB Miss



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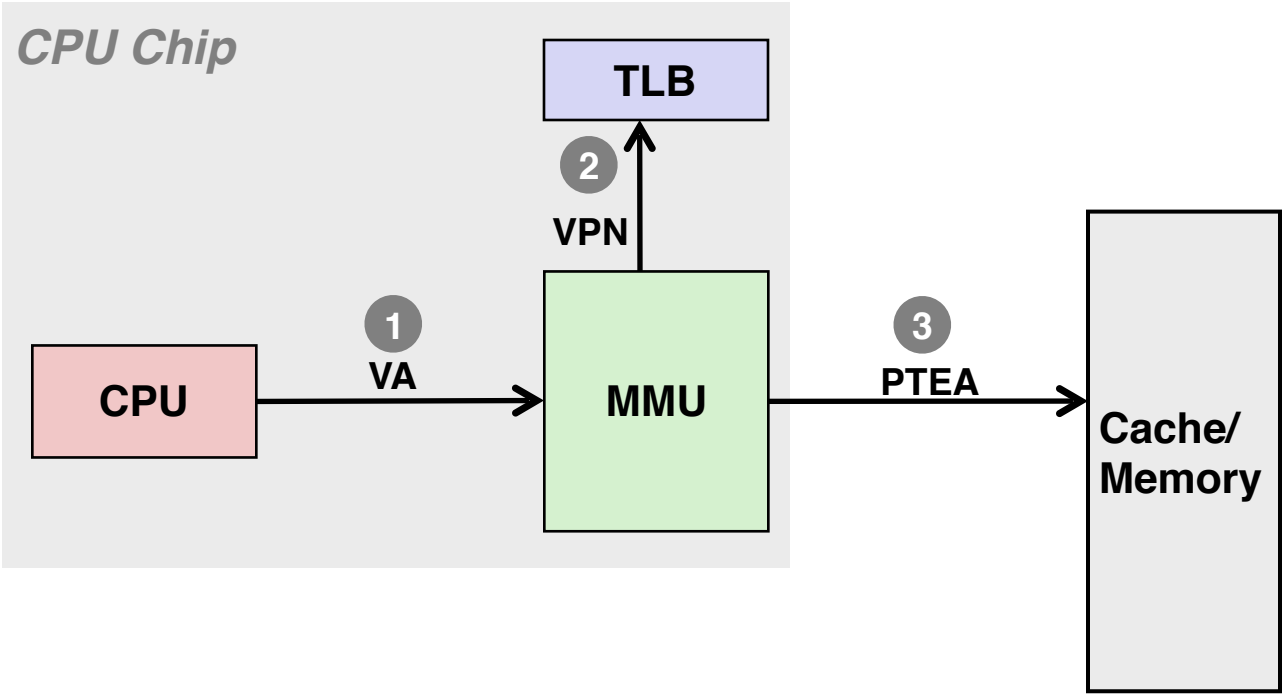

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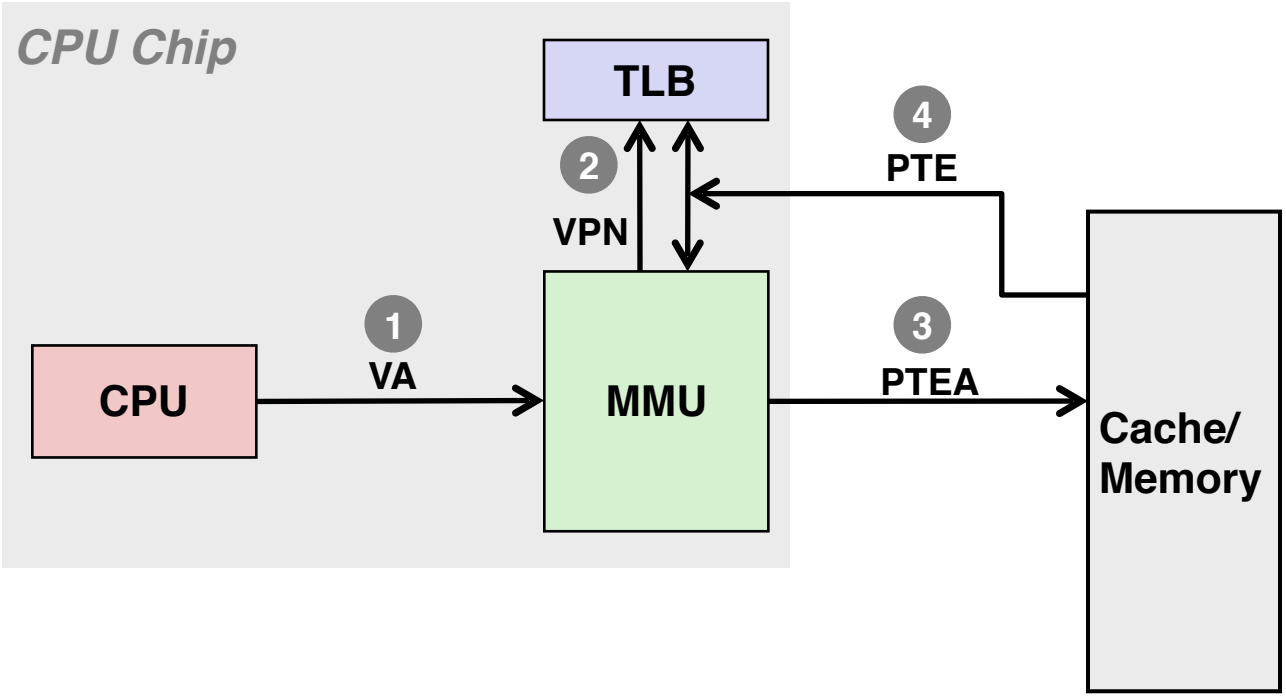

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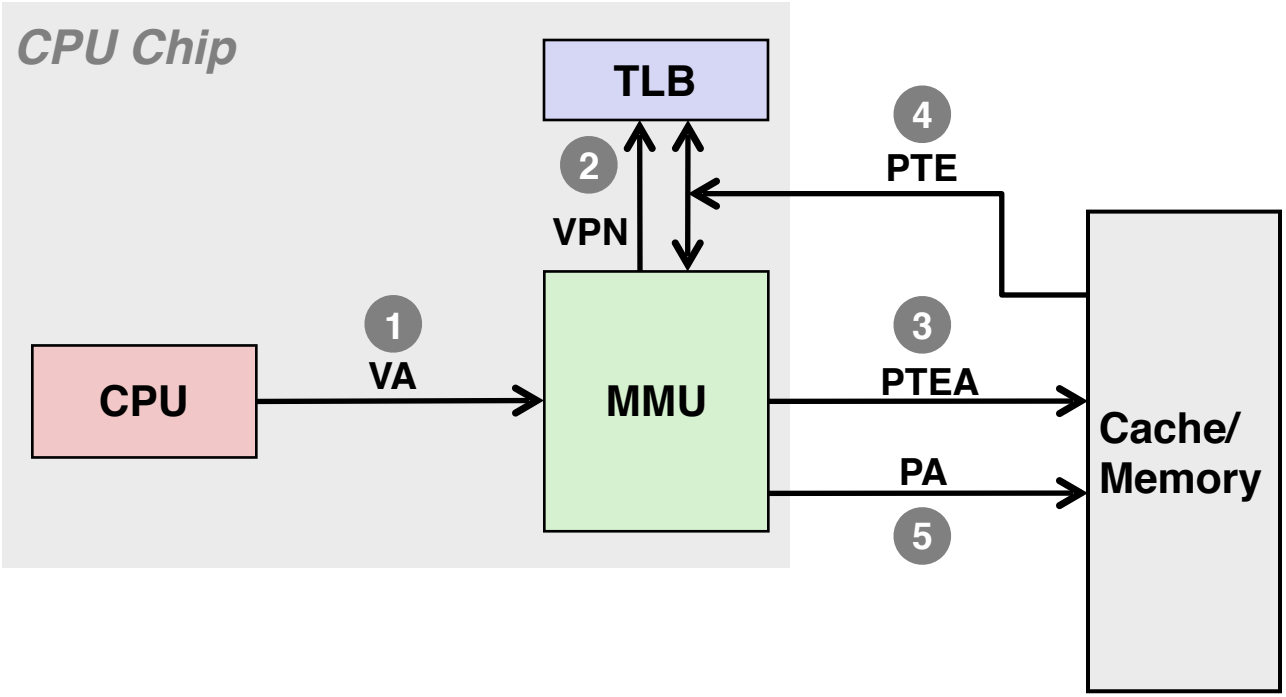

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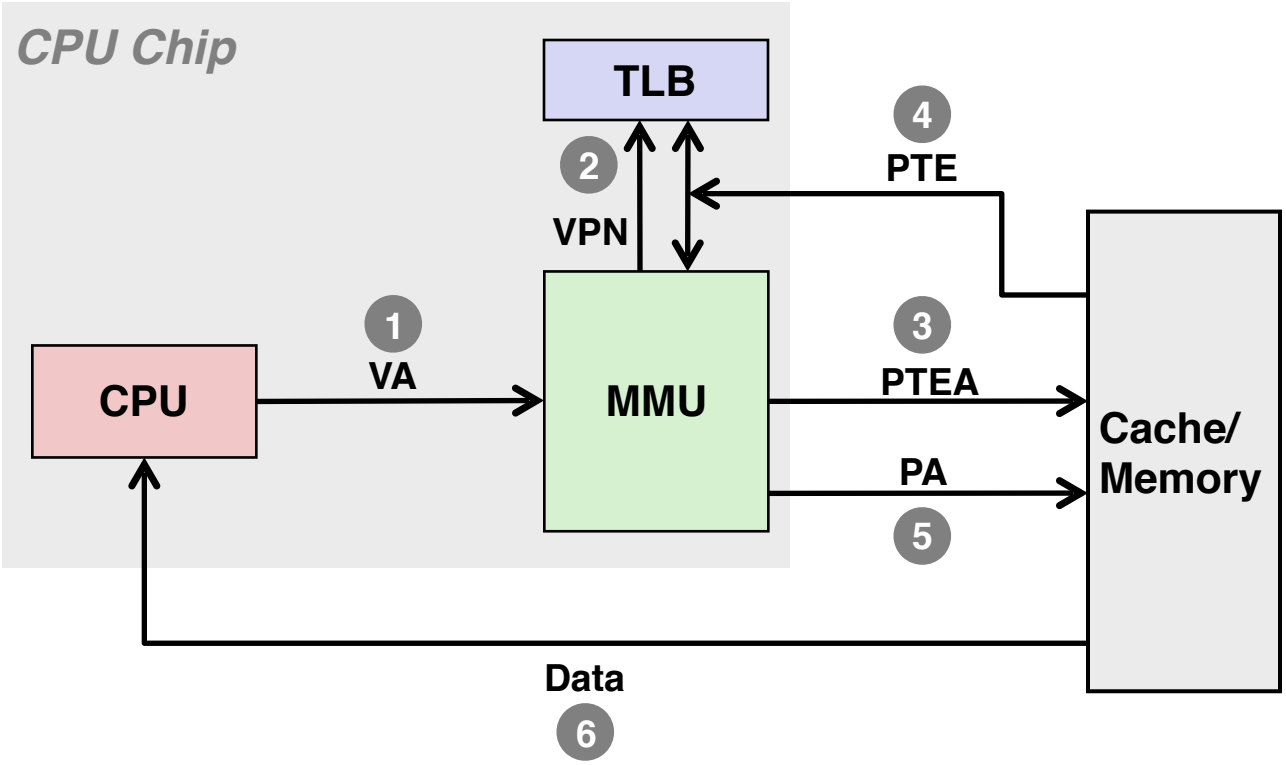
CPU Chip
TLB
4
PTE
2
VPN
1
VA
3
PTEA
CPU
MMU
Cache/
Memory
PA
5
Data
6

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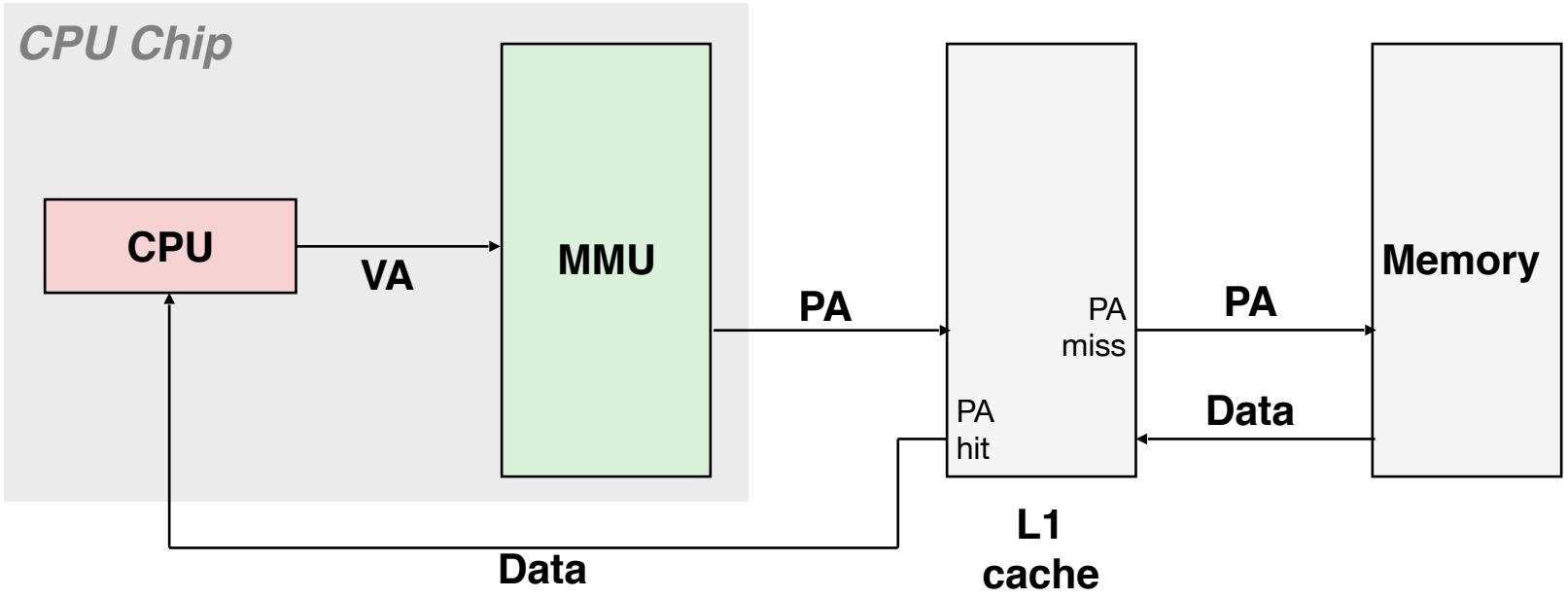
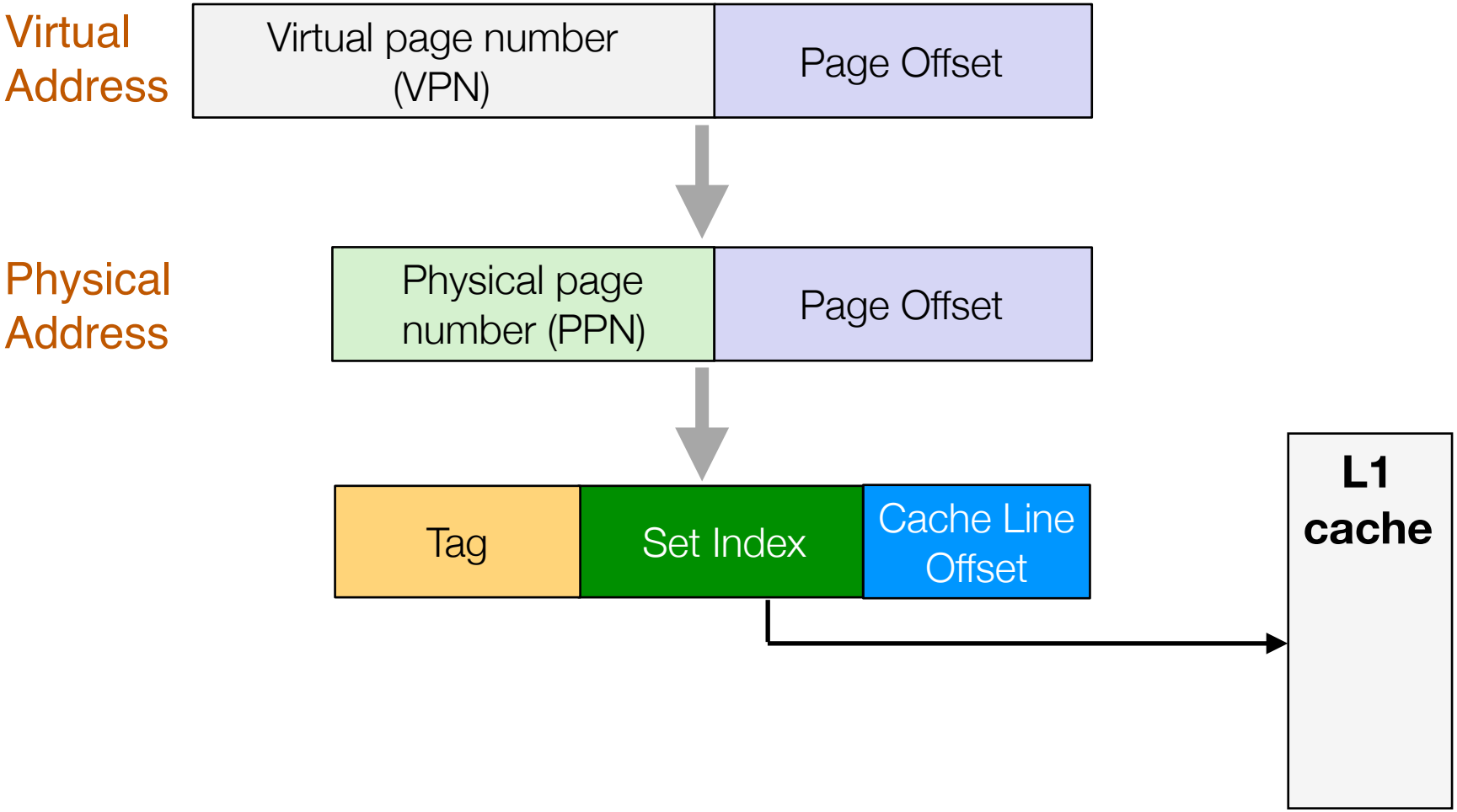
Performance Issue in VM

- Address translation and cache accesses are serialized
  - First translate from VA to PA
  - Then use PA to access cache
  - Slow! Can we speed it up?



Observe Address Translation



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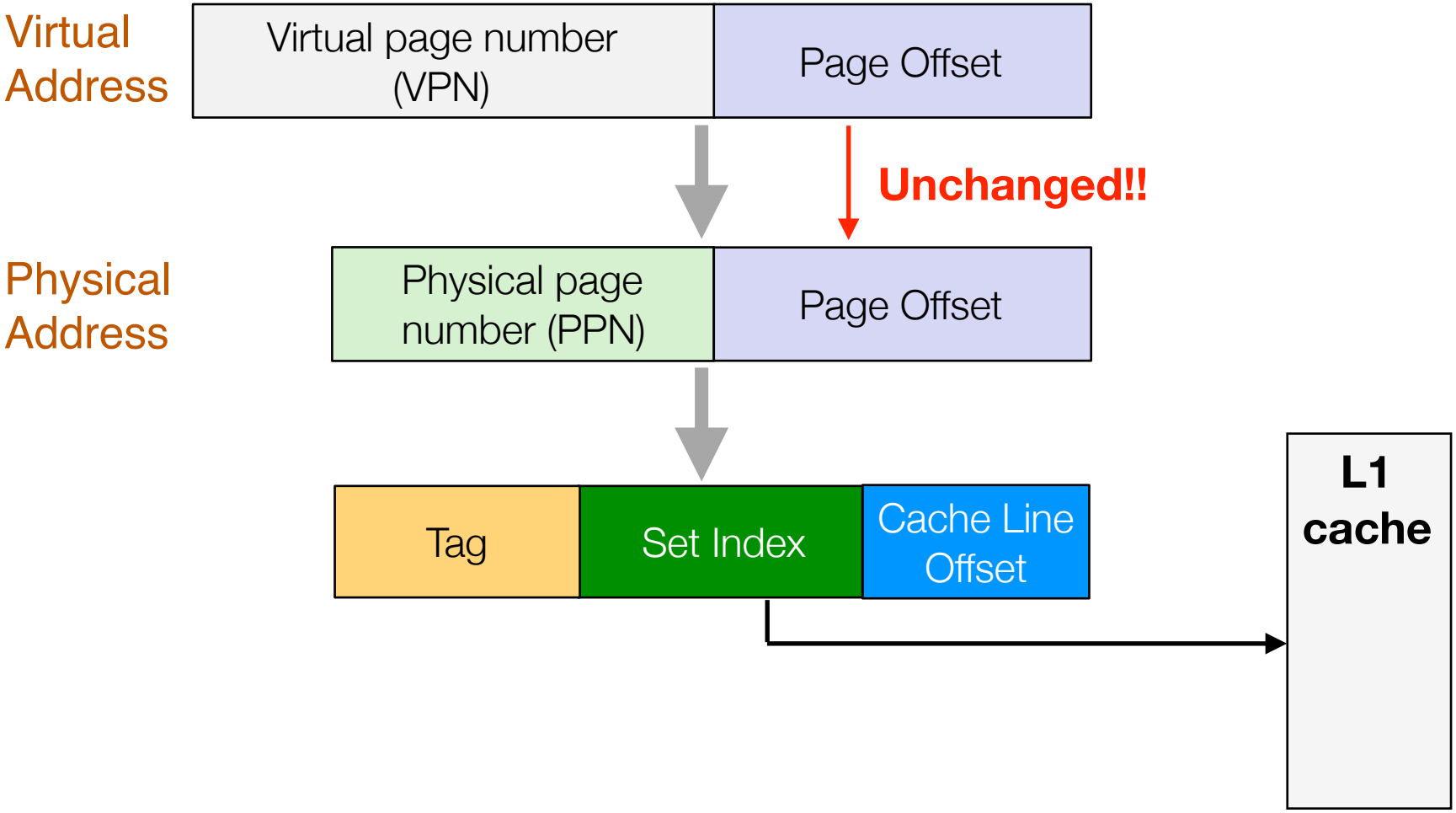

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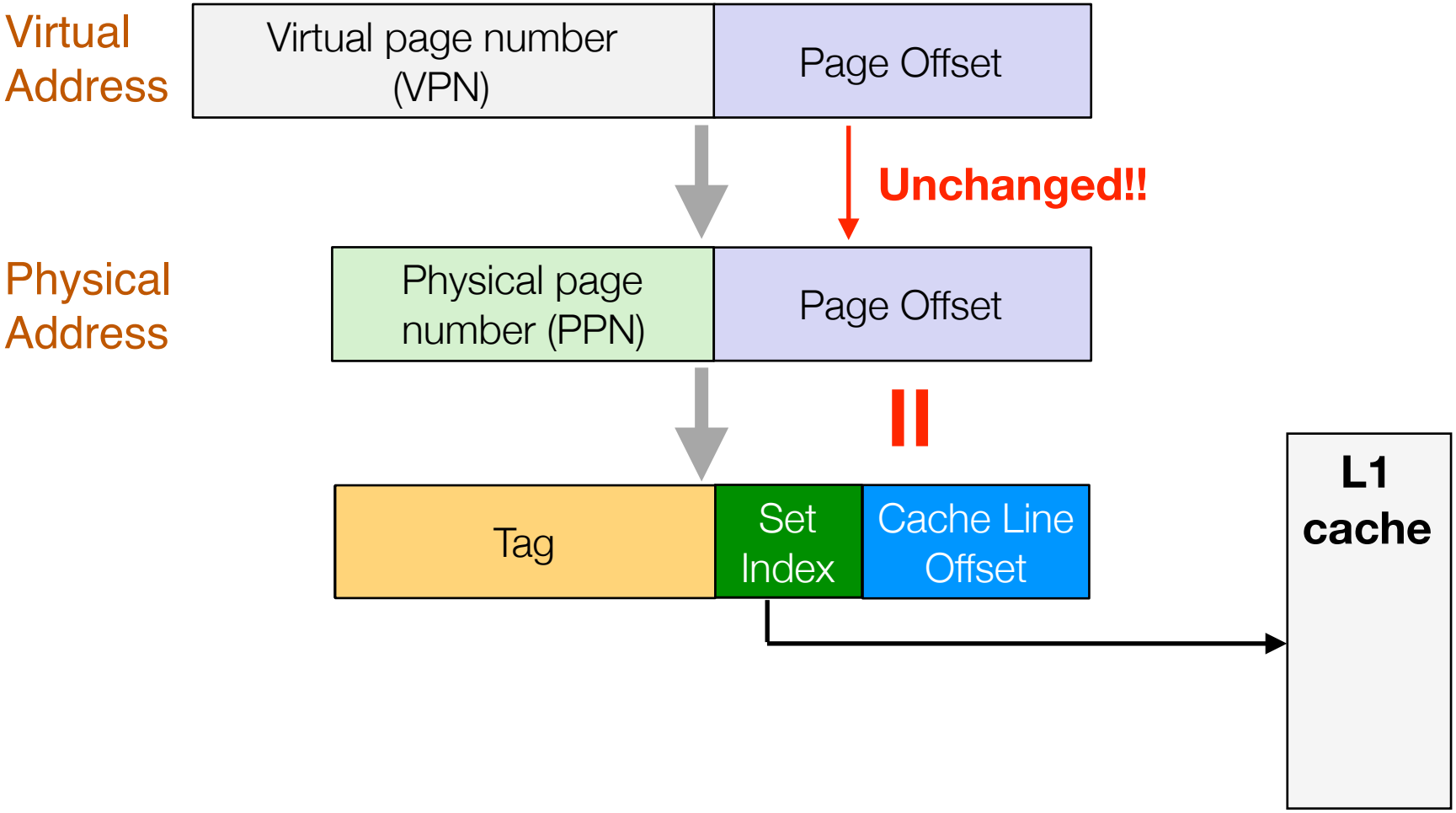

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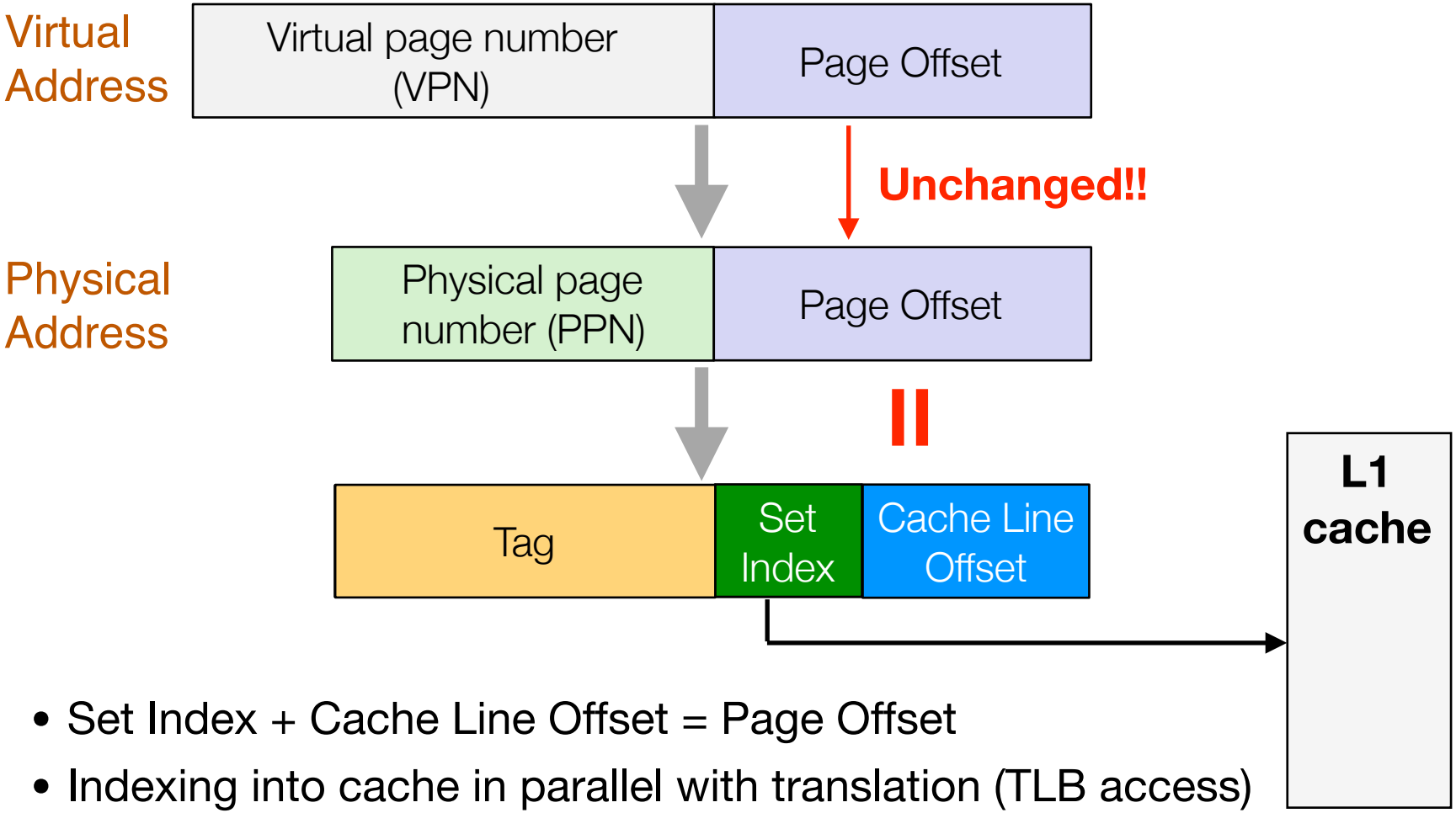

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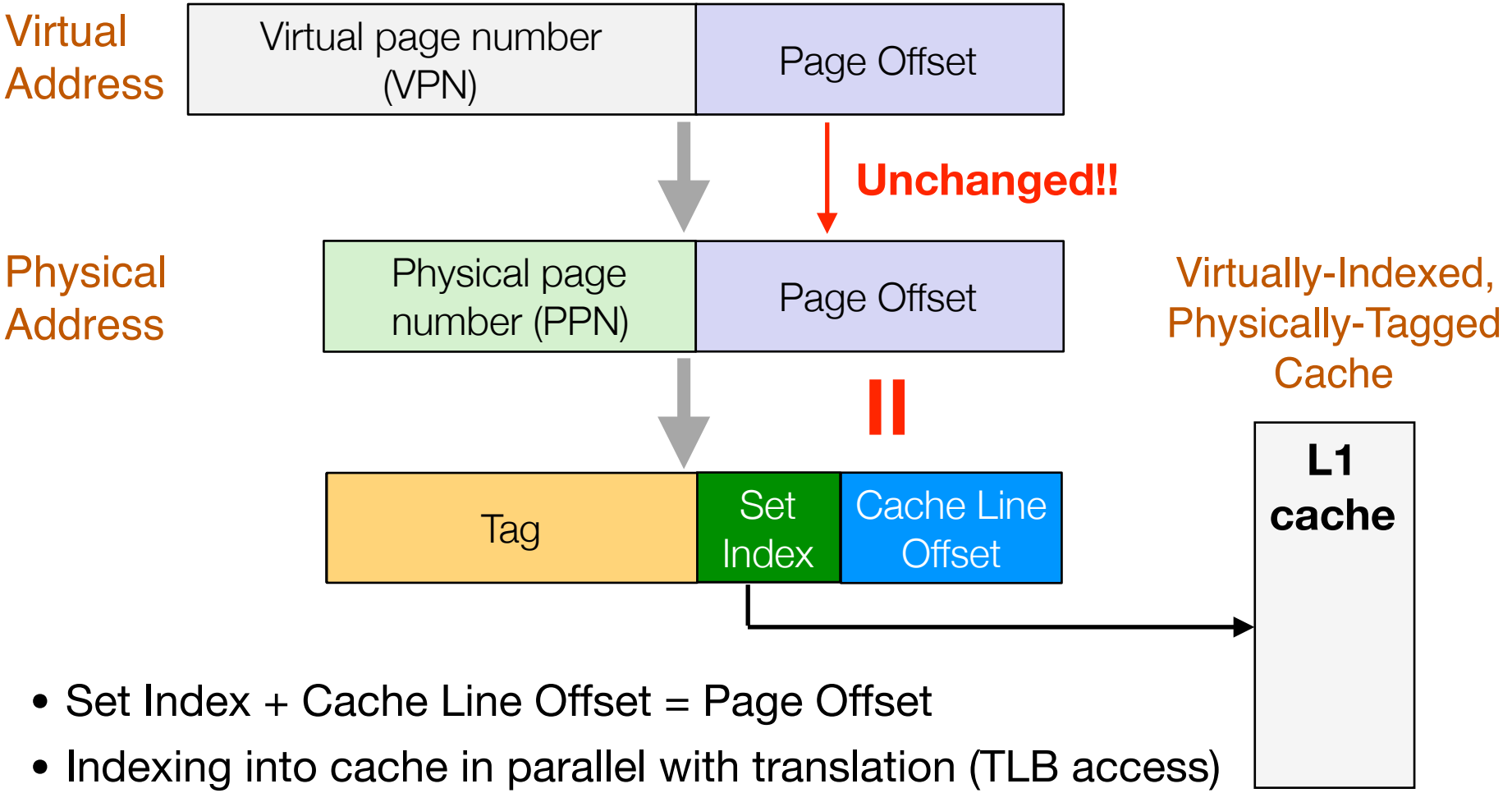

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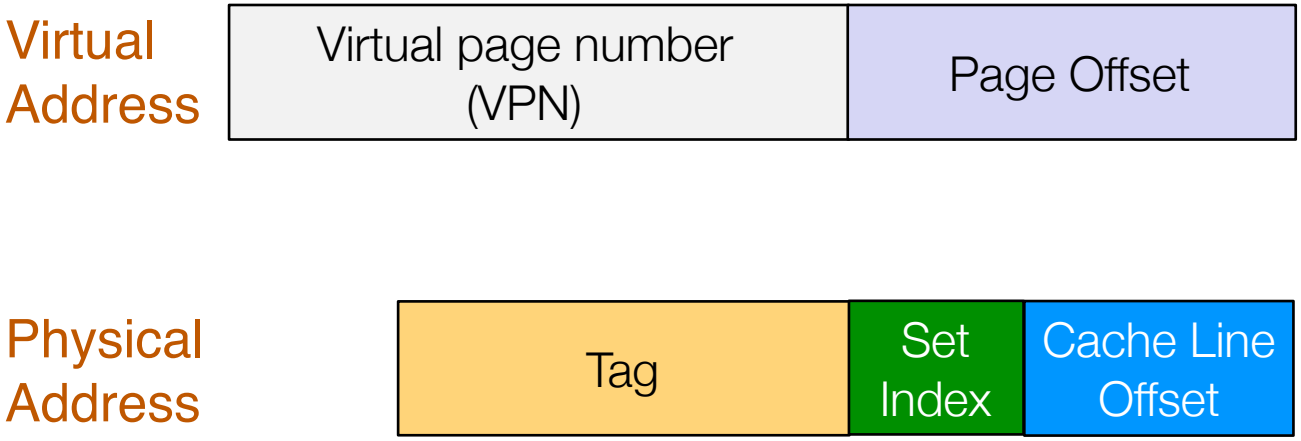

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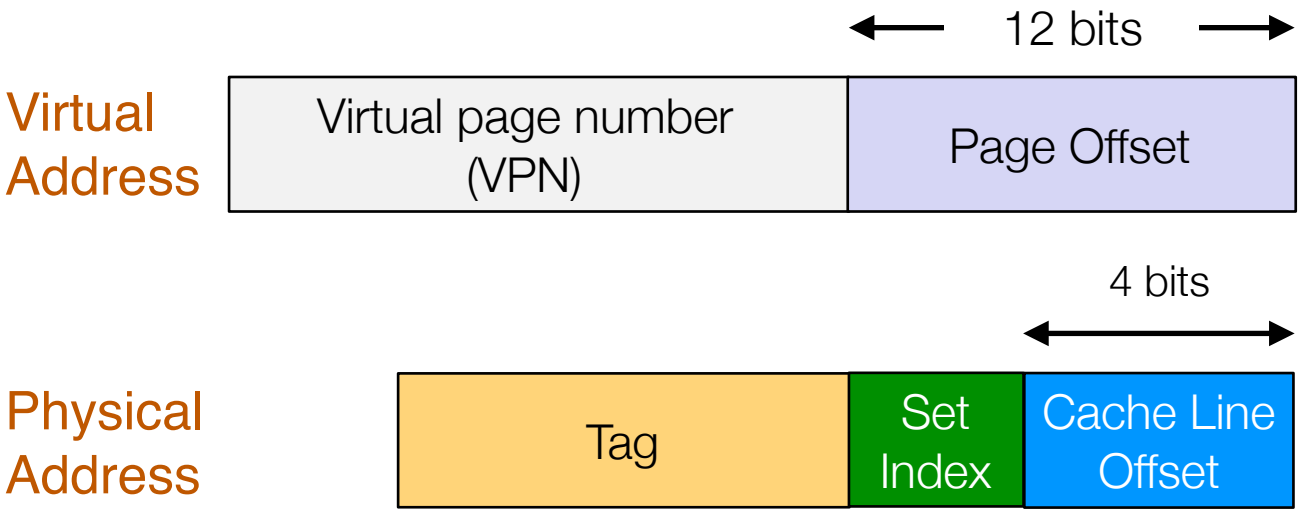

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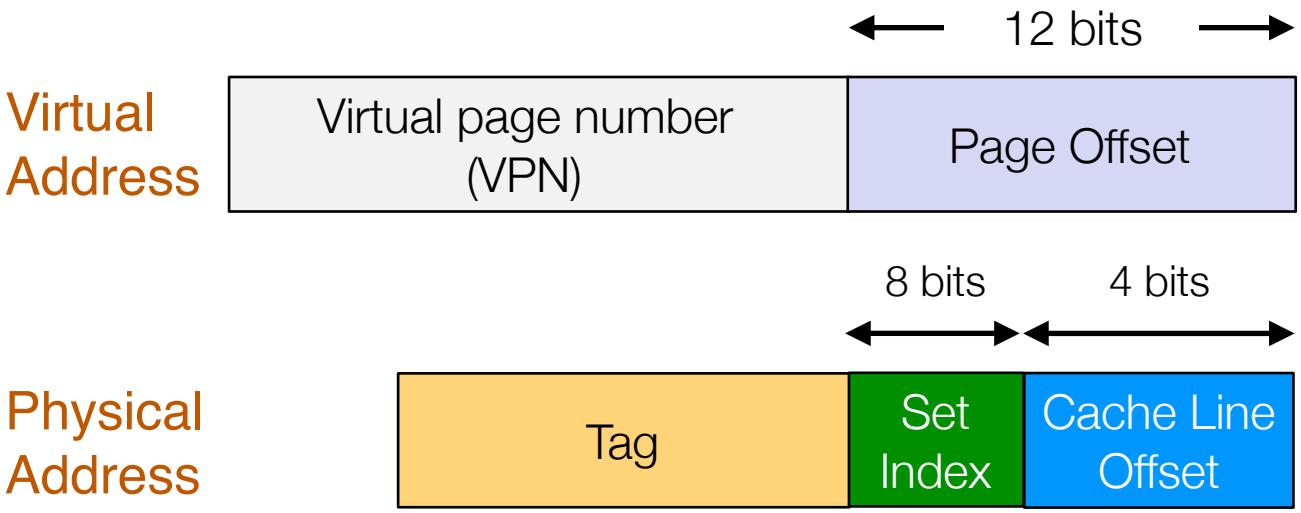

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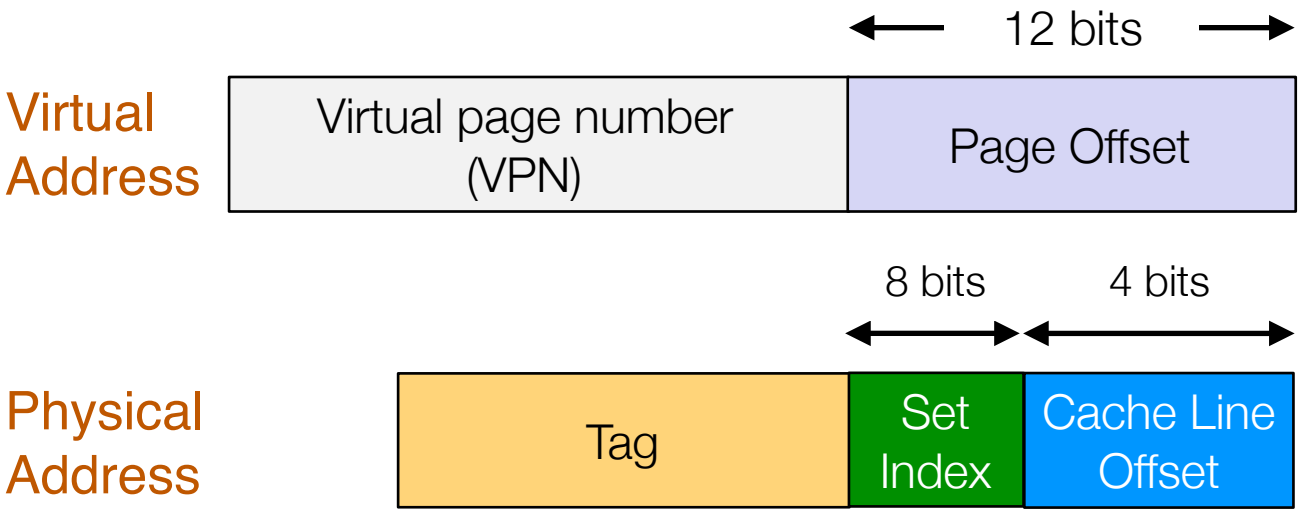

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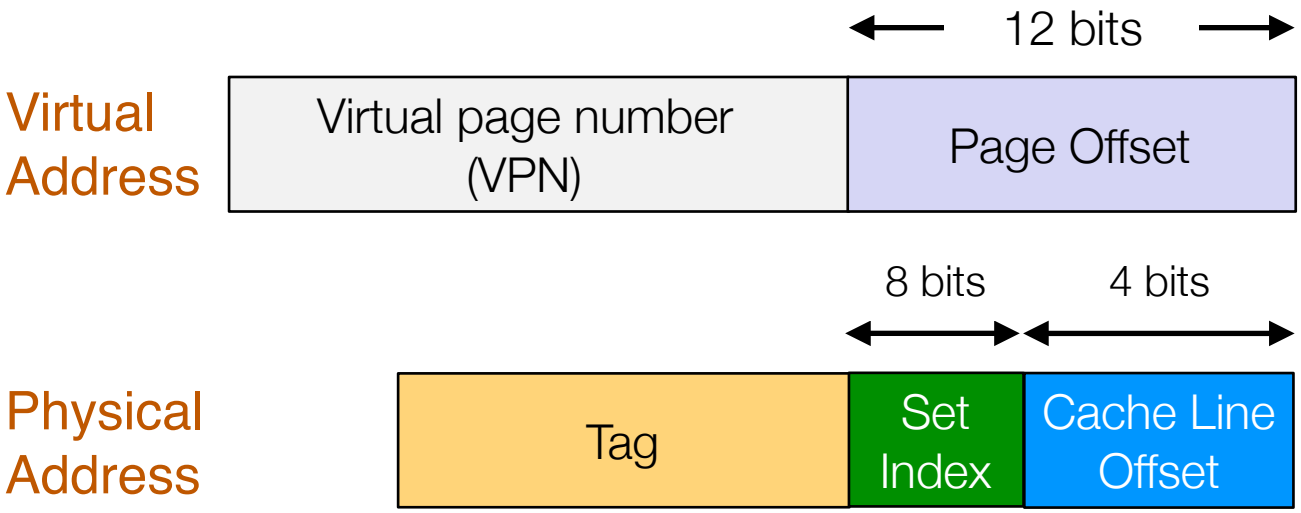

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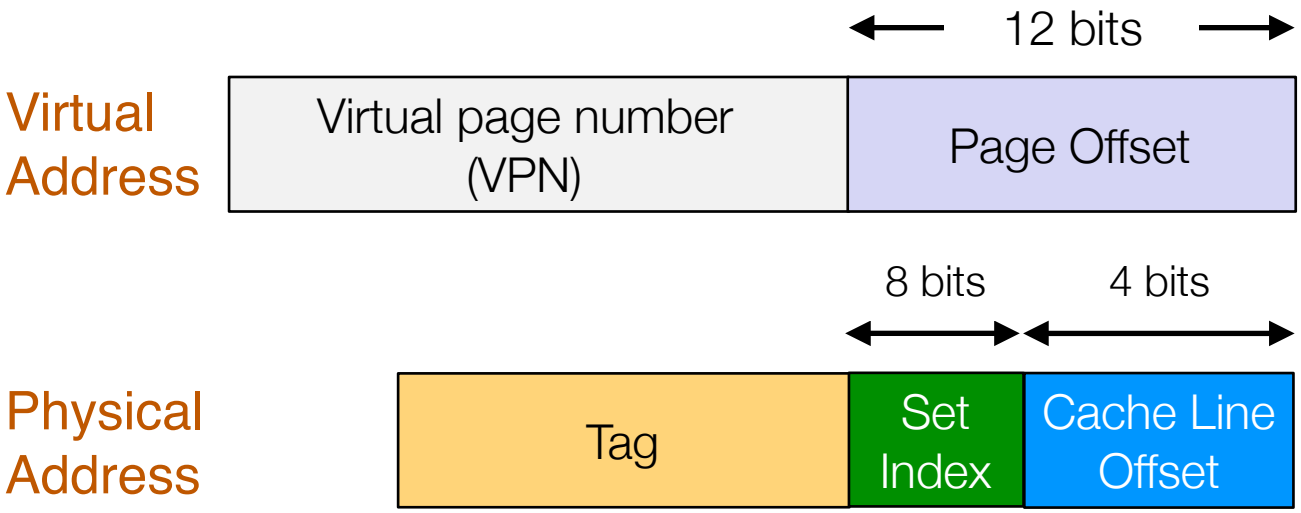

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- Solutions?

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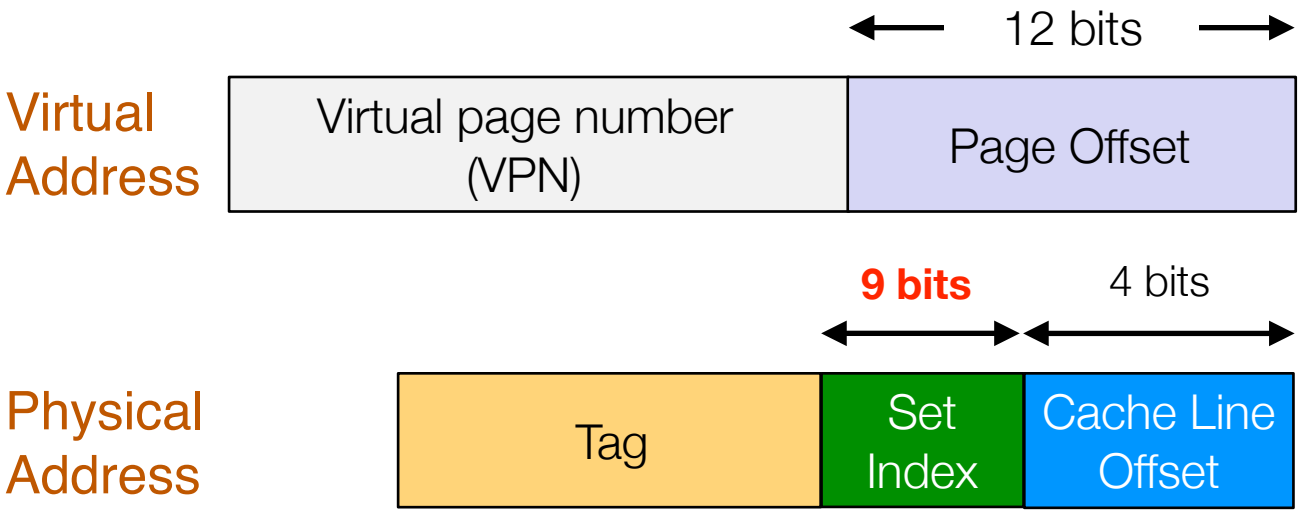

- What if we use 9 bits for Set Index? More Sets now.

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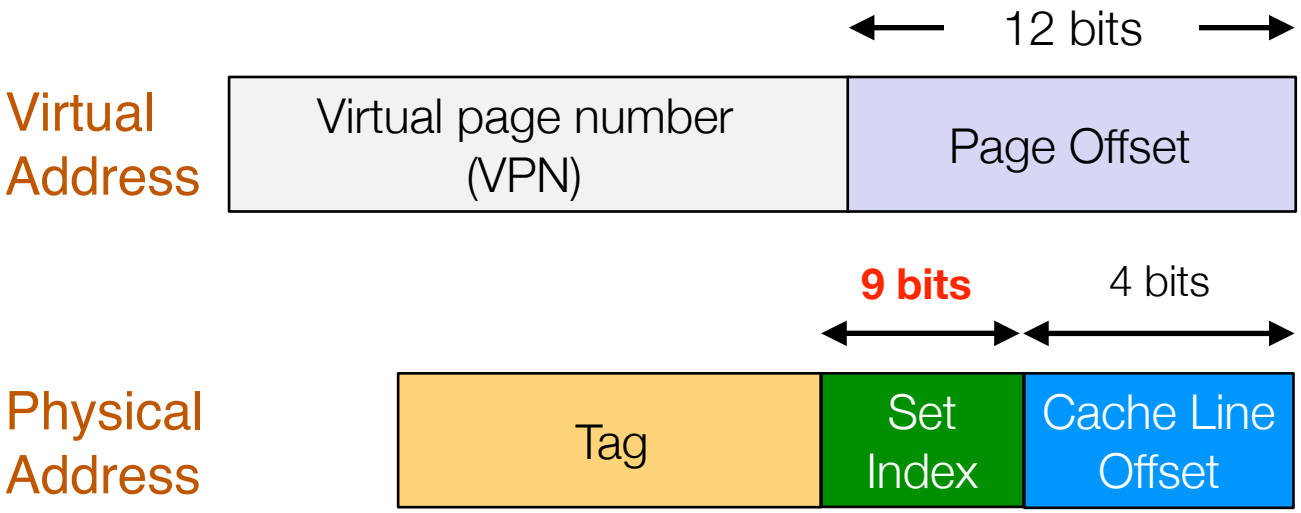

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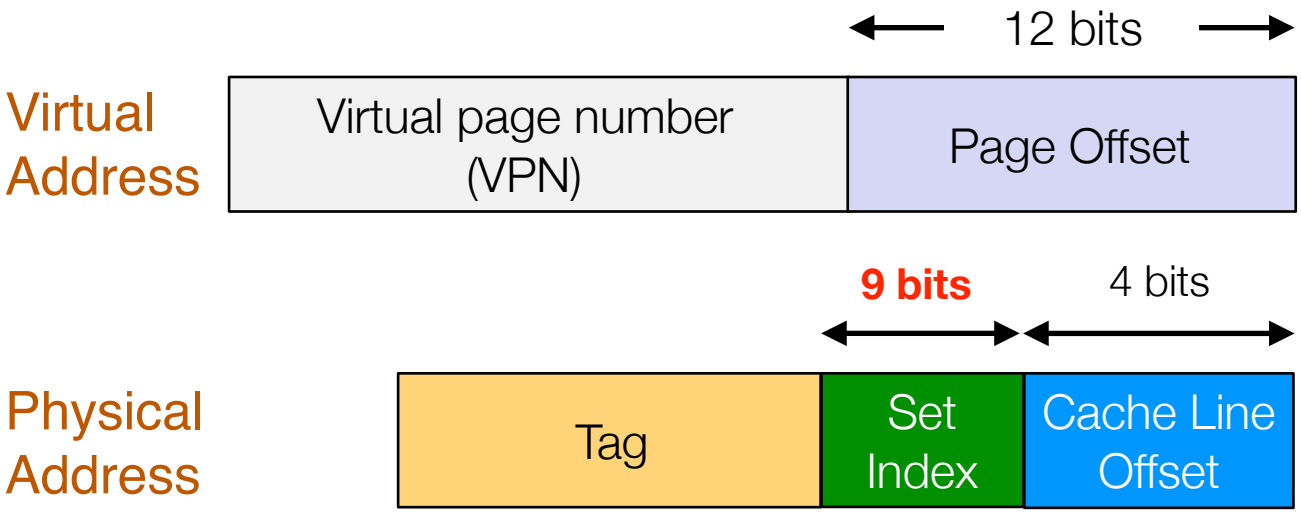

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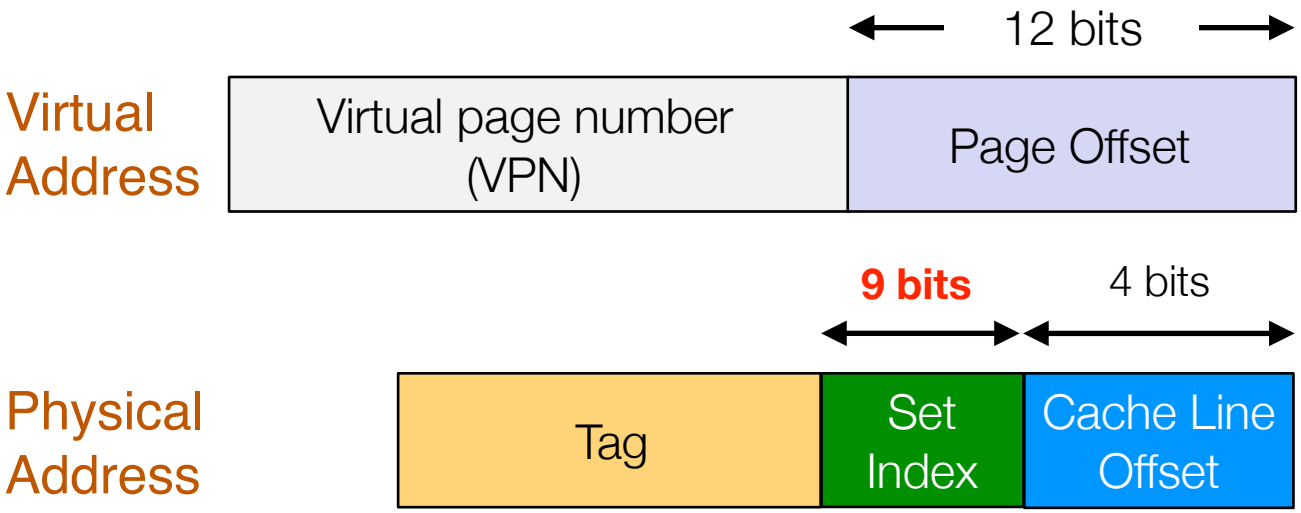

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- The least significant bit in VPN and PPN must be the same
- That is: an even VA must be mapped to an even PA, and an odd VA must be mapped to an odd PA

Today

- Three Virtual Memory Optimizations
  - TLB
  - Virtually-indexed, physically-tagged cache
  - Page the page table (a.k.a., multi-level page table)
- Case-study: Intel Core i7/Linux example

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  - 2^{36} PTEs in a page table
  - 512 GB total size per page table??!!
- Problem: Page tables are huge
  - One table per process!
  - Storing them all in main memory wastes space

Solution: Page the Page Table

- Observation: Only a small number of pages (working set) are accessed during a certain period of time, due to locality
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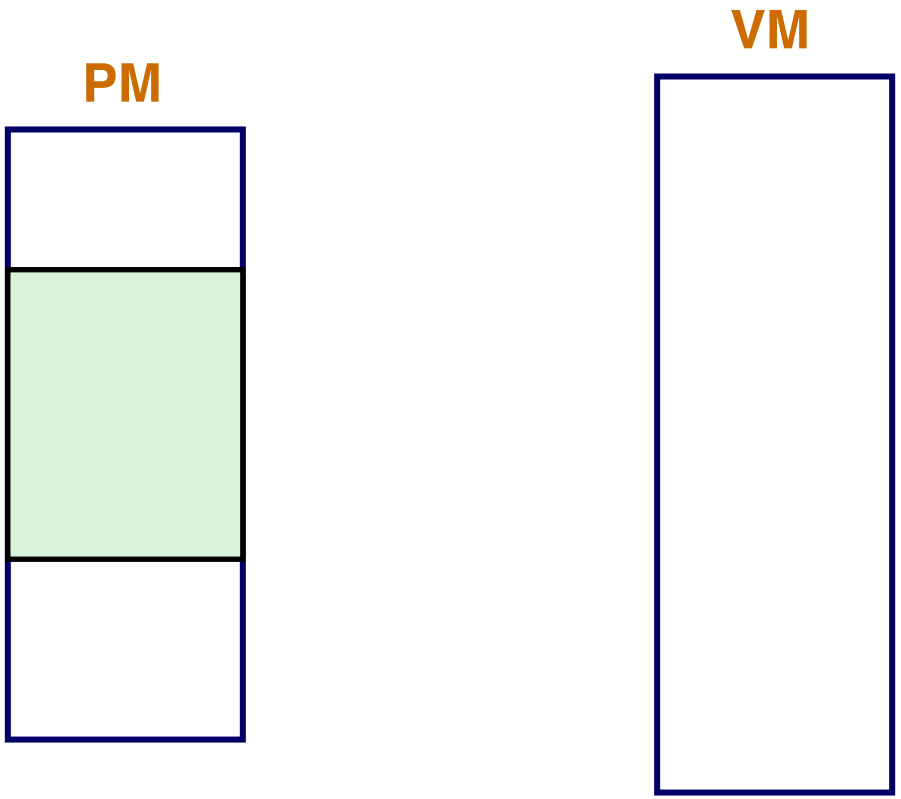

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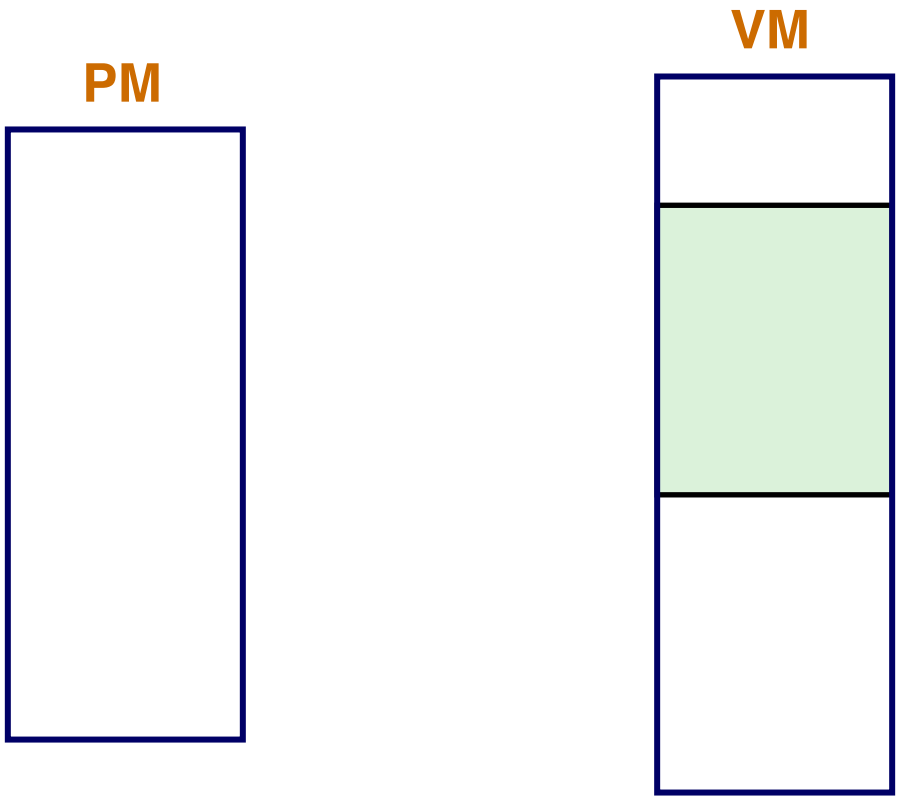

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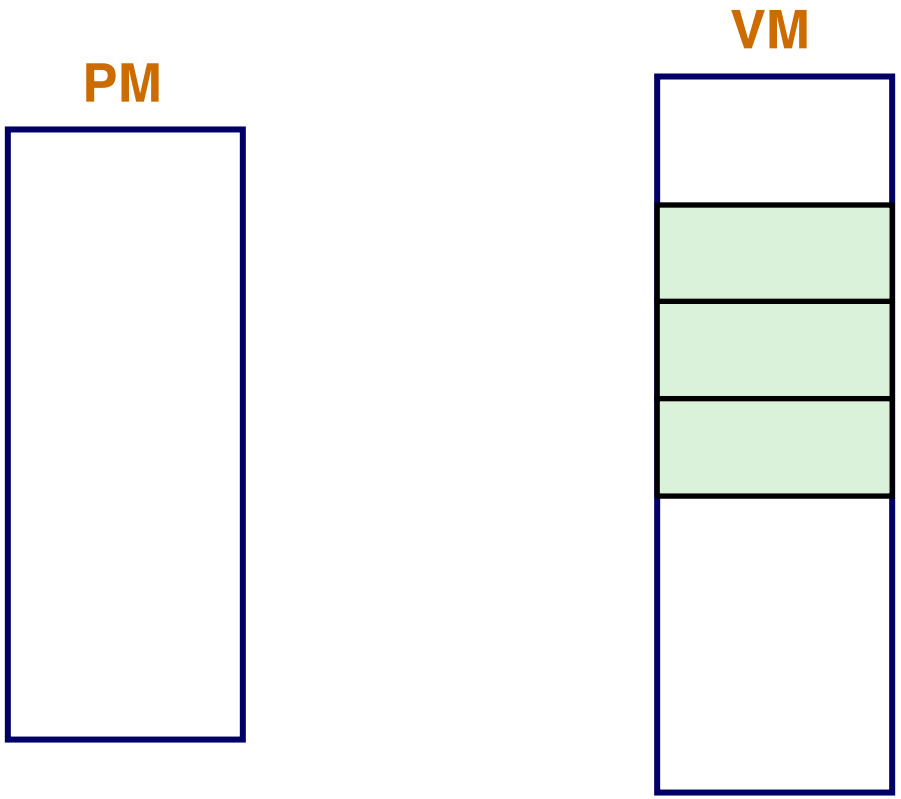

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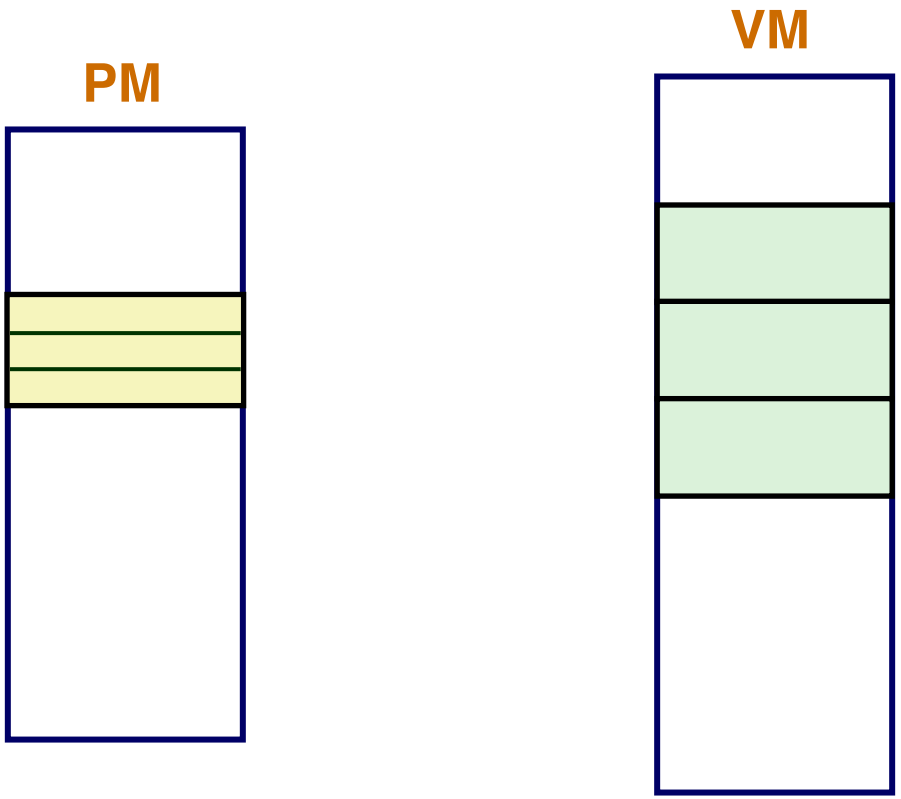

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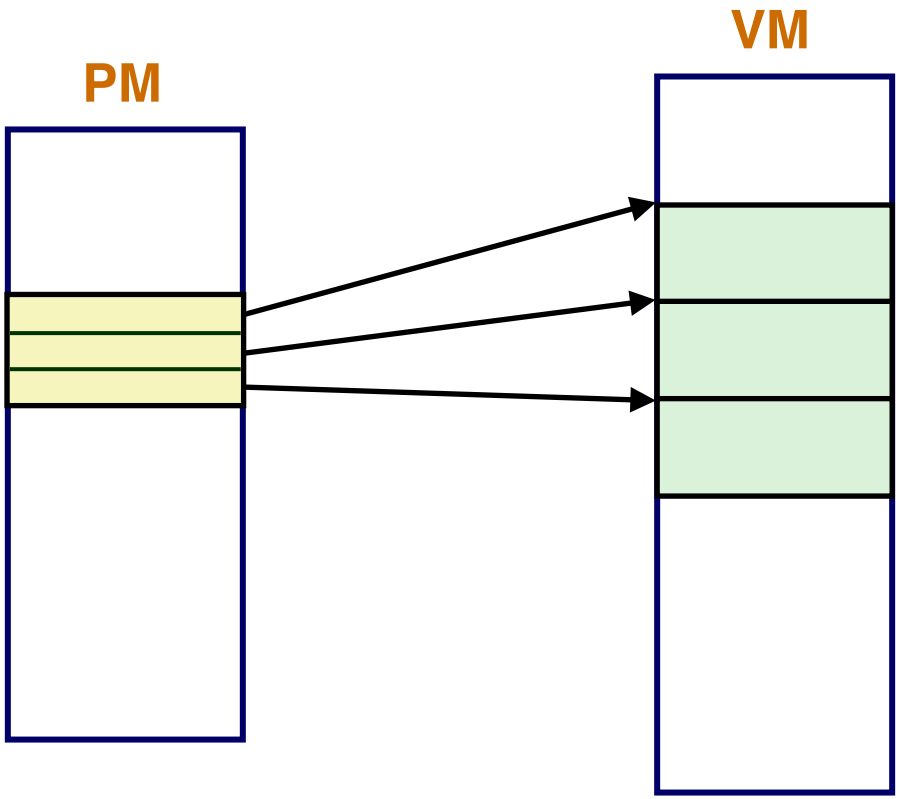

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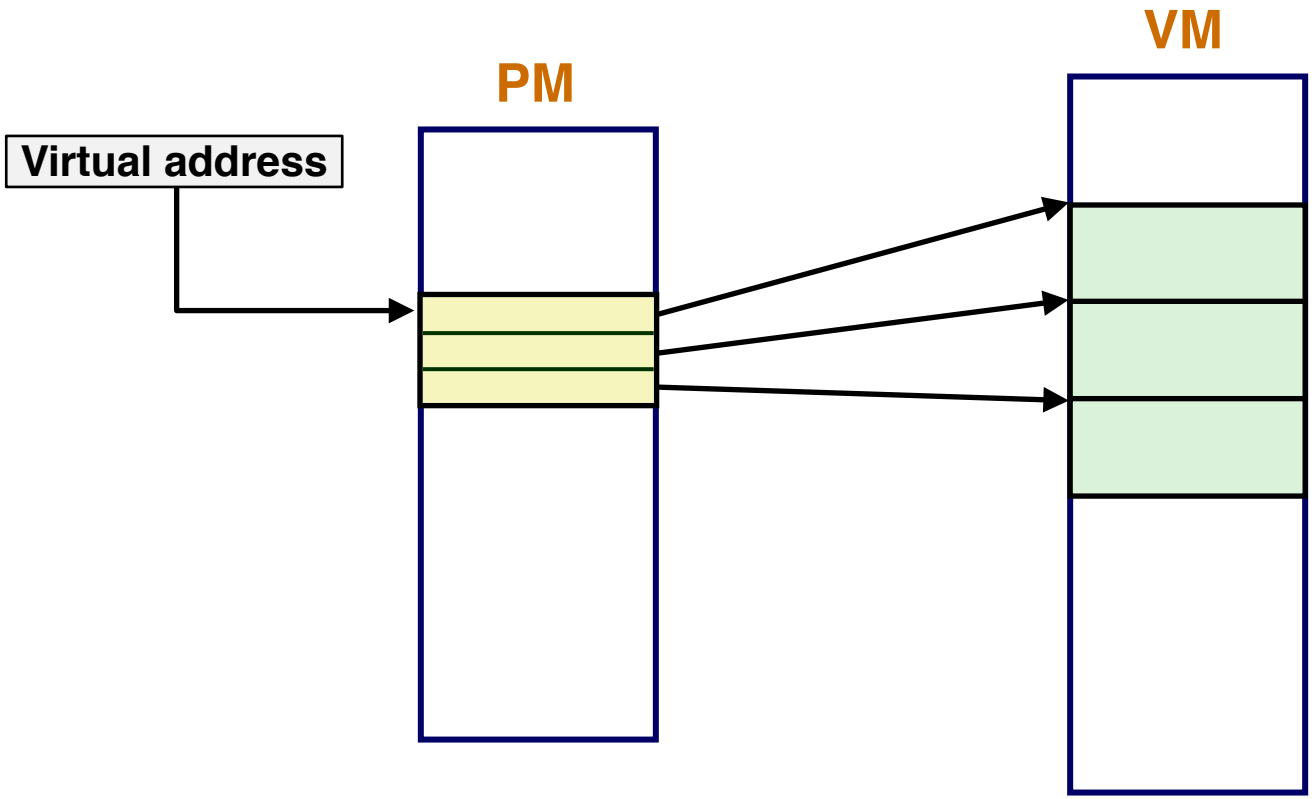

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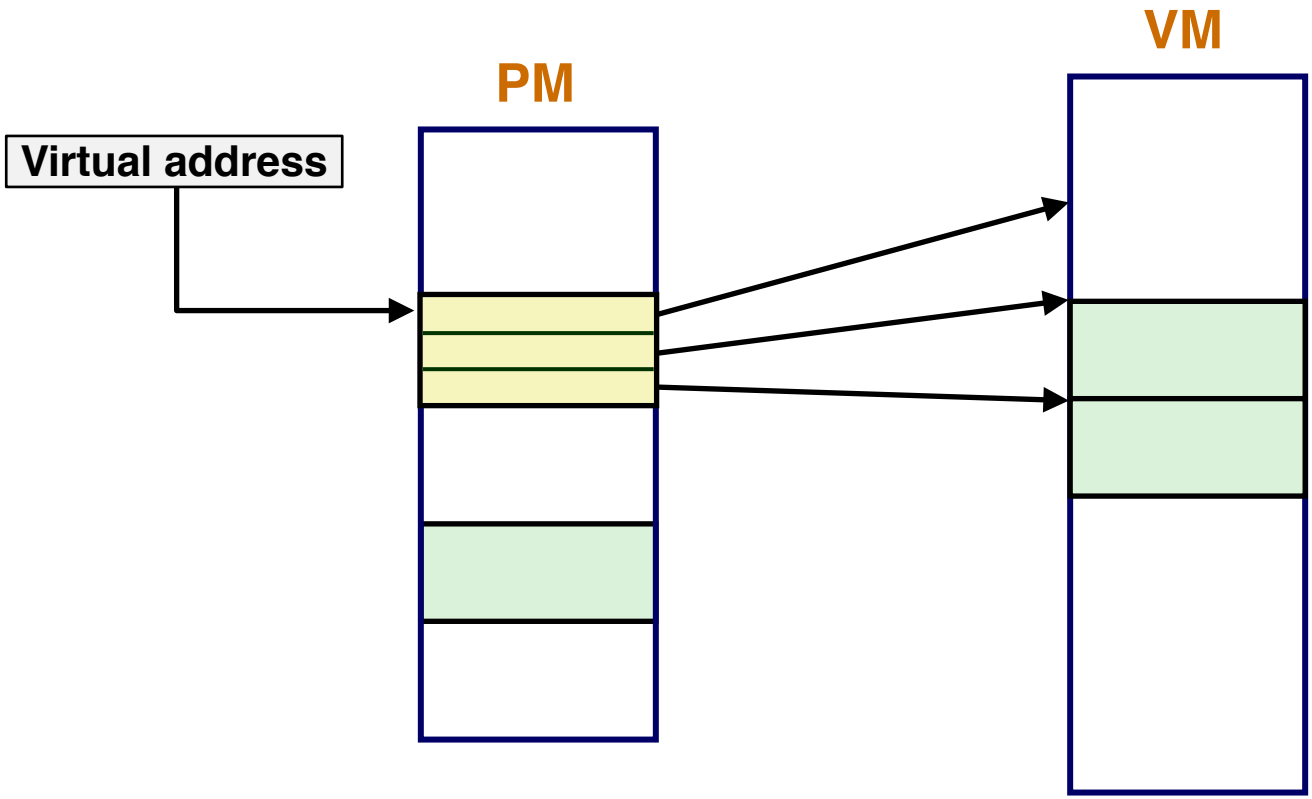

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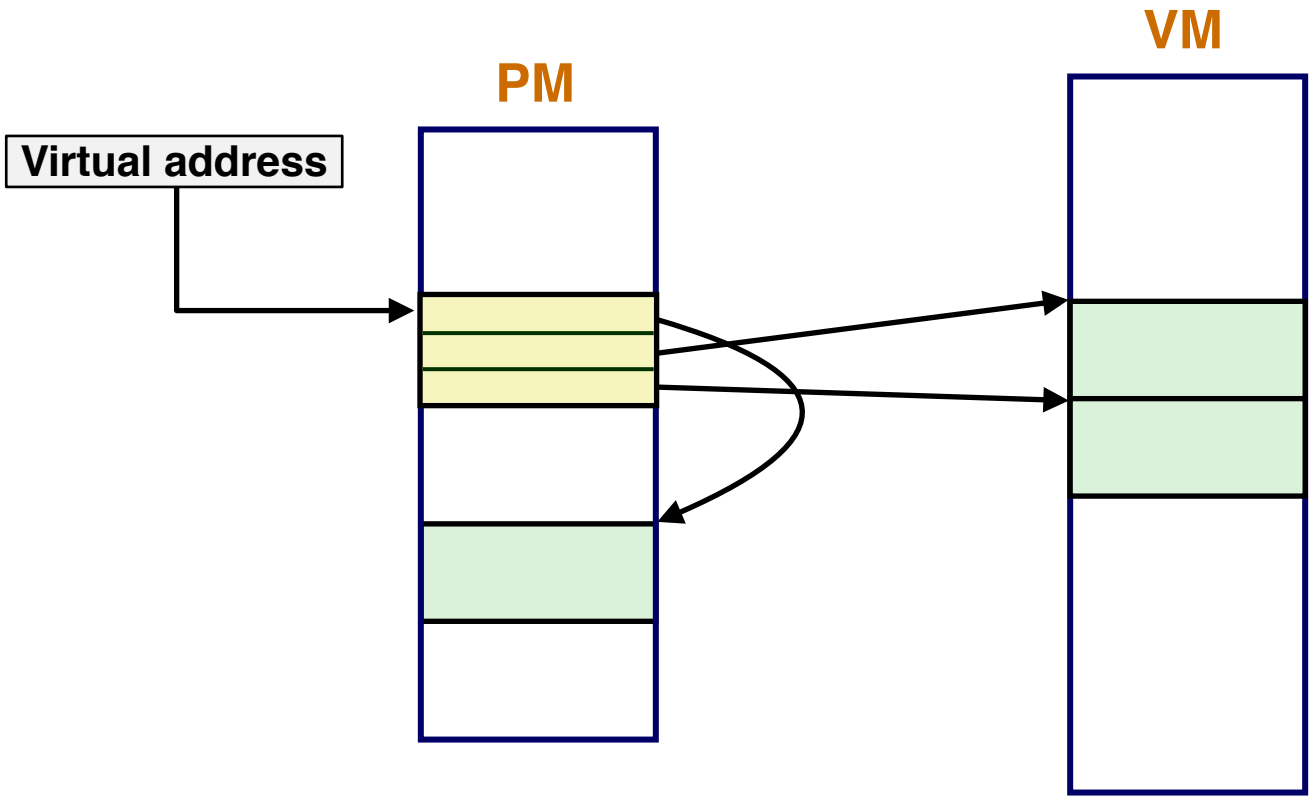
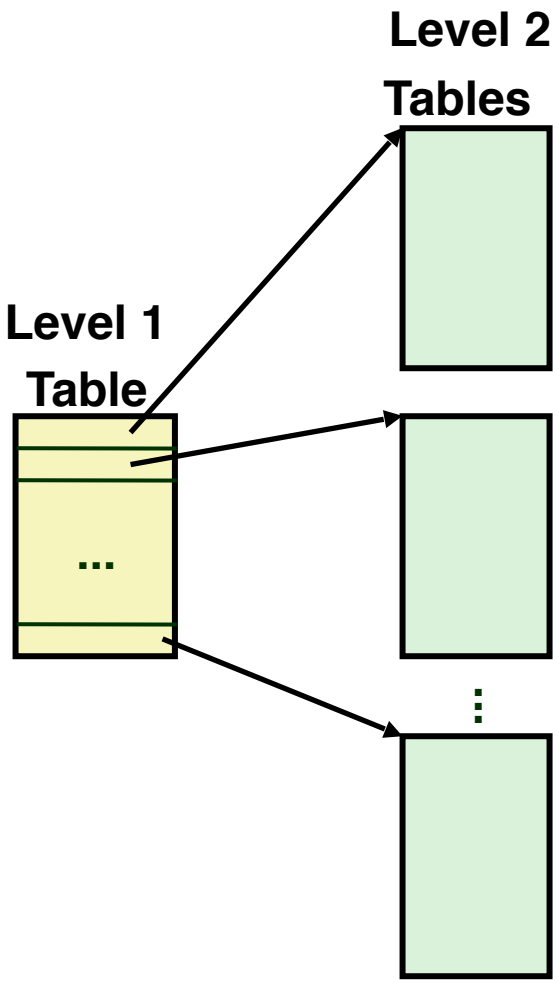
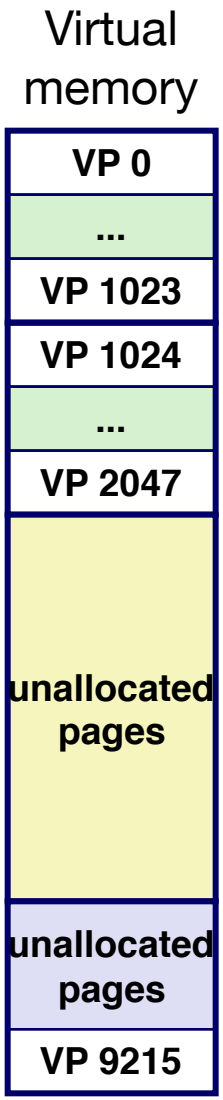


Effectively: A 2-Level Page Table

- Level 1 table:
  - Always in physical memory at a known location.
  - Each L1 PTE points to the start address of a L2 page table.
  - Bring that table to memory on-demand.
- Level 2 table:
  - Each PTE points to an actual data page



A Two-Level Page Table Hierarchy



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

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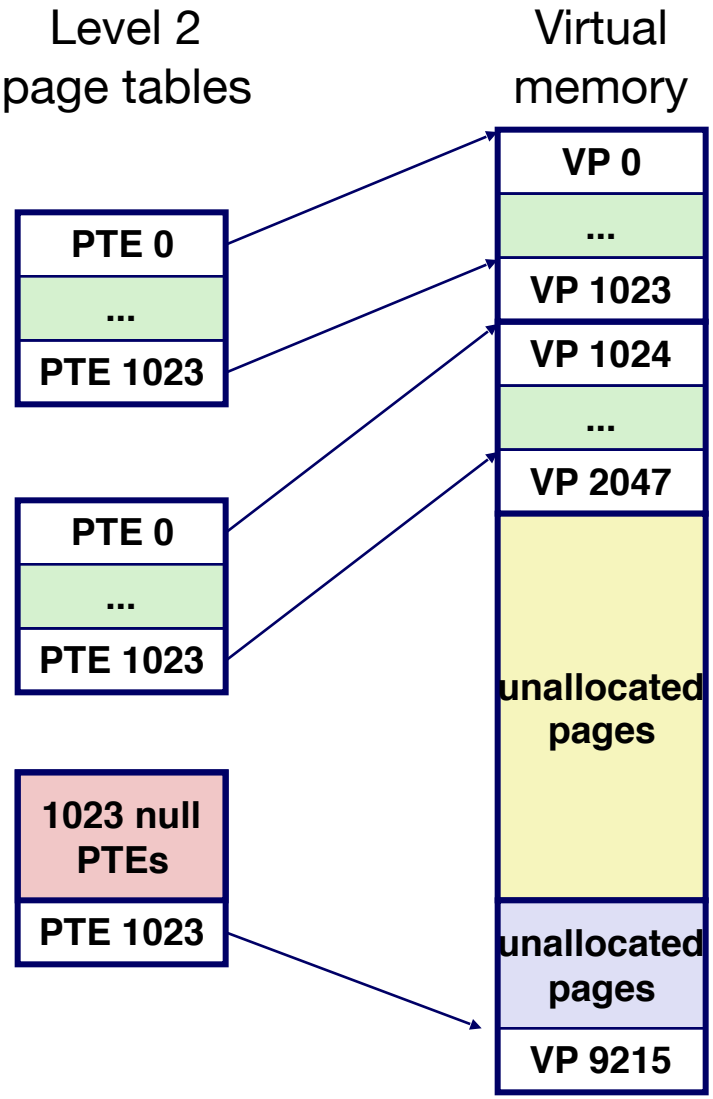

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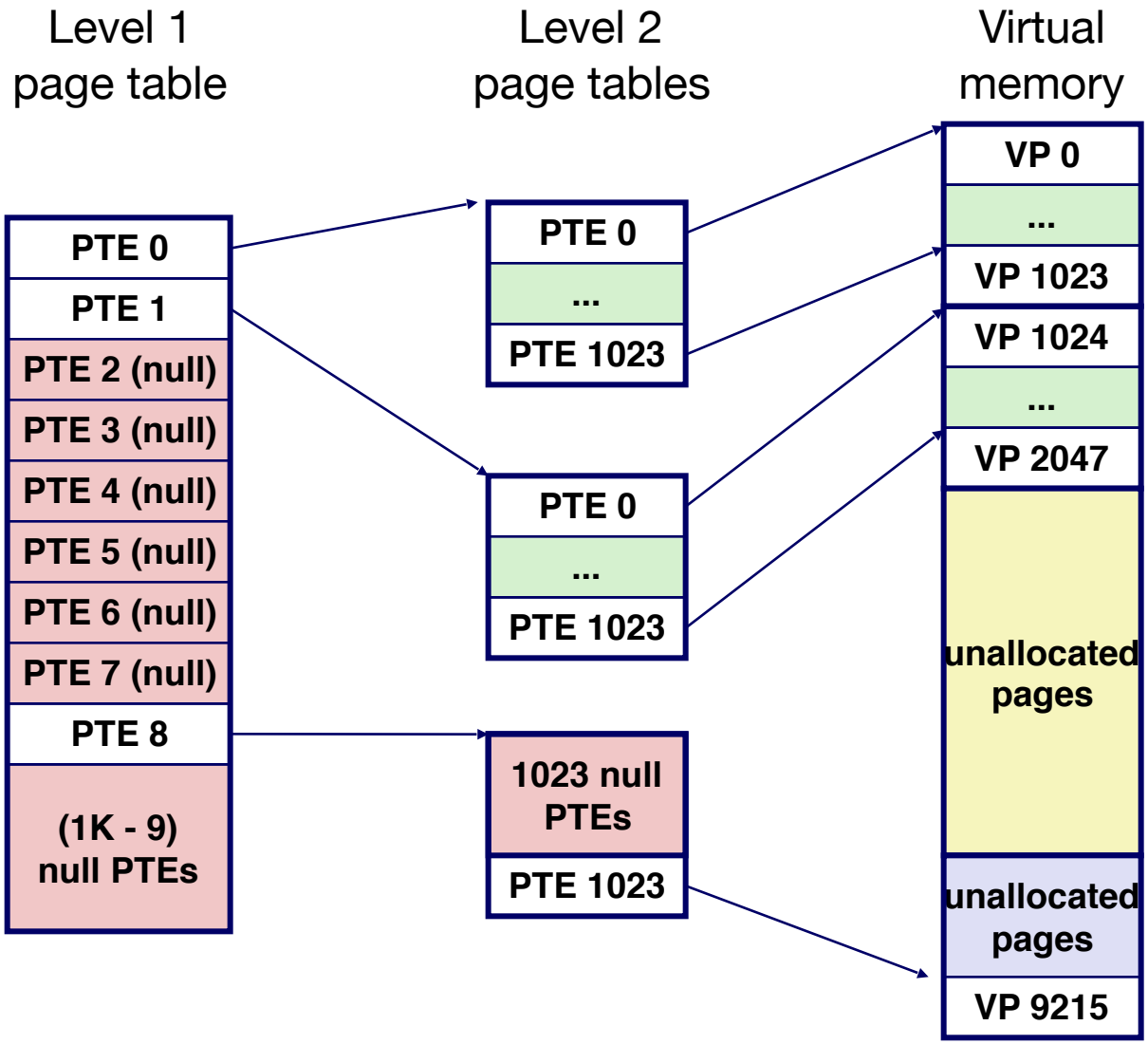

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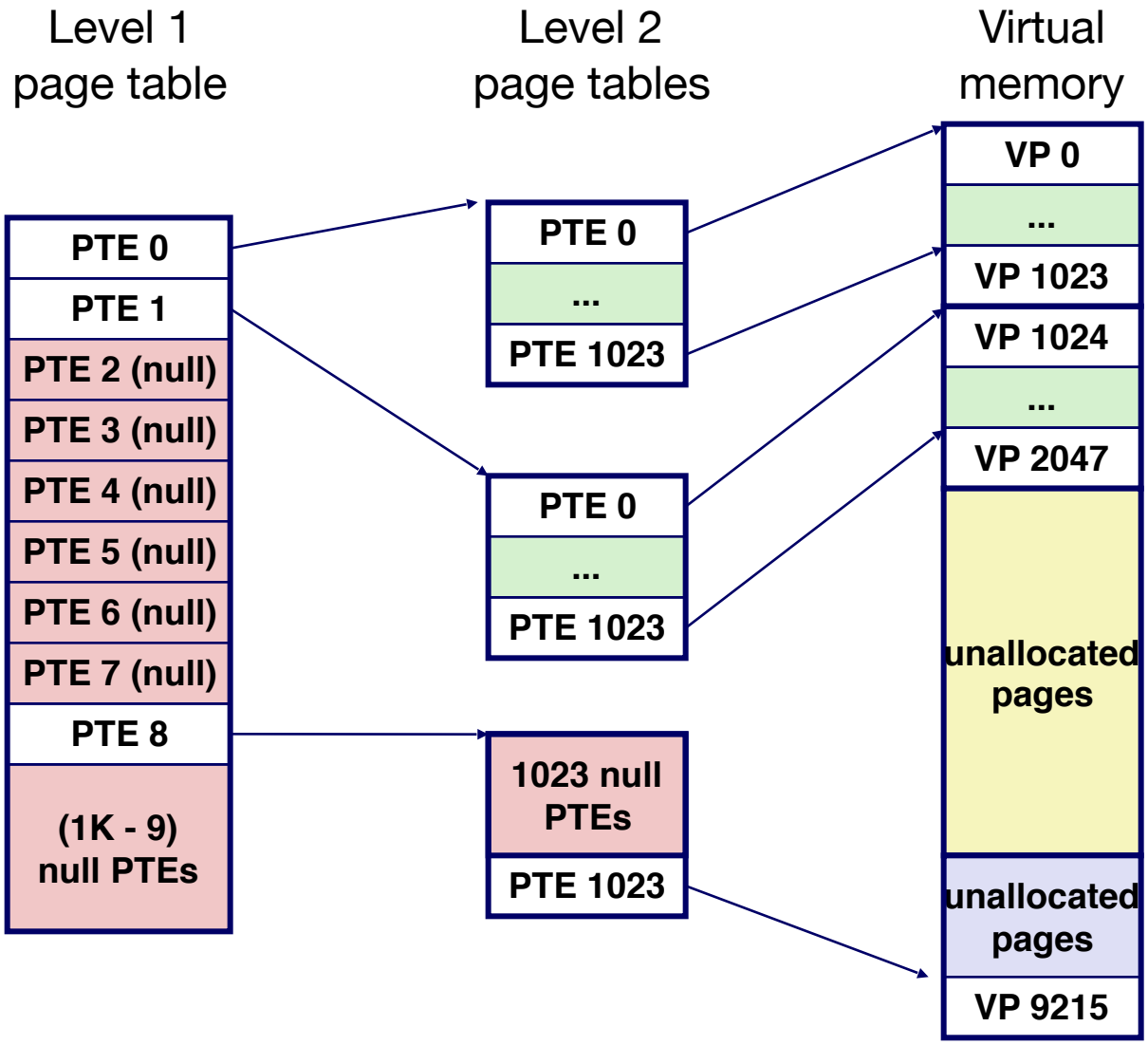

- Level 2 page table size:
  - $2^{32} / 2^{12} * 4 = 4$ MB
- Level 1 page table size:
  - $(2^{32} / 2^{12} * 4) / 2^{12} * 4 = 4$ KB

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

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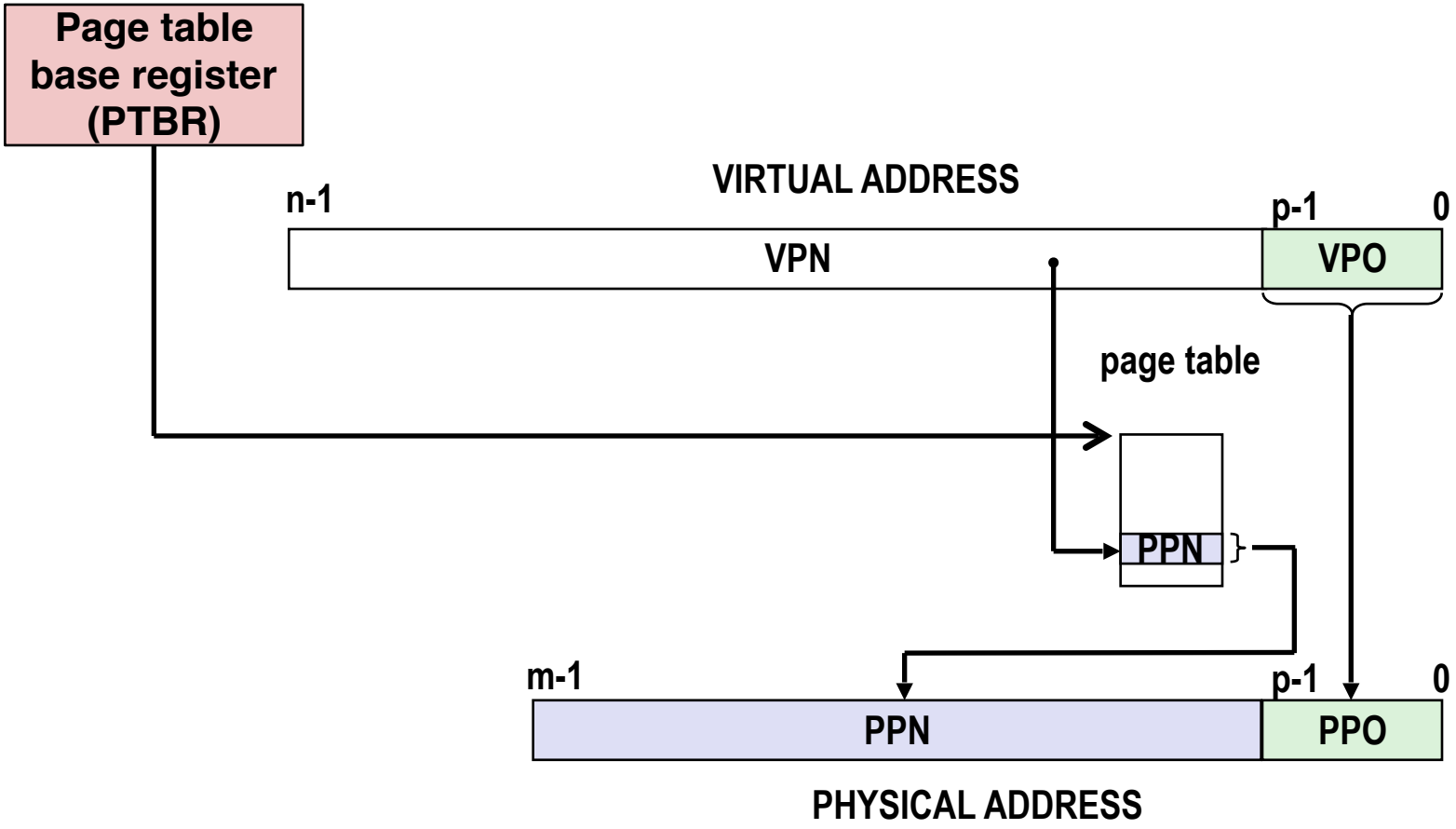
How to Access a 2-Level Page Table?



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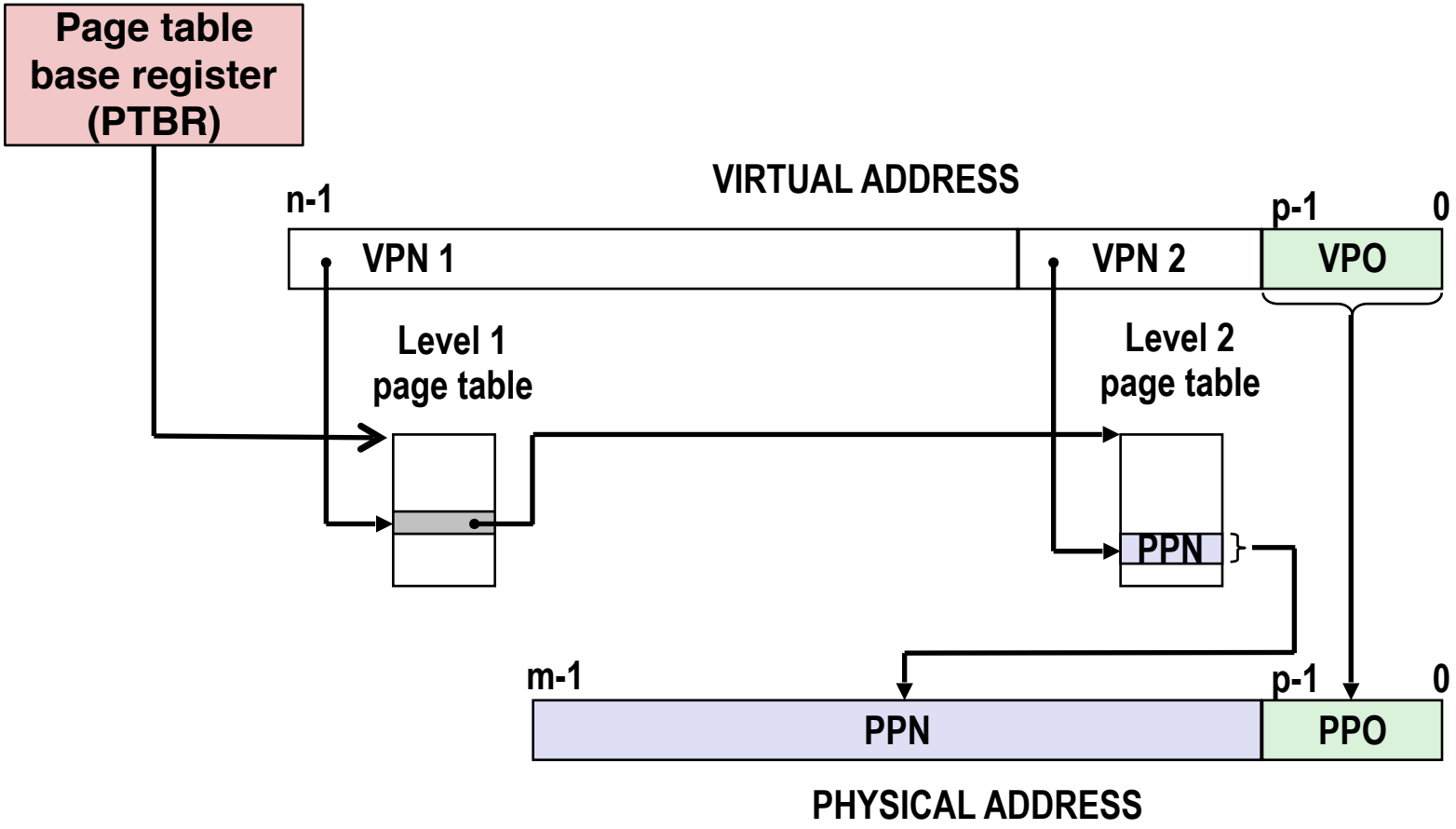
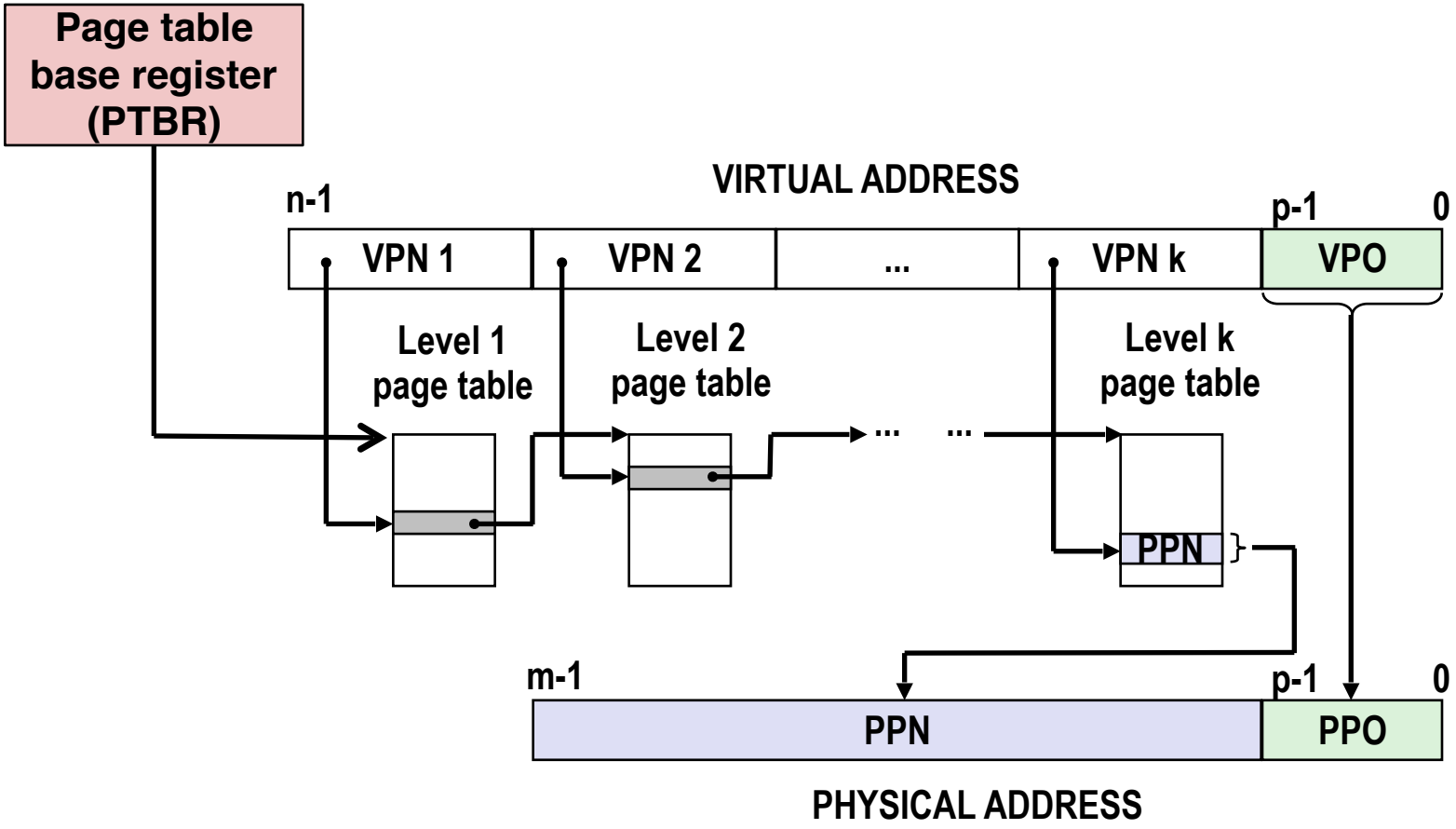


Translating with a k-level Page Table



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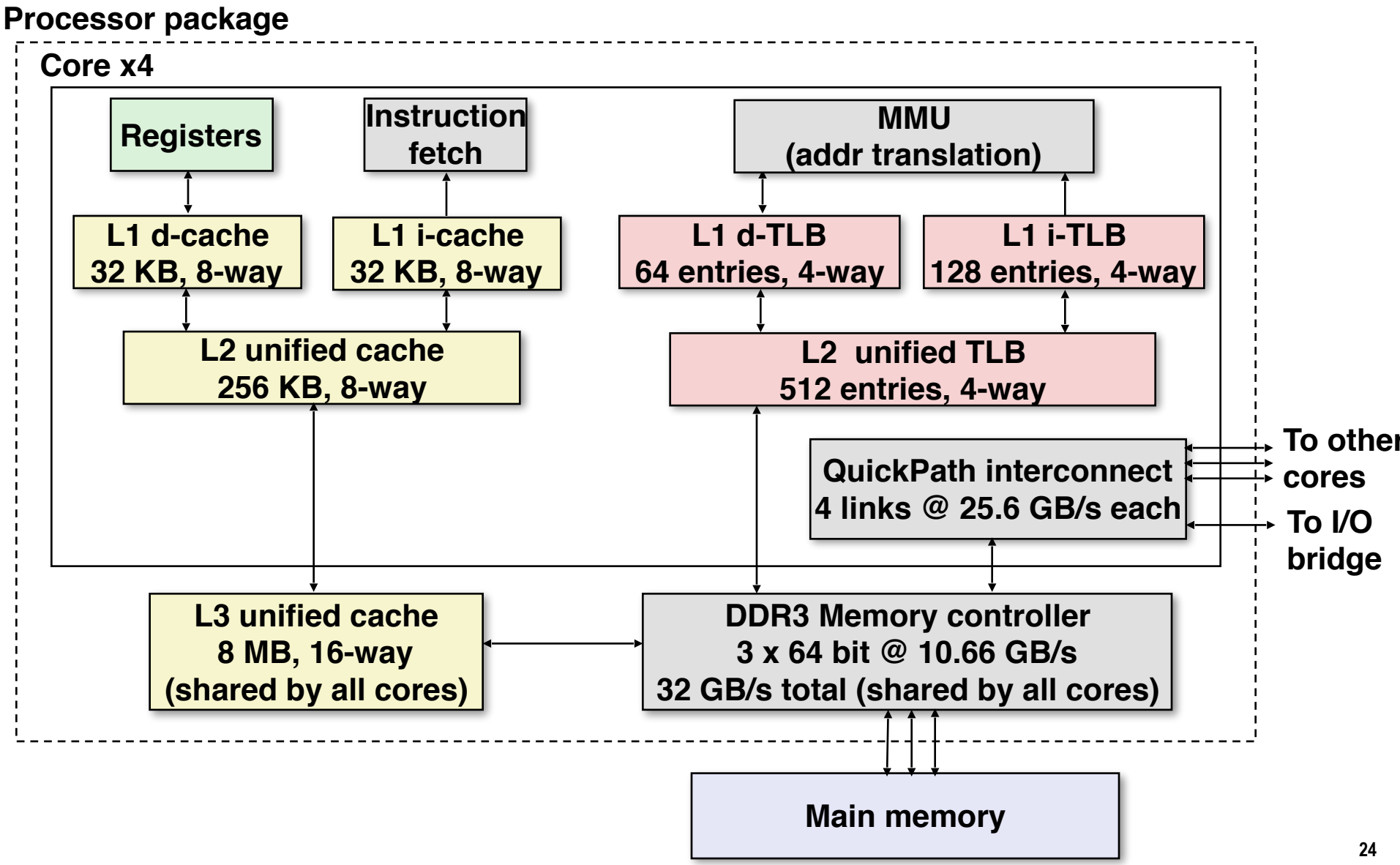
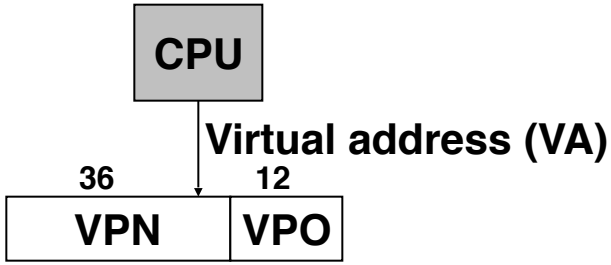
Intel Core i7 Memory System



End-to-End Core i7 Address Translation



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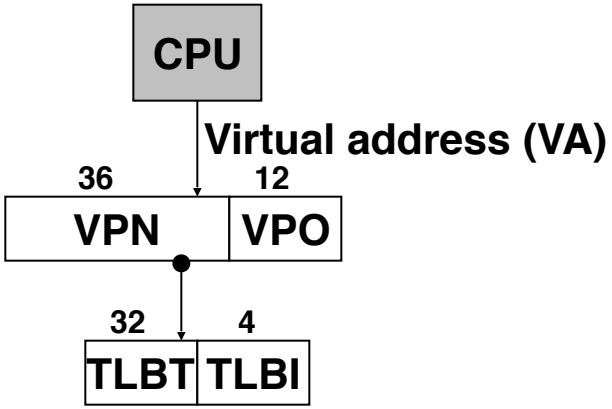

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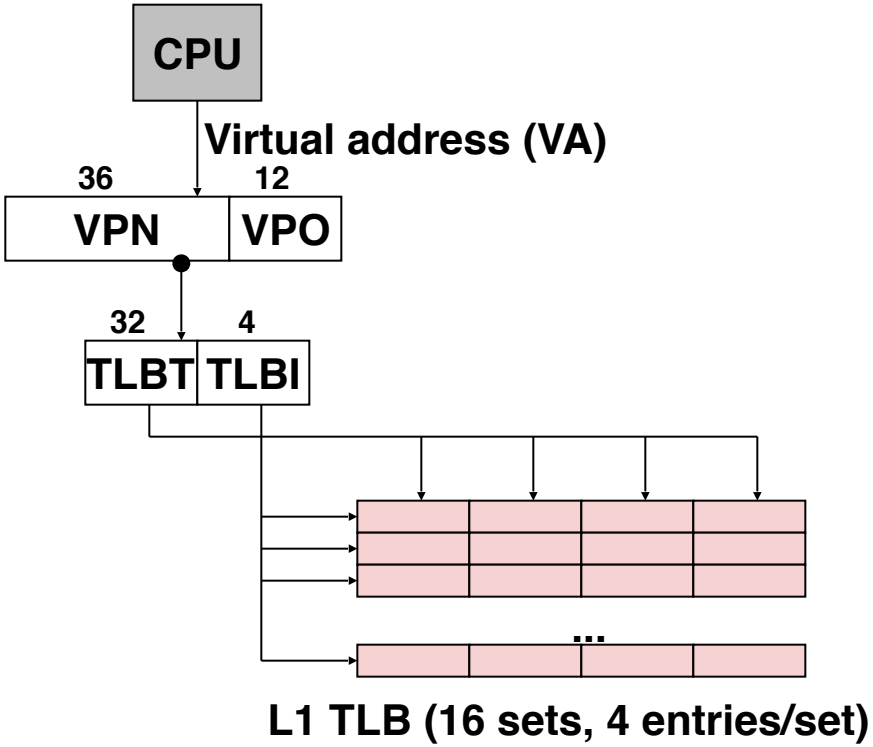

L1 TLB (16 sets, 4 entries/set)

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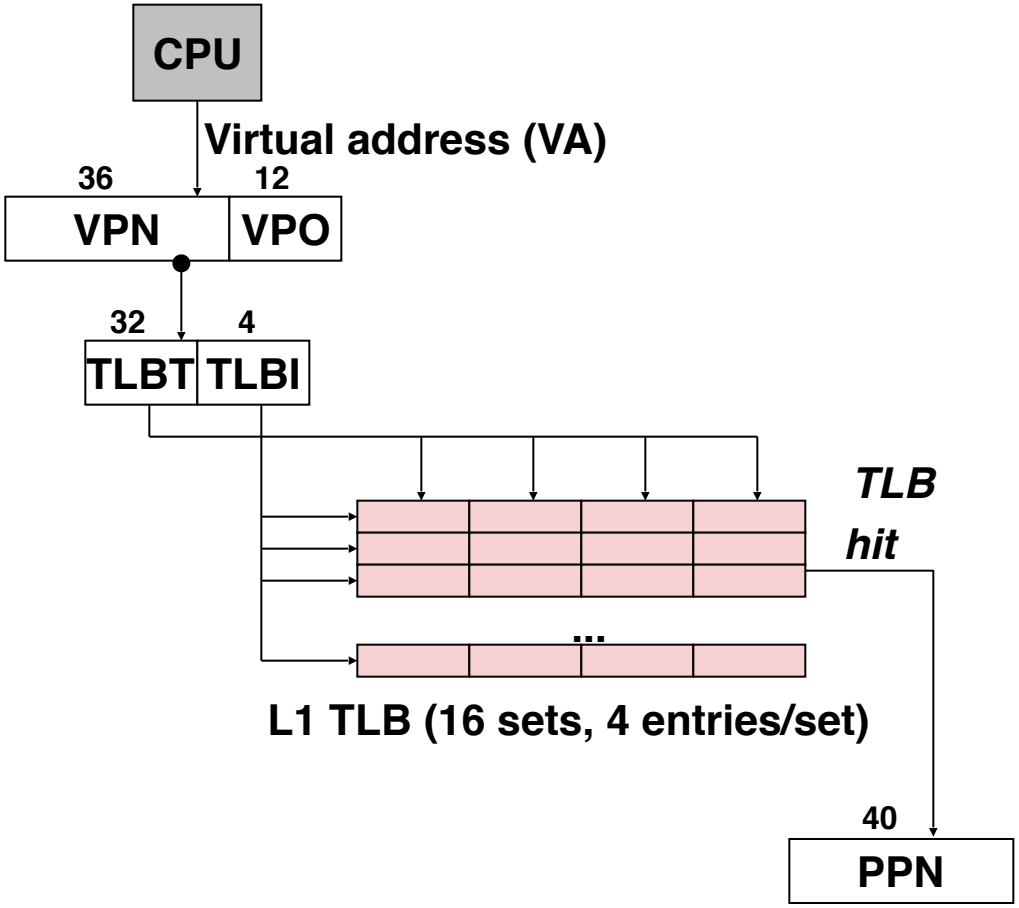

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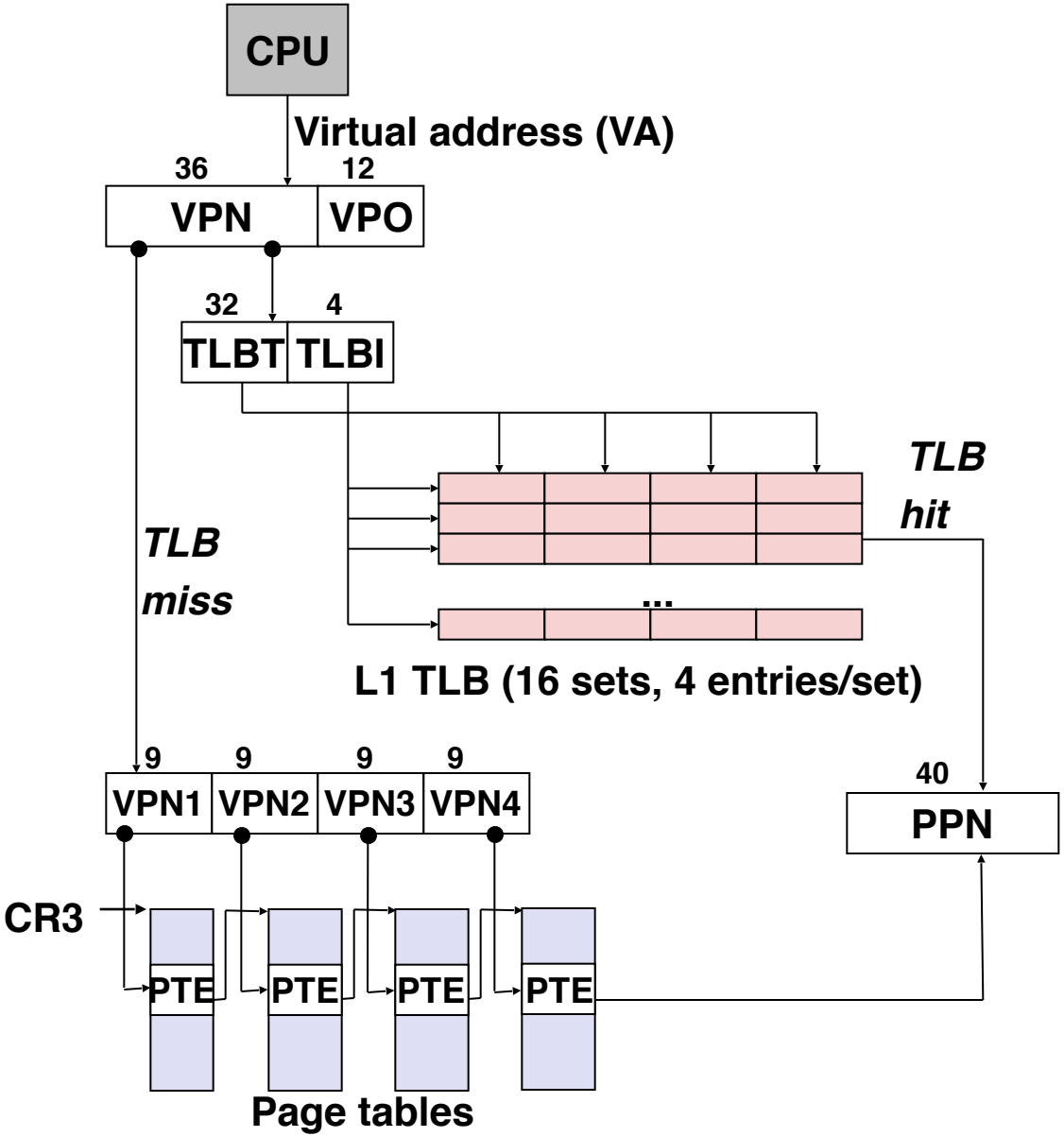

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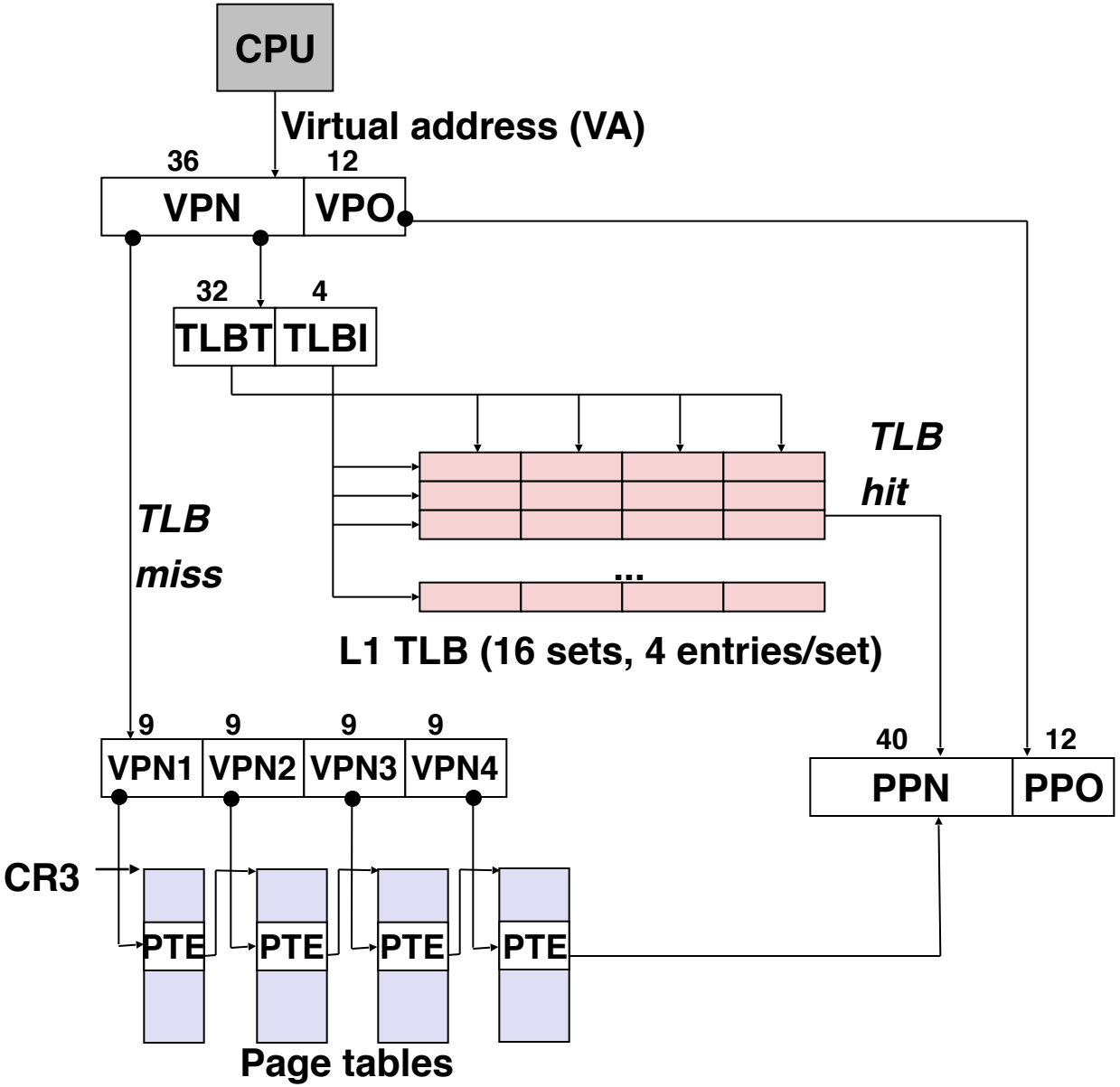

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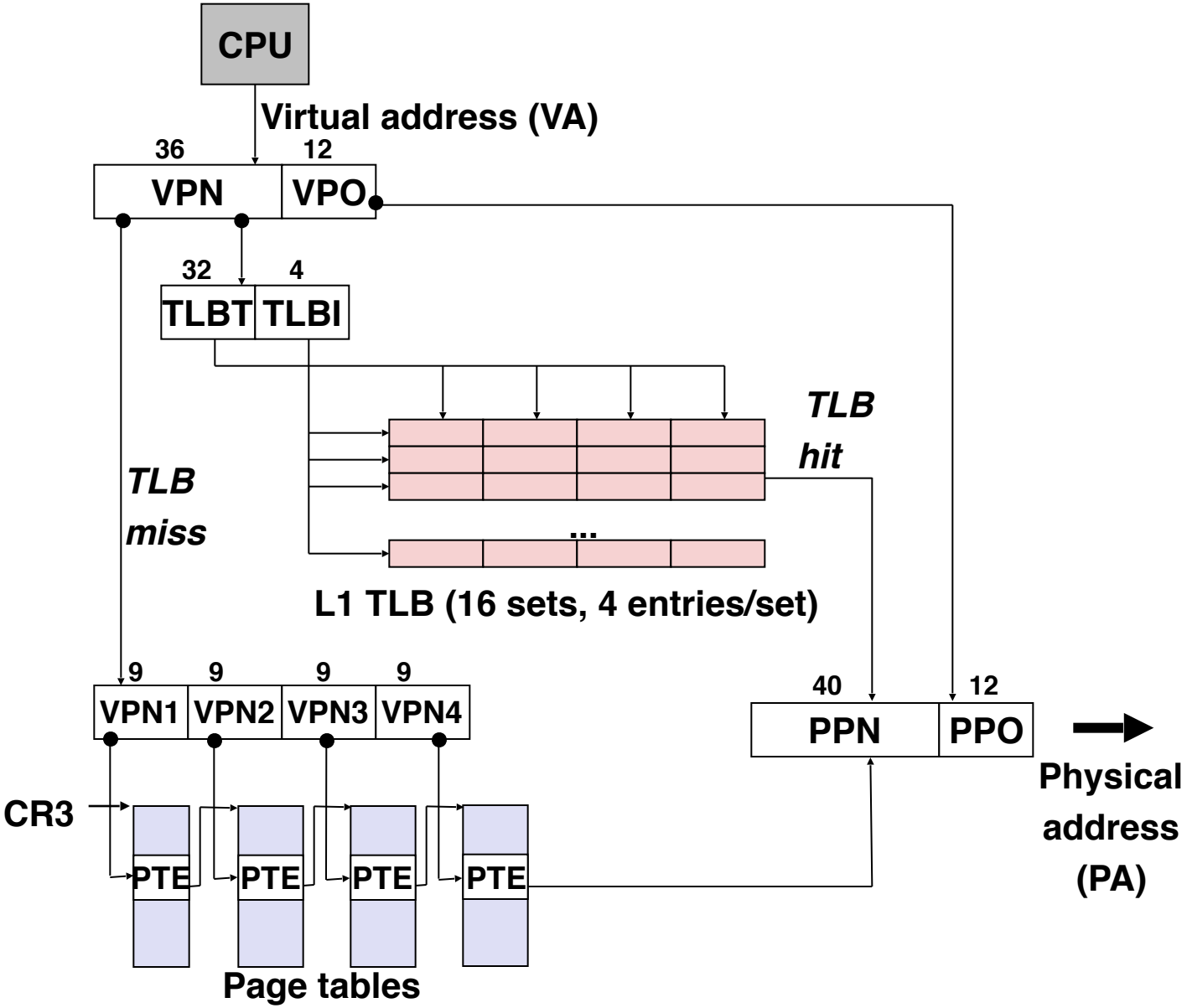

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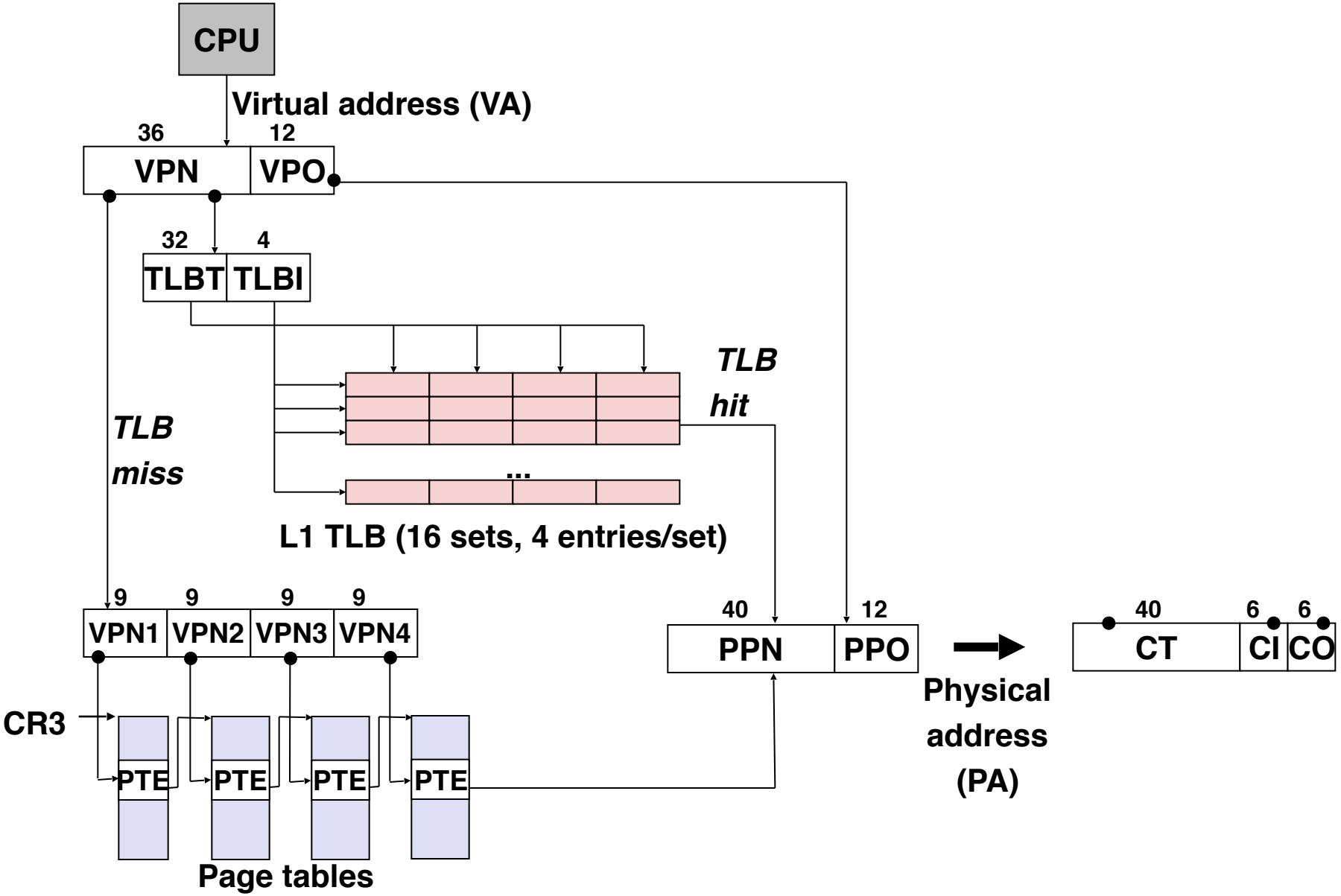

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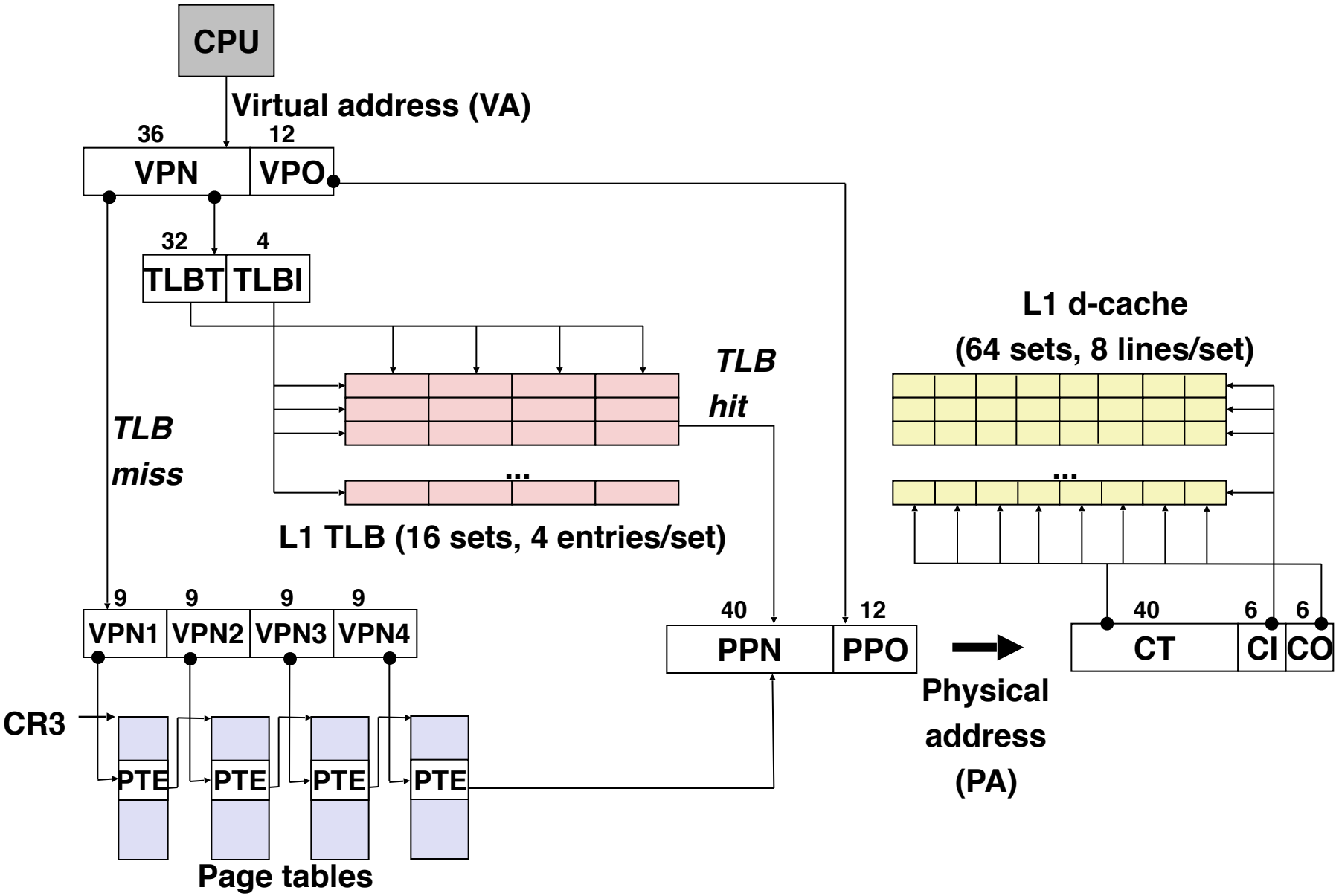

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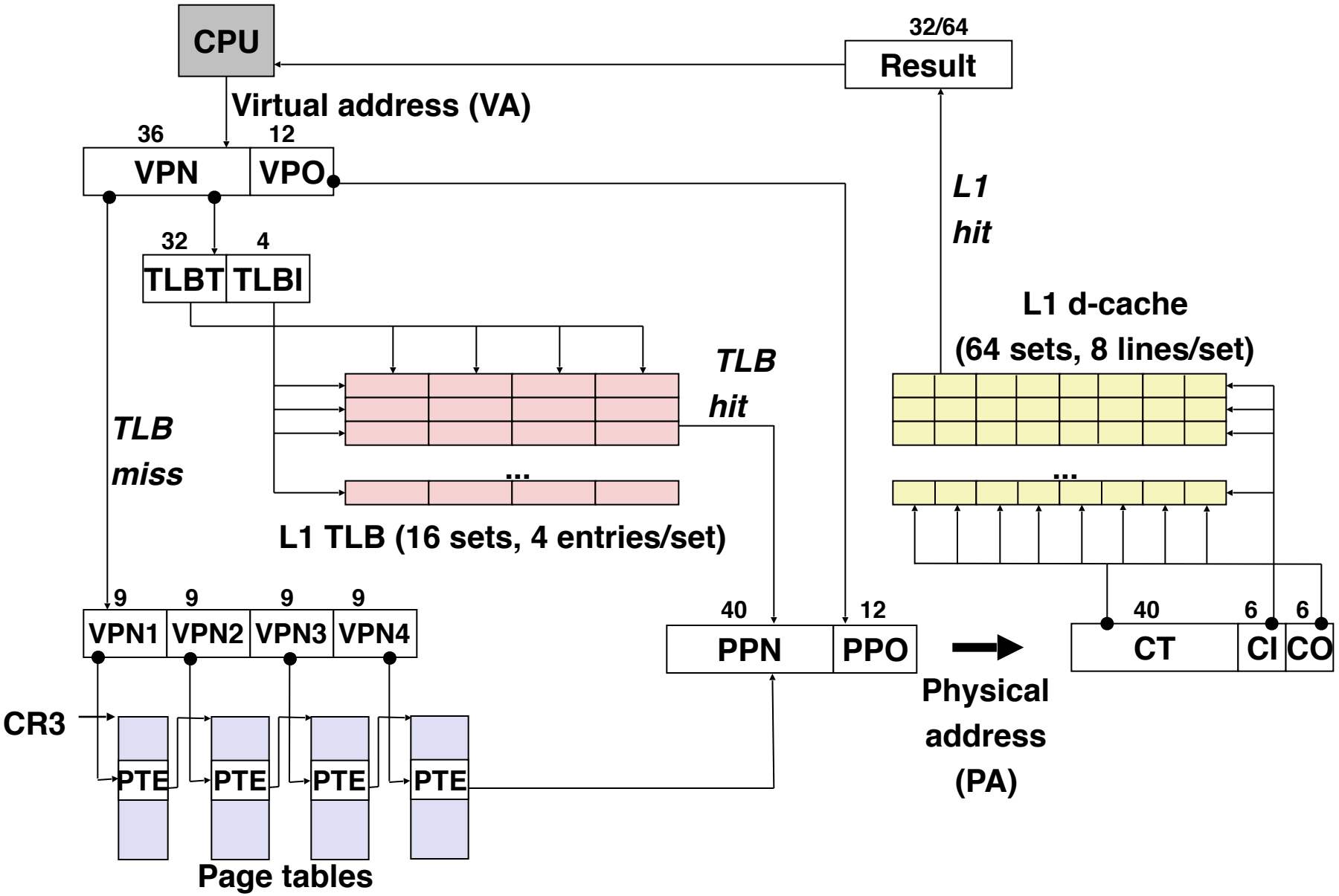

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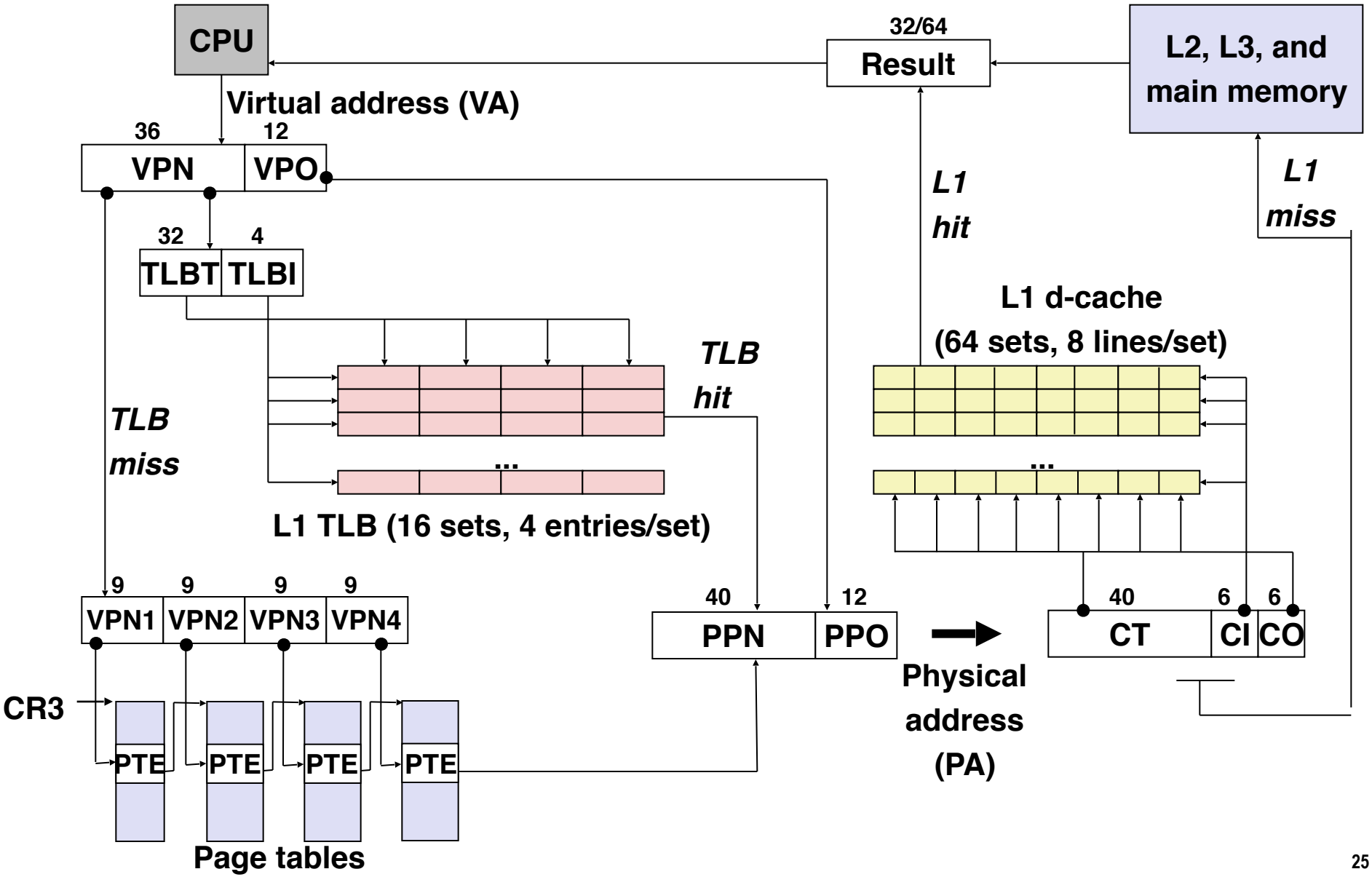
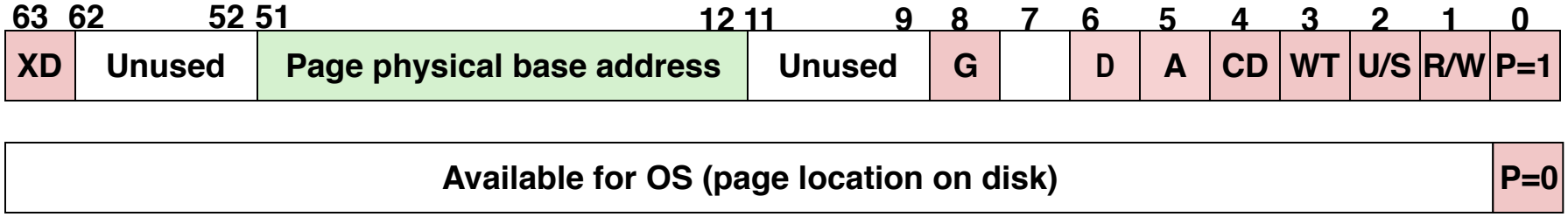


Core i7 Level 4 Page Table Entries



Each entry references a 4K child page. Significant fields:

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

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

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

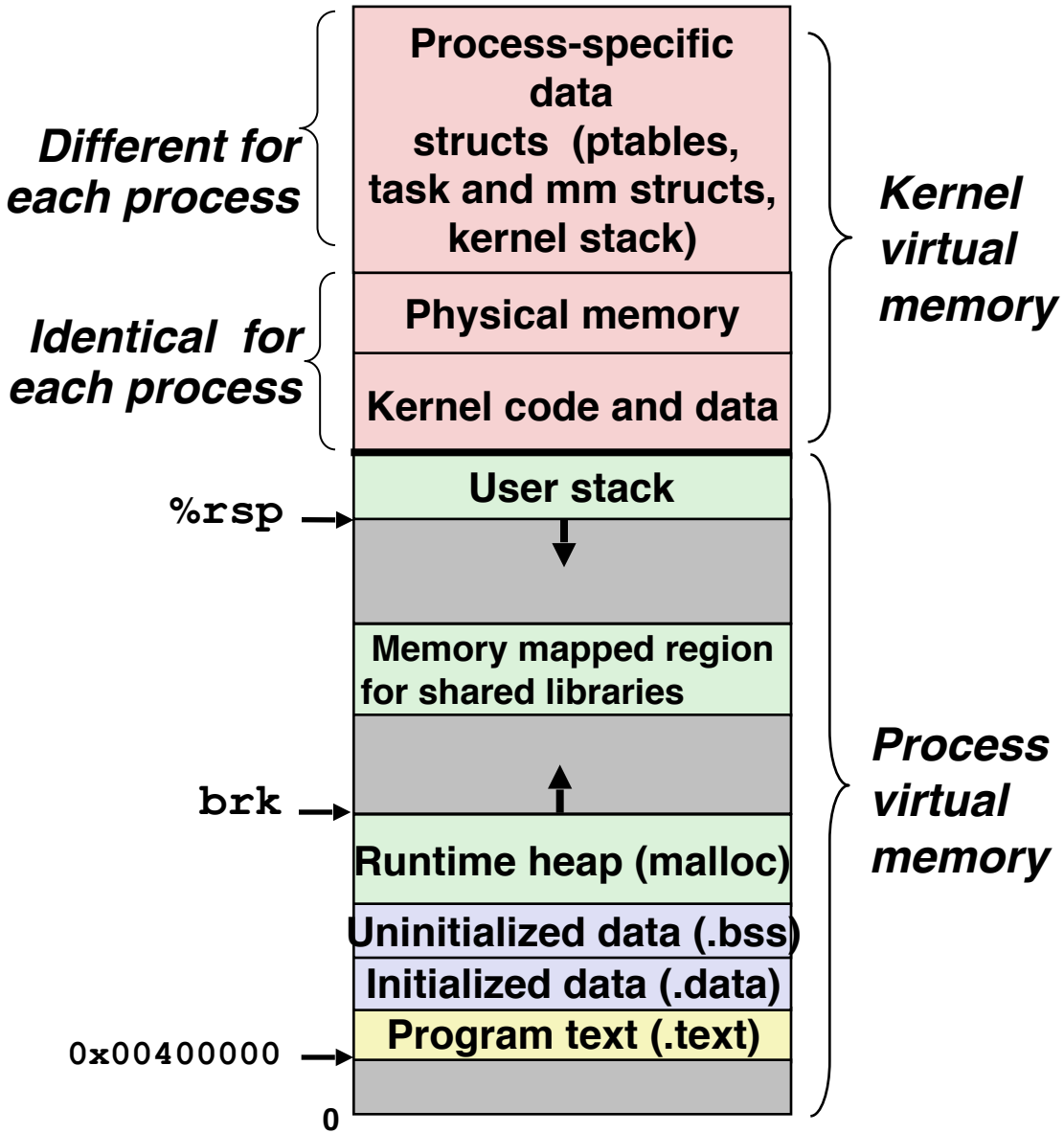
Page physical base address: 40 most significant bits of physical page address (forces pages to be 4KB aligned)

XD: Disable or enable instruction fetches from this page.

Today

- Memory mapping
- Dynamic memory allocation

Virtual Address Space of a Linux Process

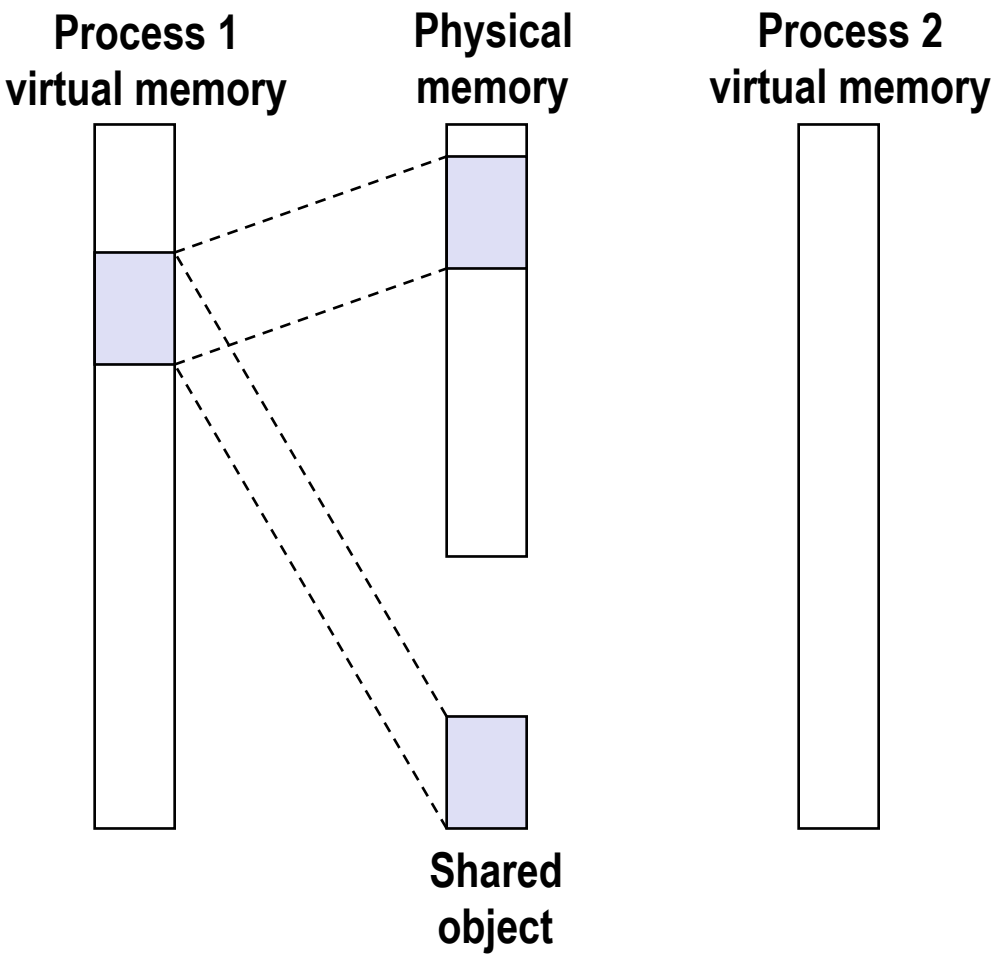


Memory Mapping For Sharing

- Multiple processes often share data
  - Different processes that run the same code (e.g., shell)
  - Different processes linked to the same standard libraries
  - Different processes share the same file
- It is wasteful to create exact copies of the share object
- Memory mapping allow us to easily share objects
  - Different VM pages point to the same physical page/object

Sharing Revisited: Shared Objects

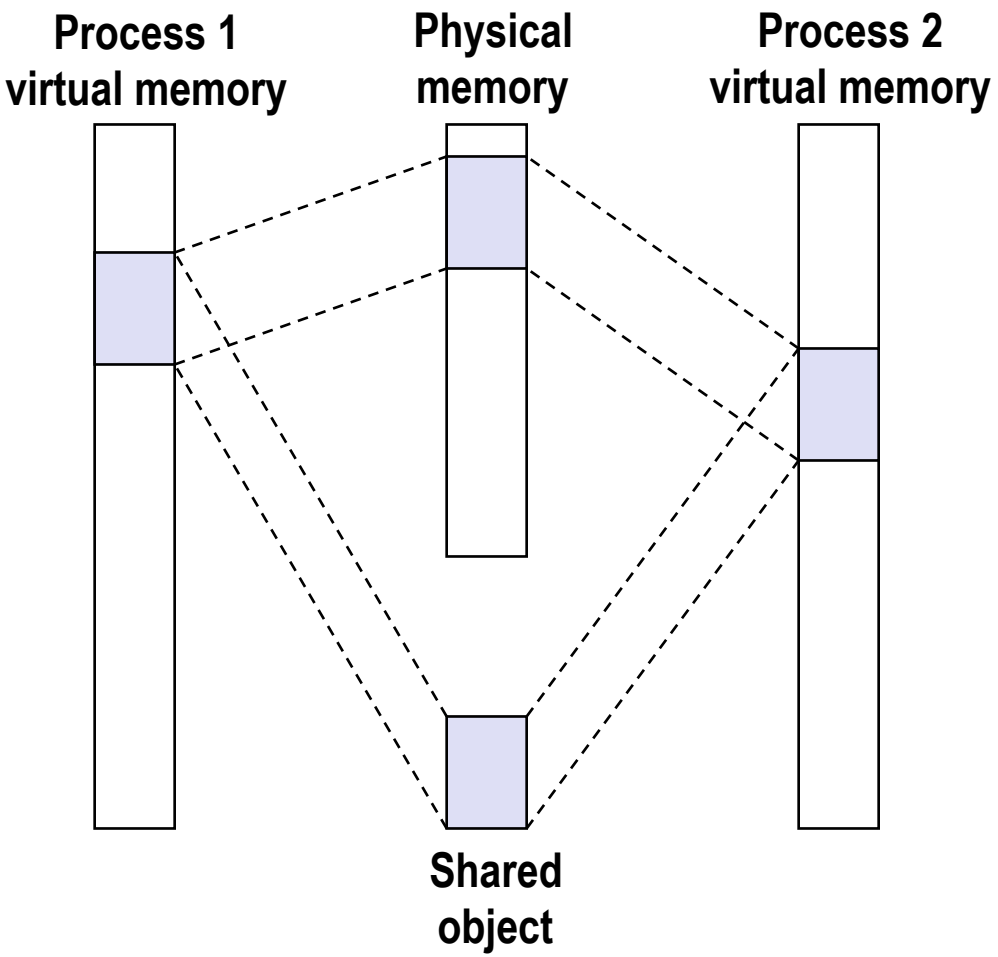
- Process 1 maps the shared object.



- The kernel remembers that the object (backed by a unique file) is mapped by Proc. 1 to some physical pages.

Sharing Revisited: Shared Objects

- Process 2 maps the shared object.



- The kernel remembers that the object (backed by a unique file) is mapped by Proc. 1 to some physical pages.
- Now when Proc. 2 wants to access the same object, the kernel can simply point the PTEs of Proc. 2 to the already-mapped physical pages.

The Problem…

- What if Proc. 1 now wants to modify the shared object, but doesn’t want the modification to be visible to Proc. 2

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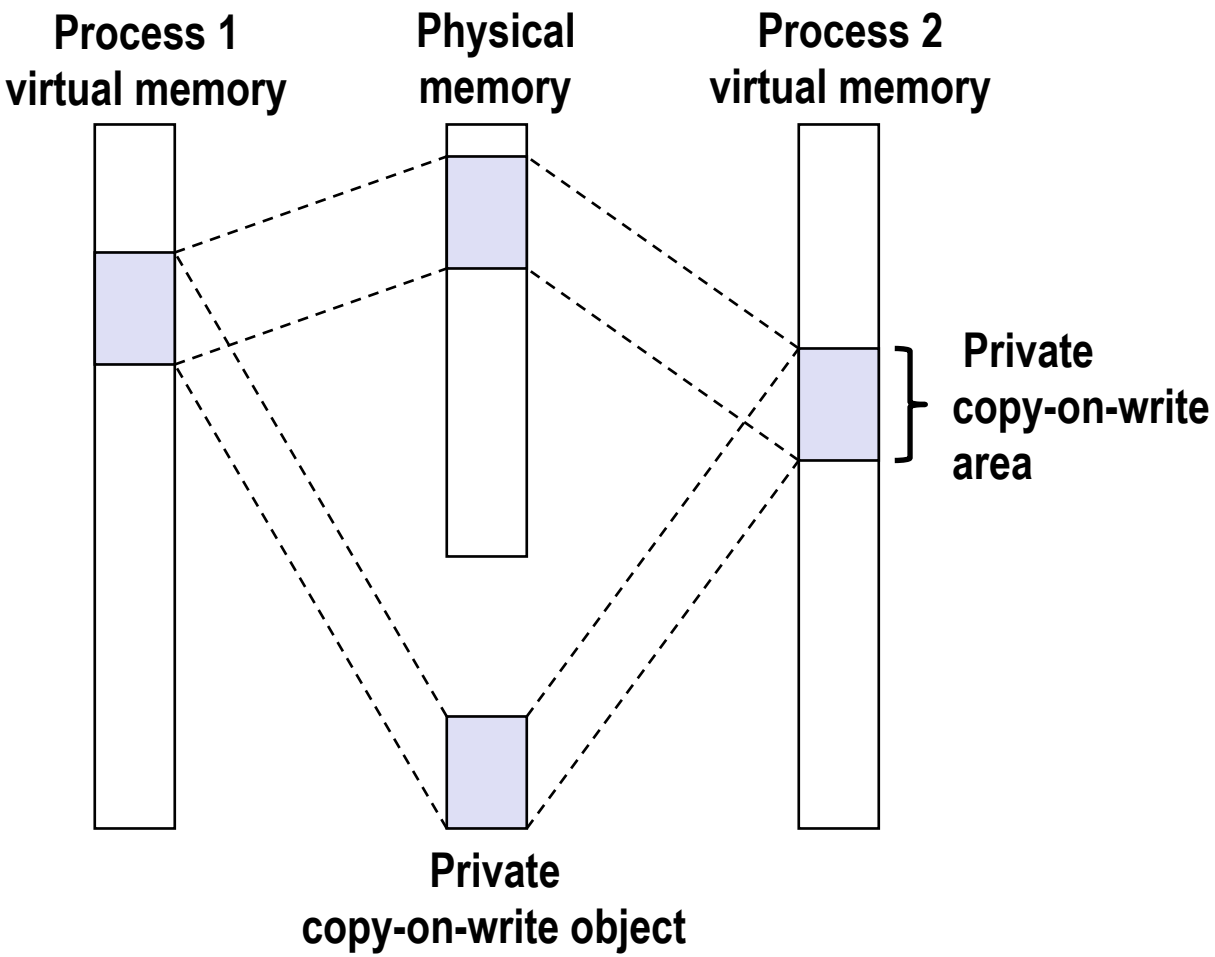
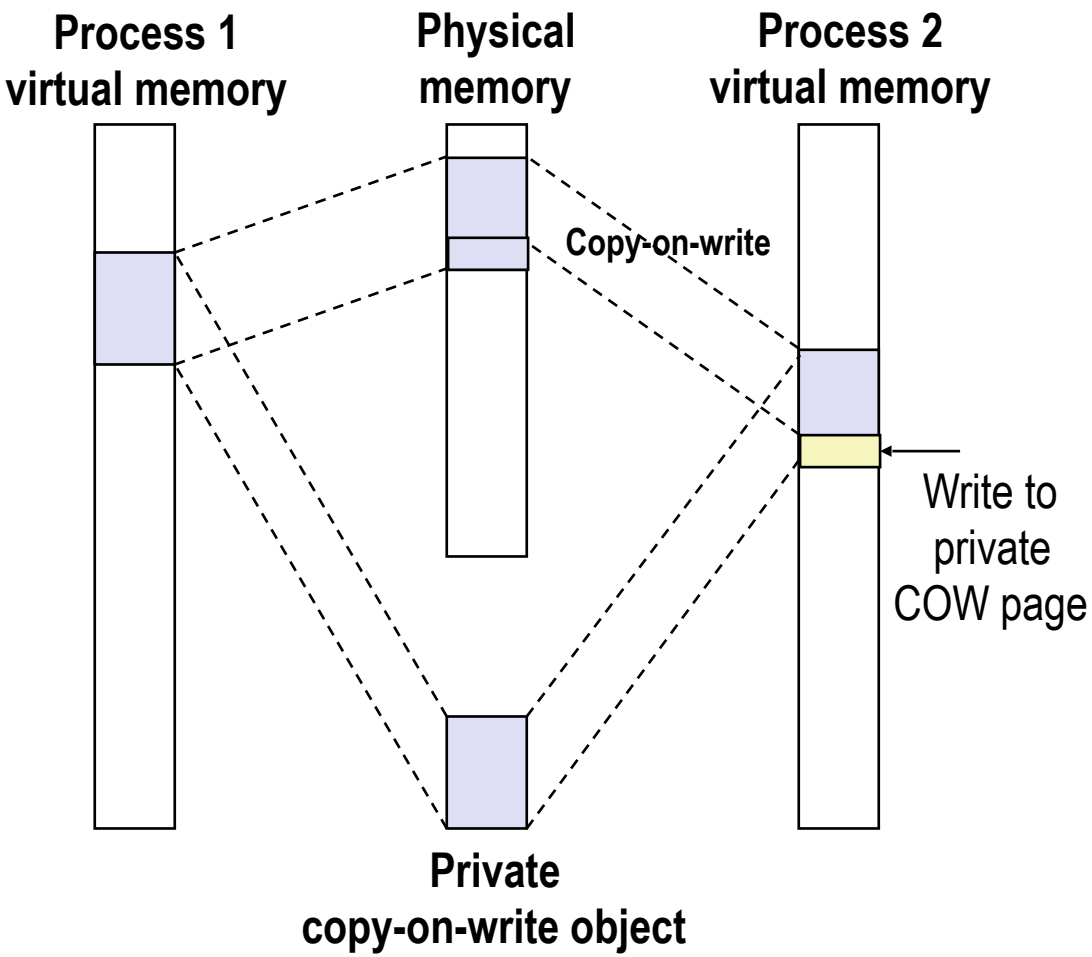
- Simplest solution: always create duplicate copies of shared objects at the cost of wasting space. Not ideal.
- Idea: Copy-on-write (COW)
  - First pretend that both processes will share the objects without modifying them. If modification happens, create separate copies.

Private Copy-on-write (COW) Objects



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

Private Copy-on-write (COW) Objects



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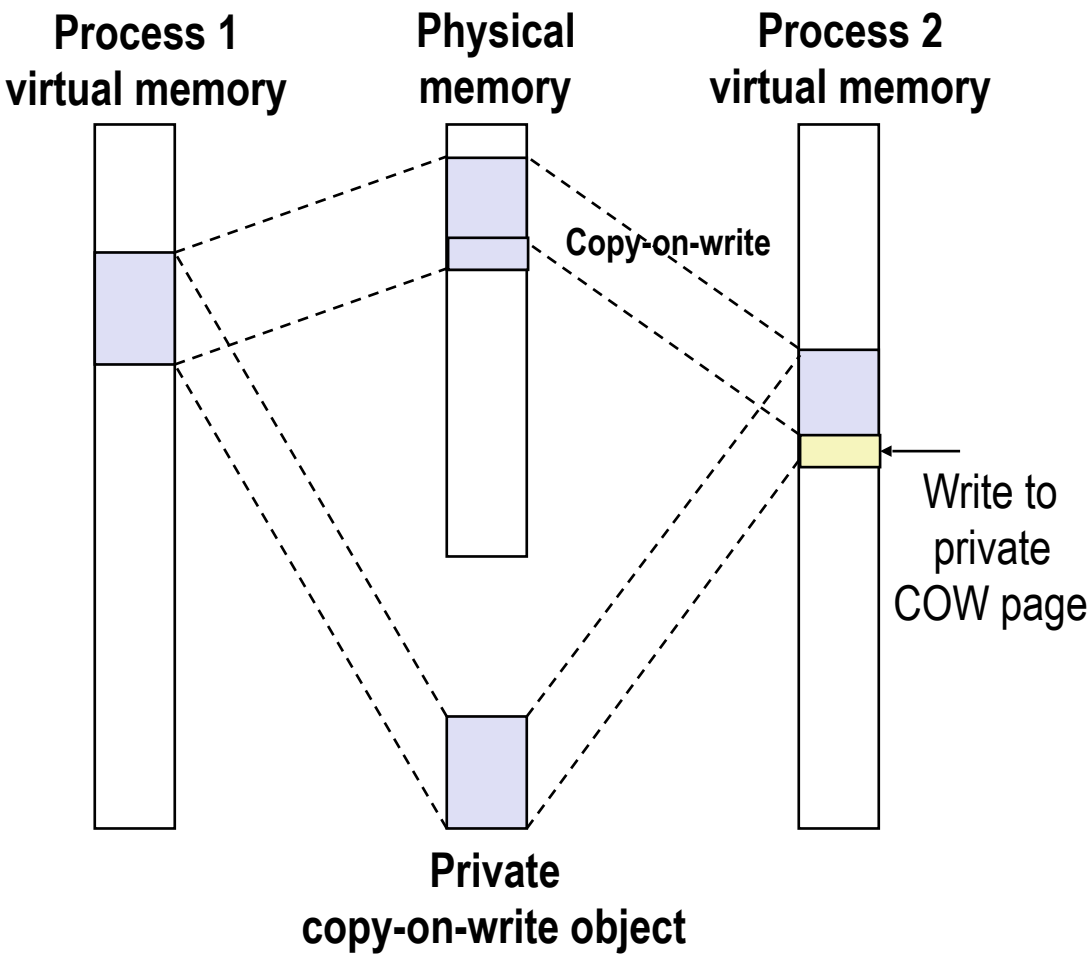

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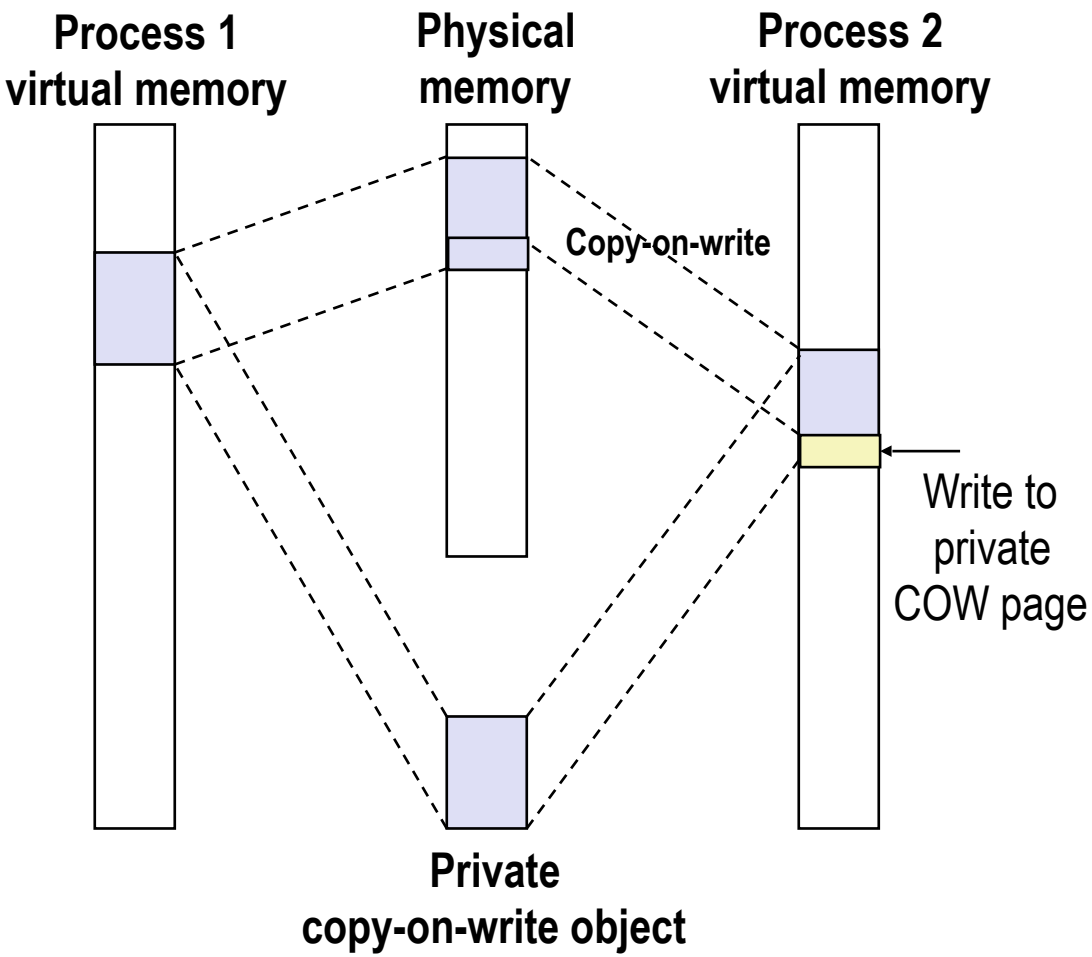

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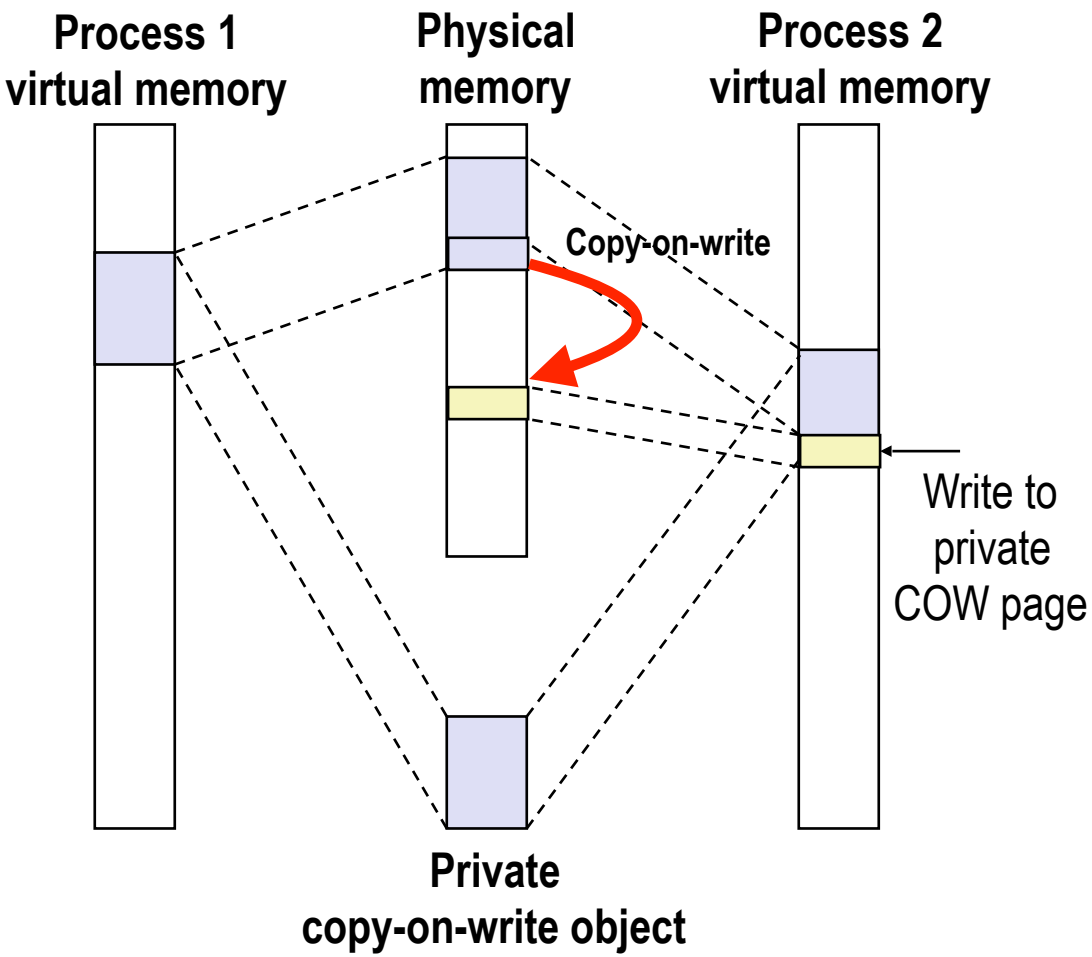

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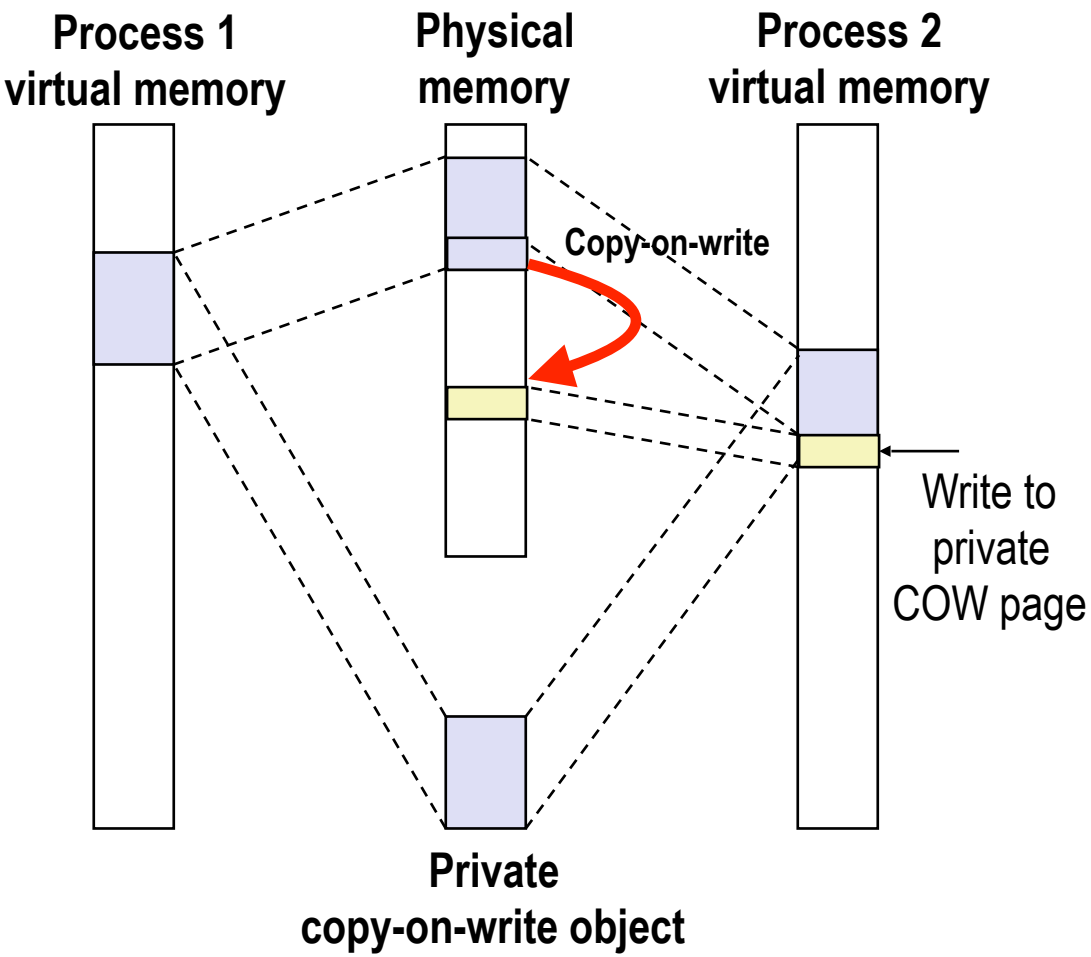

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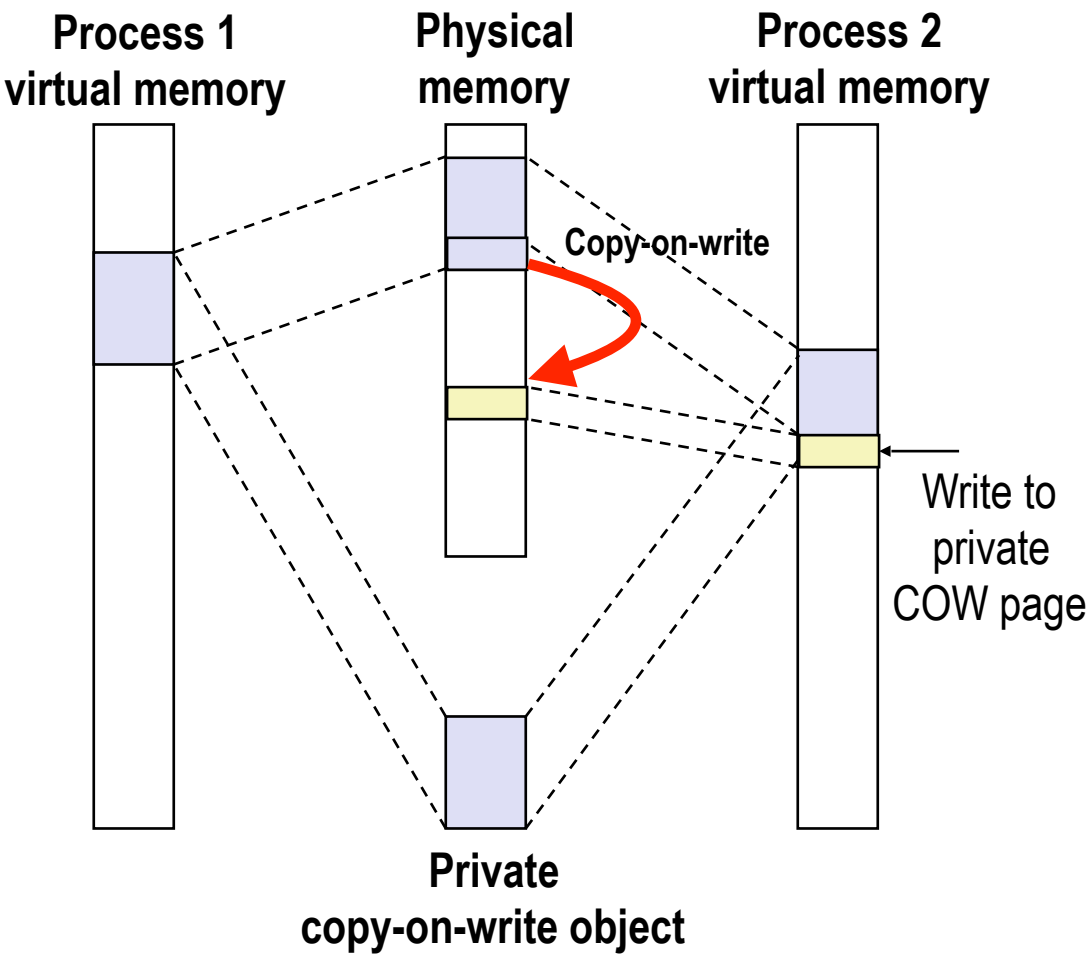

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- Instruction restarts upon handler return.
- Copying deferred as long as possible!

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 NULL for “pick an address”
  - `prot`: PROT_READ, PROT_WRITE, ...
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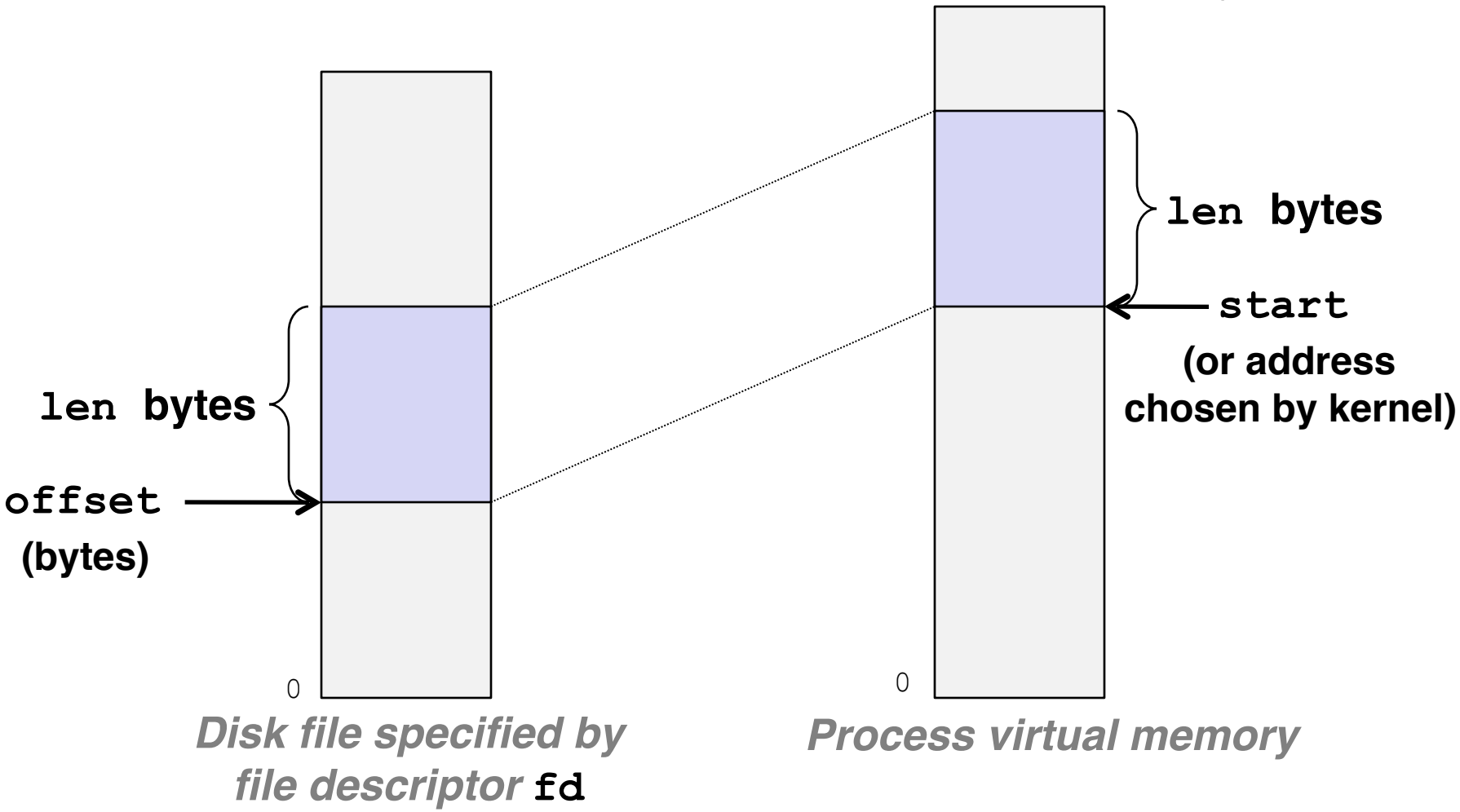

Example: Using `mmap` to Copy Files

- Copying a file to stdout without transferring data to user space
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```c
#include "csapp.h"

void mmapcopy(int fd, int size)
{

    /* Ptr to memory mapped area */
    char *bufp;

    bufp = mmap(NULL, size,
                PROT_READ,
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    Write(1, bufp, size);
    return;
}
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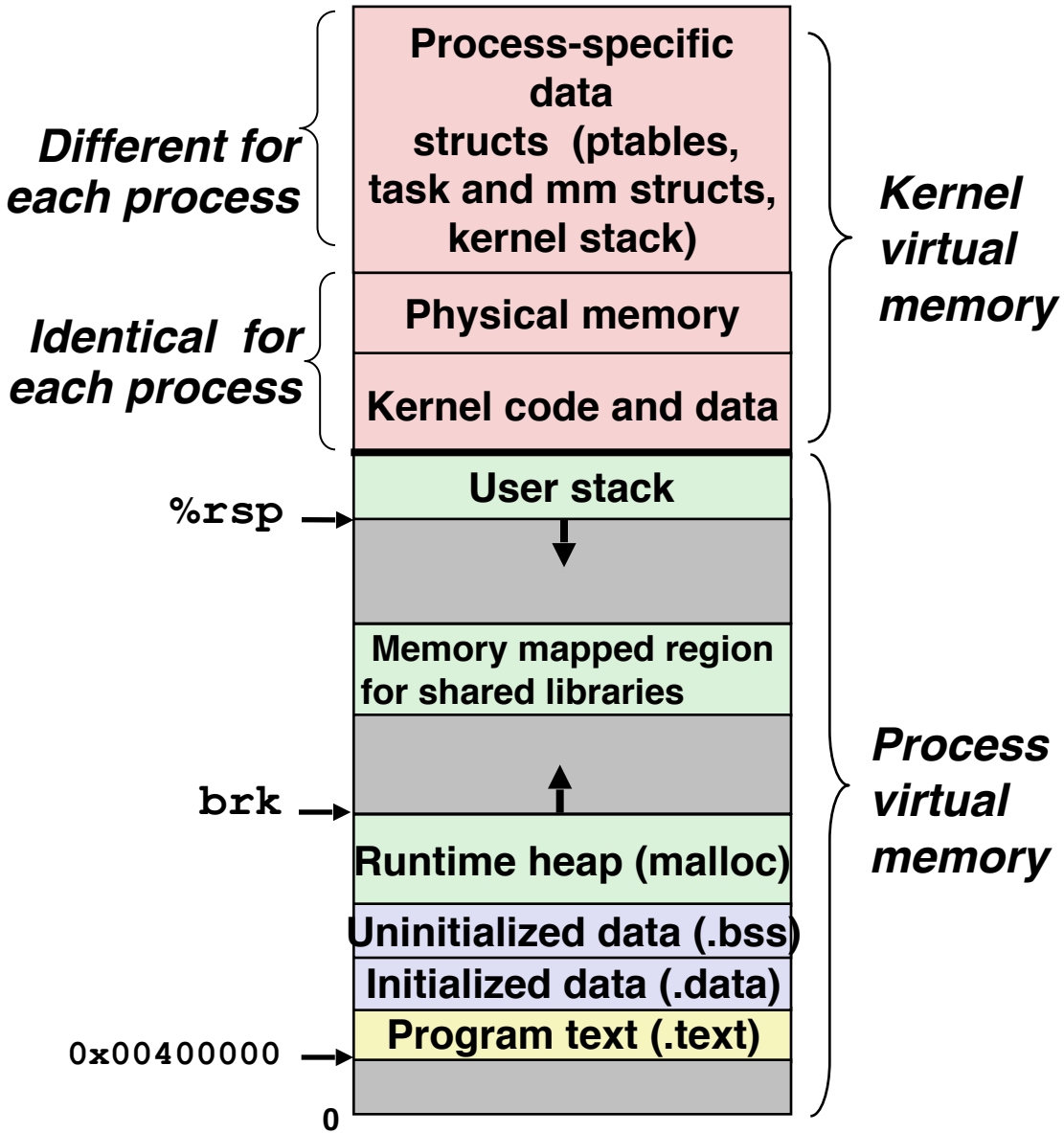
```c
/* mmapcopy driver */
int main(int argc, char **argv)
{
    struct stat stat;
    int fd;

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

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

mmapcopy.c

Today

- Memory mapping
- Dynamic memory allocation

Virtual Address Space of a Linux Process

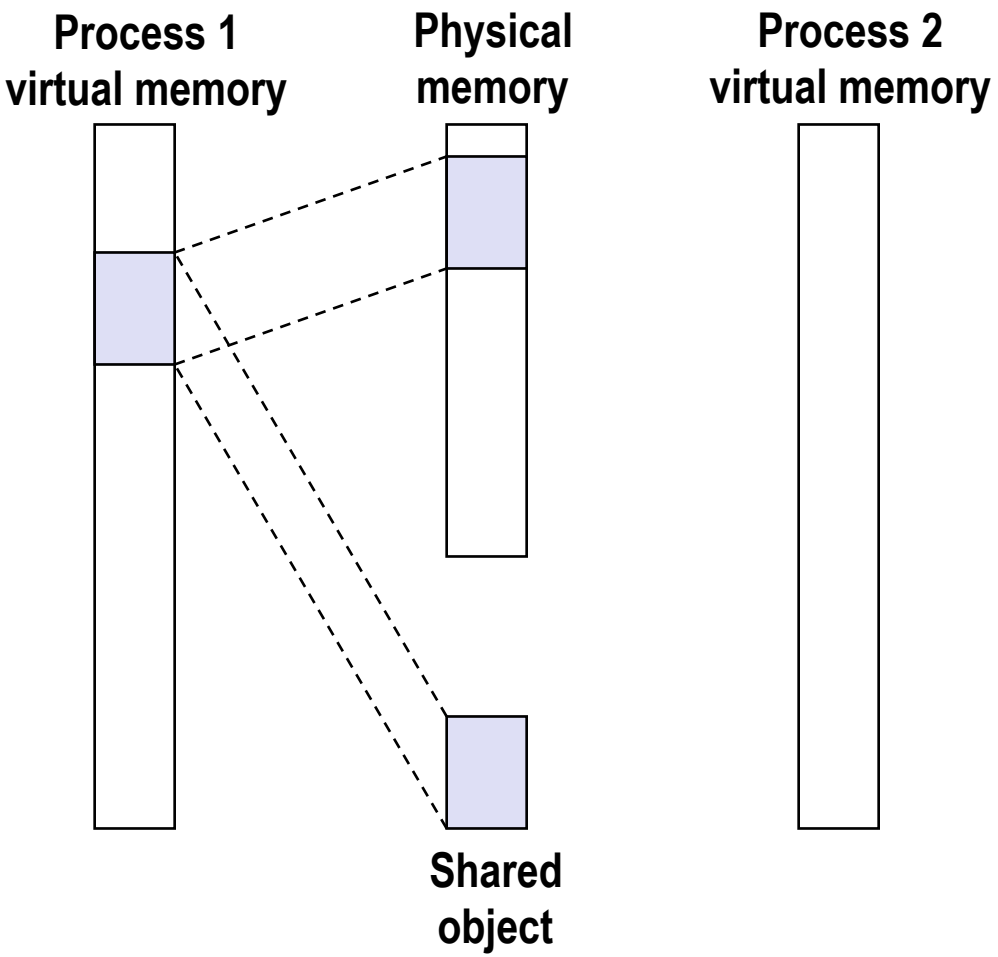


Memory Mapping For Sharing

- Multiple processes often share data
  - Different processes that run the same code (e.g., shell)
  - Different processes linked to the same standard libraries
  - Different processes share the same file
- It is wasteful to create exact copies of the share object
- Memory mapping allow us to easily share objects
  - Different VM pages point to the same physical page/object

Sharing Revisited: Shared Objects

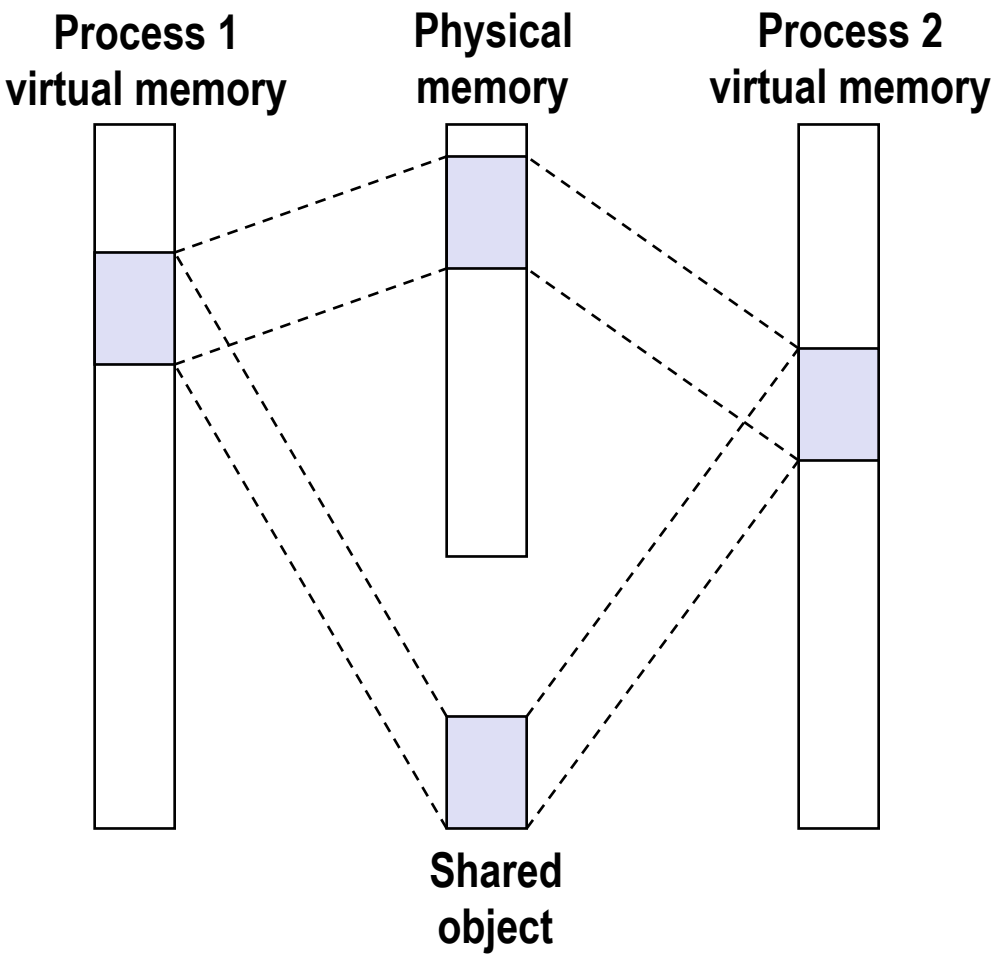
- Process 1 maps the shared object.



- The kernel remembers that the object (backed by a unique file) is mapped by Proc. 1 to some physical pages.

Sharing Revisited: Shared Objects

- Process 2 maps the shared object.



- The kernel remembers that the object (backed by a unique file) is mapped by Proc. 1 to some physical pages.
- Now when Proc. 2 wants to access the same object, the kernel can simply point the PTEs of Proc. 2 to the already-mapped physical pages.

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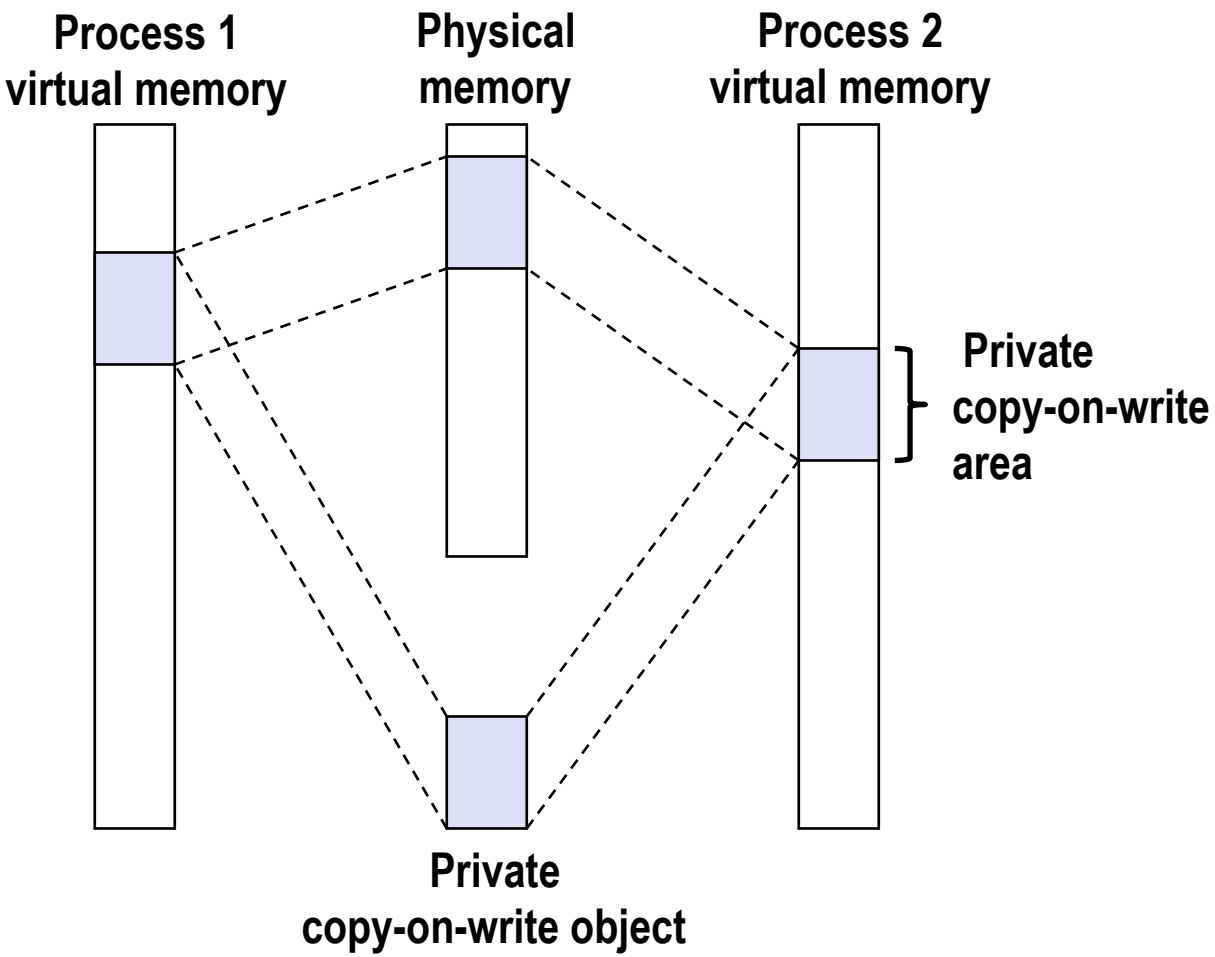
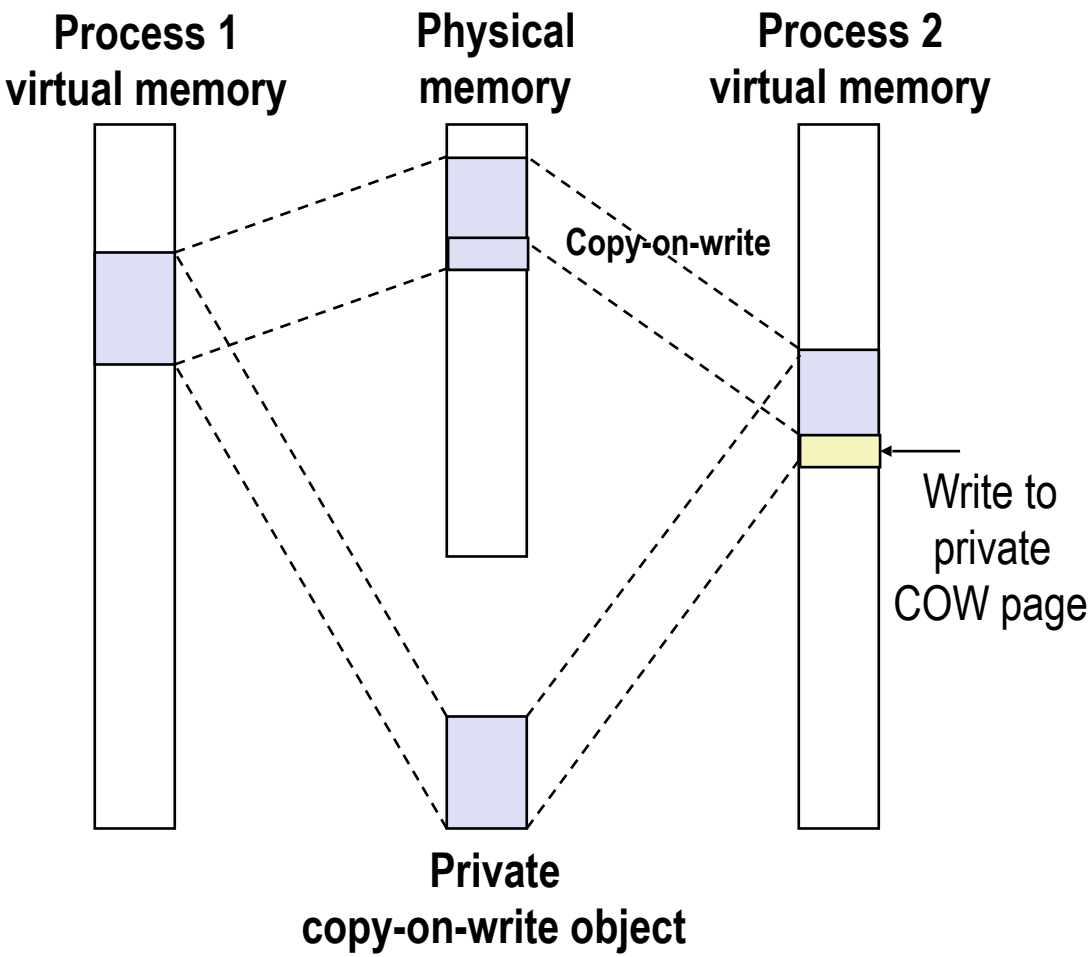
- Simplest solution: always create duplicate copies of shared objects at the cost of wasting space. Not ideal.
- Idea: Copy-on-write (COW)
  - First pretend that both processes will share the objects without modifying them. If modification happens, create separate copies.

Private Copy-on-write (COW) Objects



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

Private Copy-on-write (COW) Objects



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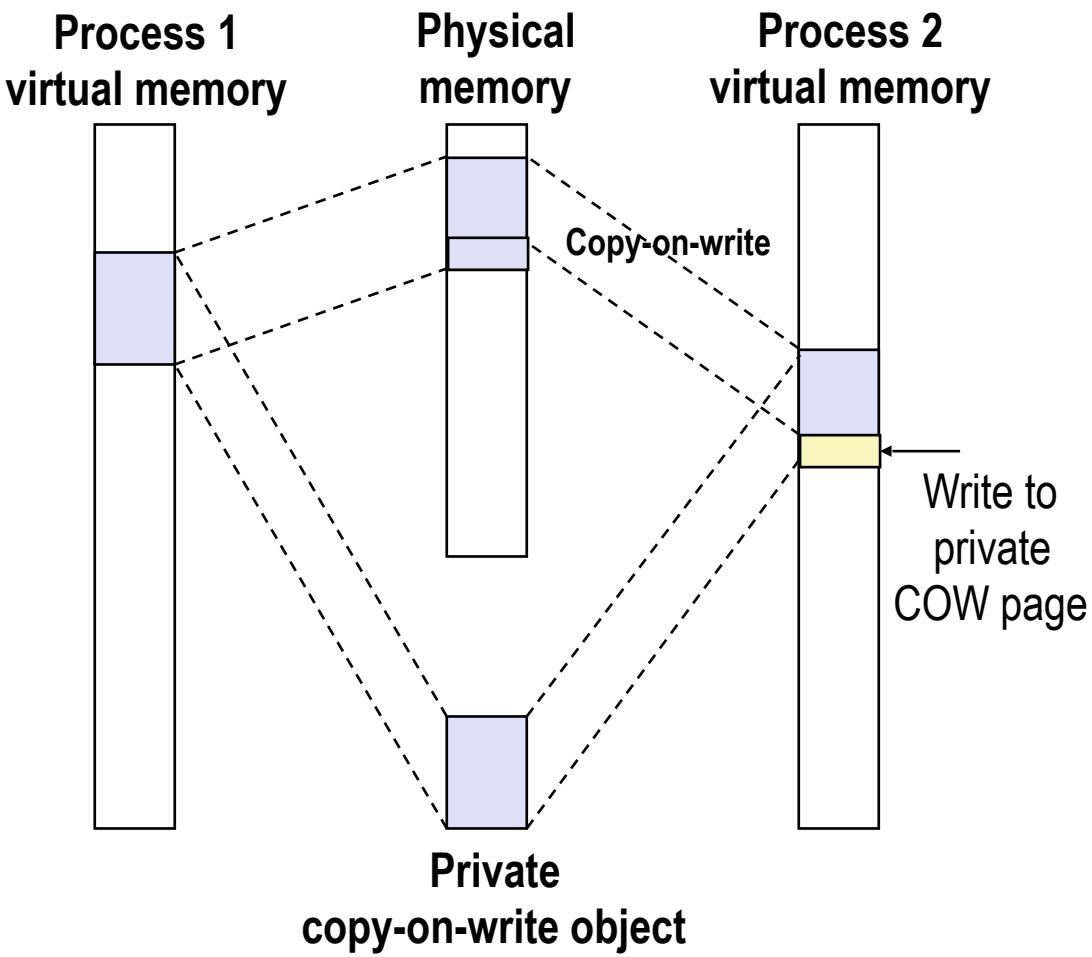

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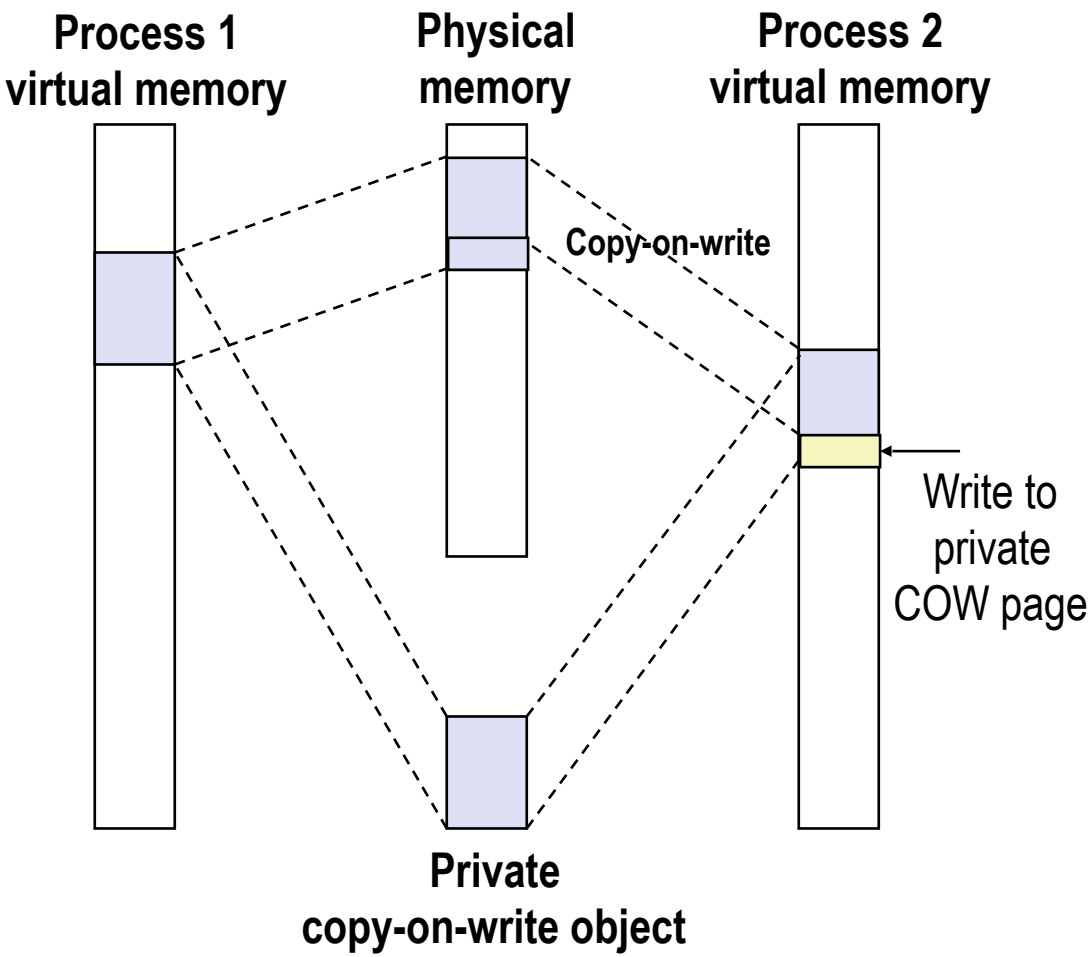

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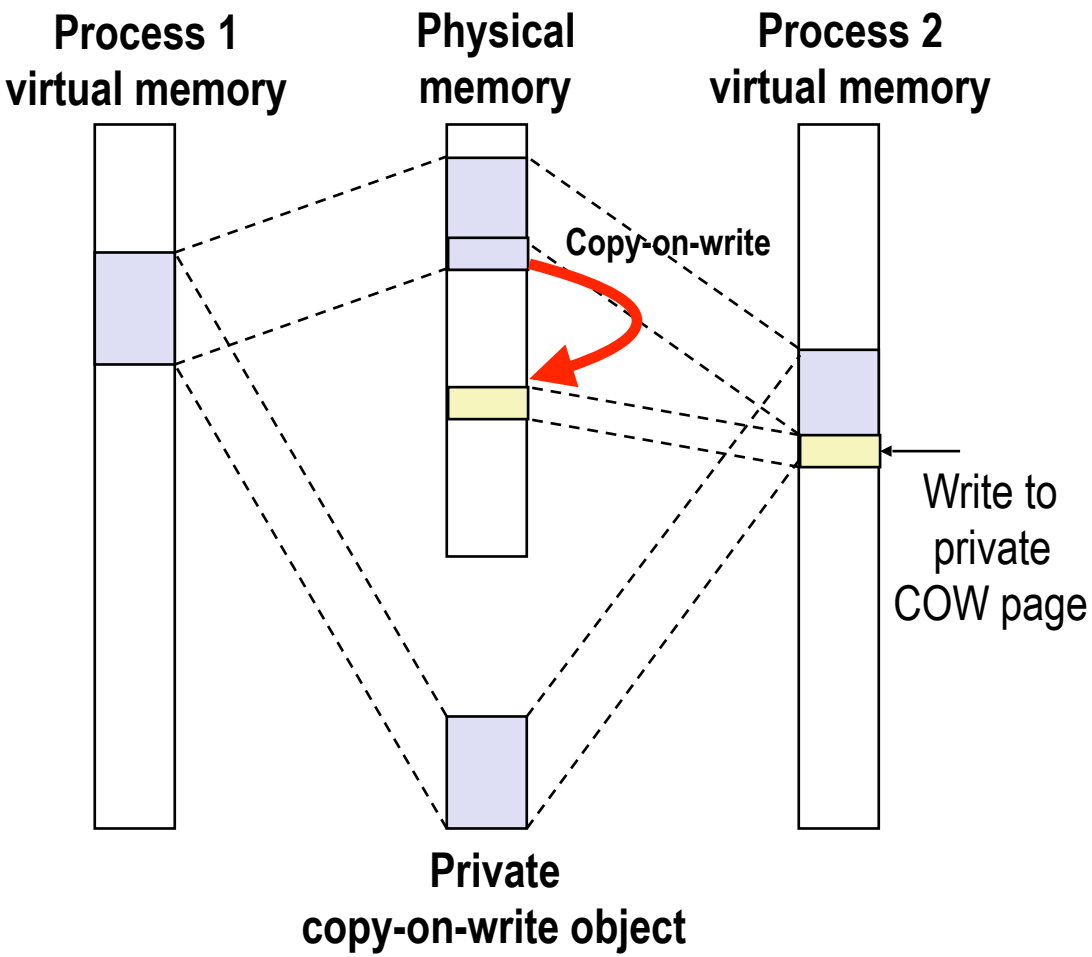

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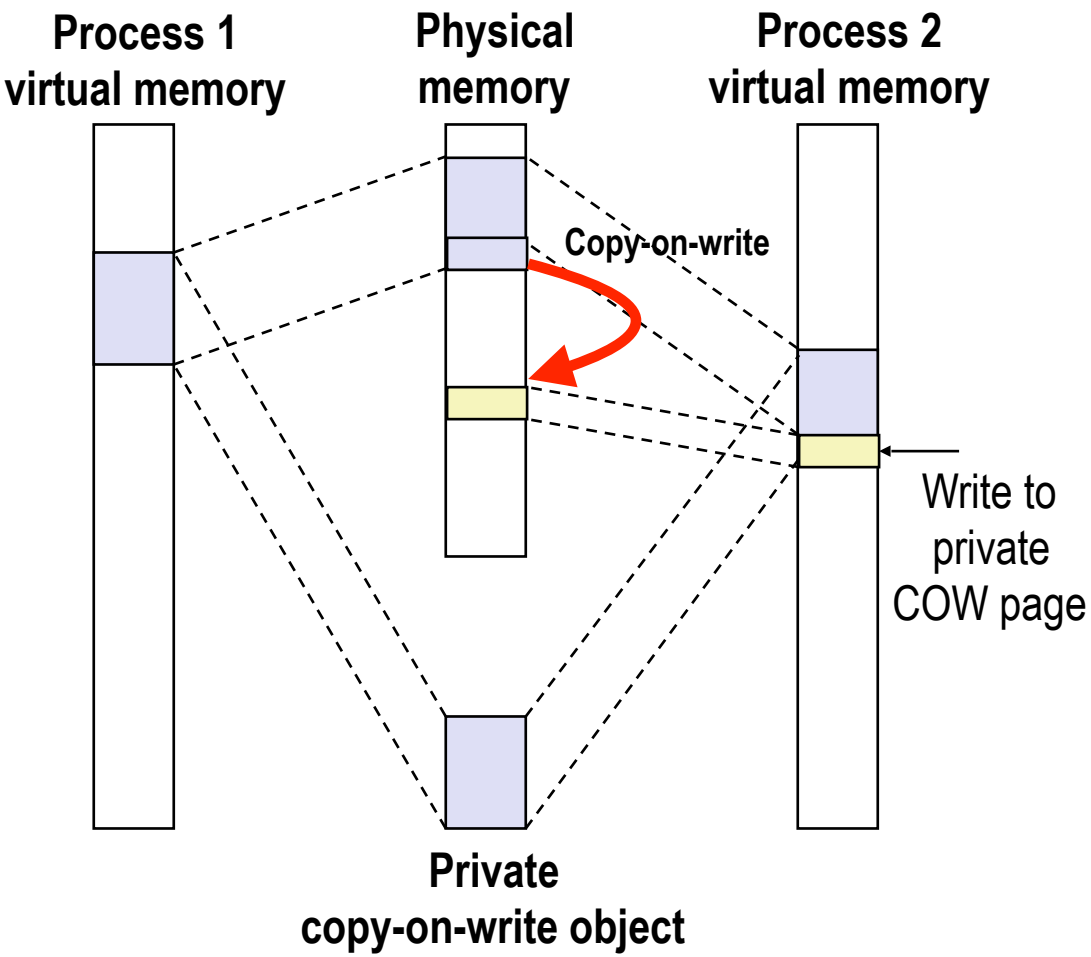

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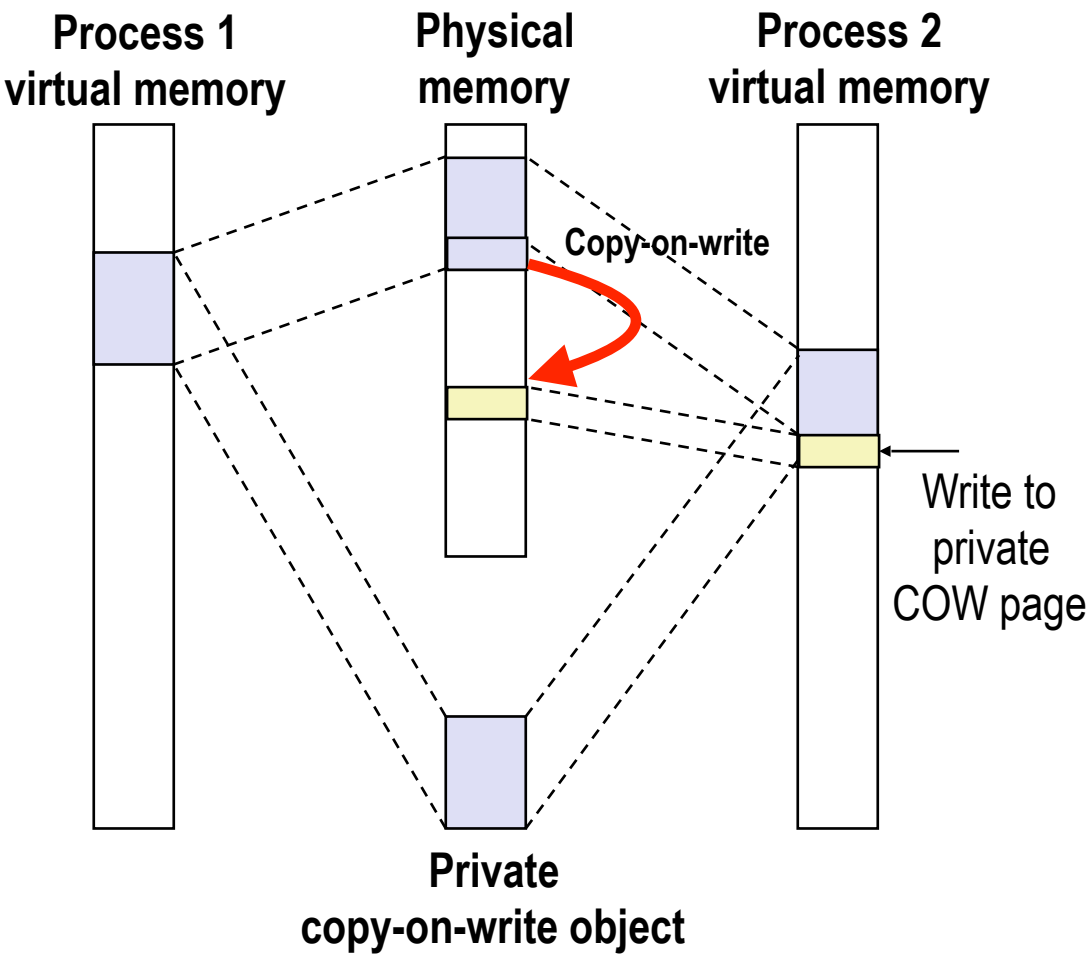

- Instruction writing to private page triggers page (protection) fault.
- Handler checks the area protection, and sees that it's a COW object
- Handler then creates new R/W page.
- Instruction restarts upon handler return.
- Copying deferred as long as possible!

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 NULL 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`)

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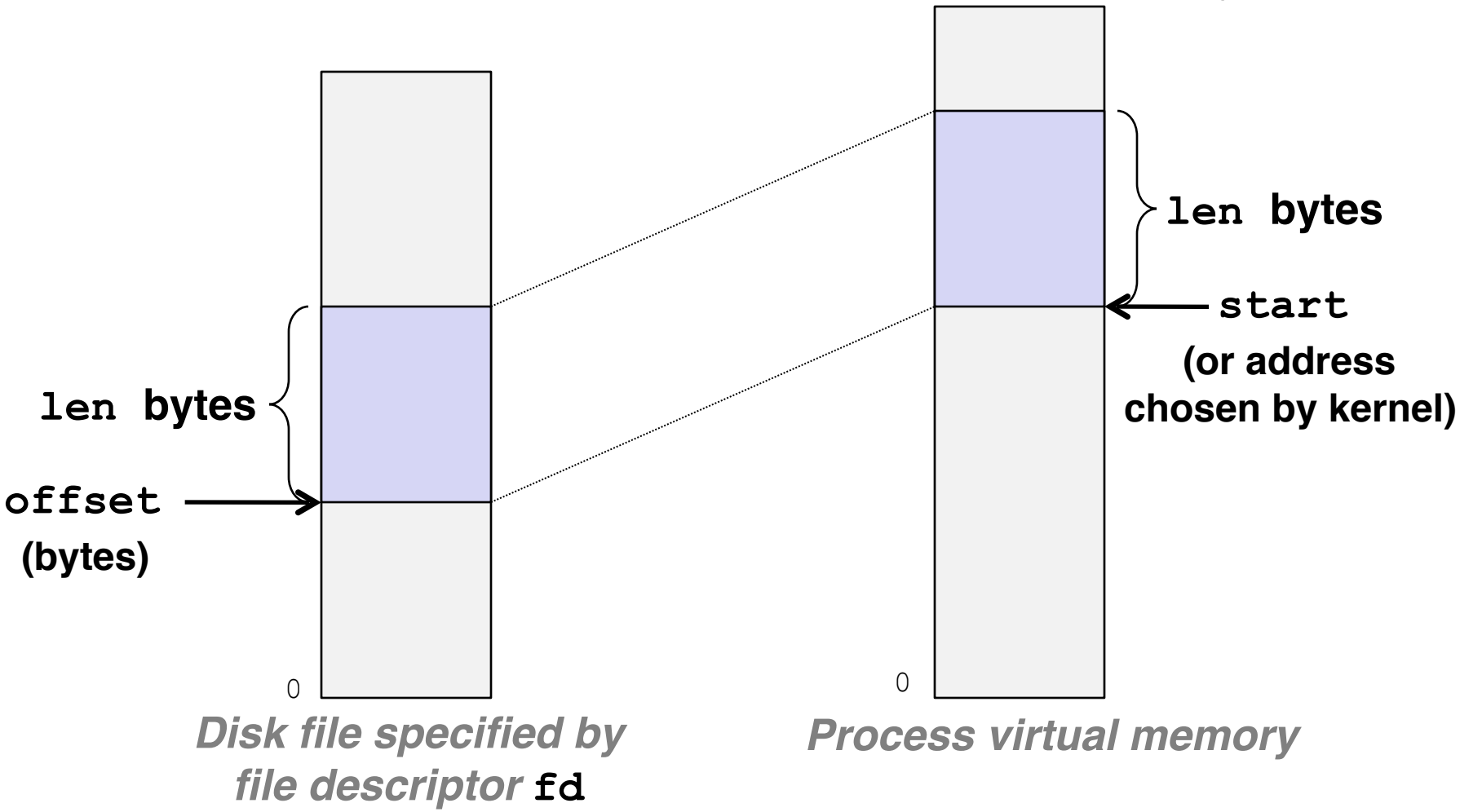

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    Fstat(fd, &stat);
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}
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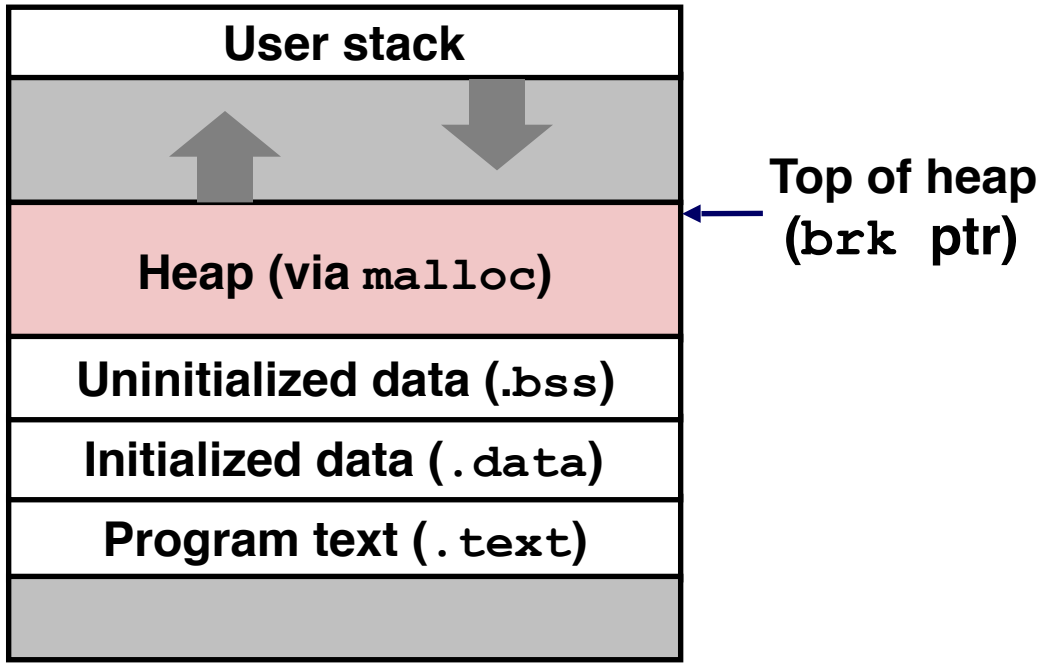
mmapcopy.c

Today

- Memory mapping
- Dynamic memory allocation
  - Basic concepts
  - Implicit free lists

Dynamic Memory Allocation

- Programmers use *dynamic memory allocators* (such as `malloc`) to acquire VM at run time.
- Dynamic memory allocators manage an area of process virtual memory known as the *heap*.



The `malloc/free` Functions

```
#include <stdlib.h>

void *malloc(size_t size)
```

- Successful:
  - Returns a pointer to a memory block of at least **`size`** bytes aligned to an 8-byte (x86) or 16-byte (x86-64) boundary
  - If **`size == 0`**, returns NULL
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Other functions

- `calloc`: Version of `malloc` that initializes allocated block to zero.
- `realloc`: Changes the size of a previously allocated block.
- `sbrk`: Used internally by allocators to grow or shrink the heap

`malloc` Example

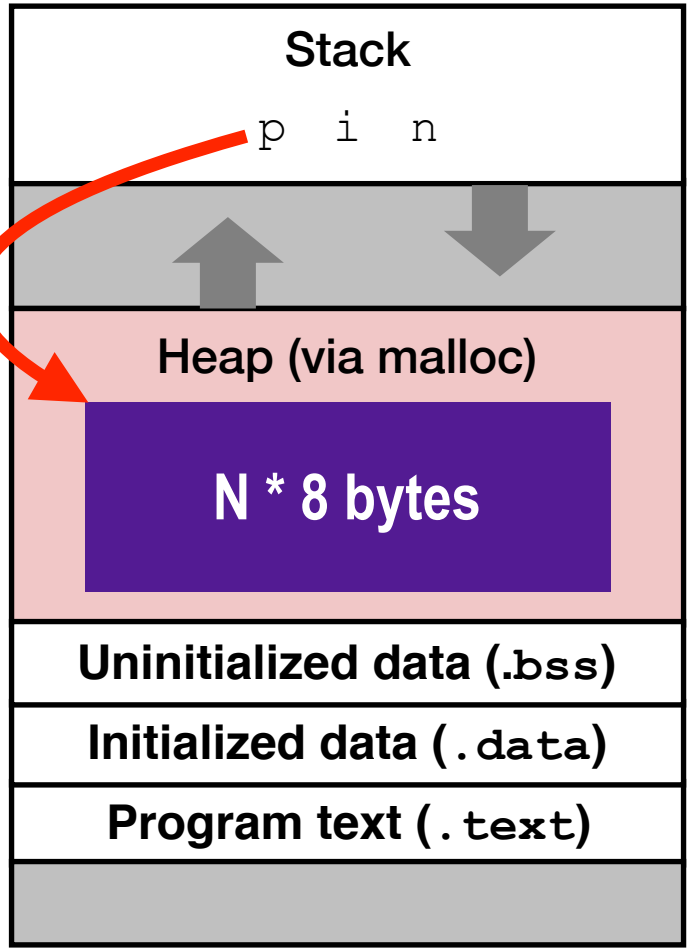
```c
#include <stdio.h>
#include <stdlib.h>

void foo(int n) {
    int i, *p;

    /* Allocate a block of n ints */
    p = (int *) malloc(n * sizeof(int));
    if (p == NULL) {
        perror("malloc");
        exit(0);
    }

    /* Initialize allocated block */
    for (i=0; i<n; i++)
        p[i] = i;


    /* Return allocated block to the heap */
    free(p);
}
```



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- Some data structures' size is only known at runtime. Statically allocating the space would be a waste.
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void bar() {
  int *p = foo(5);

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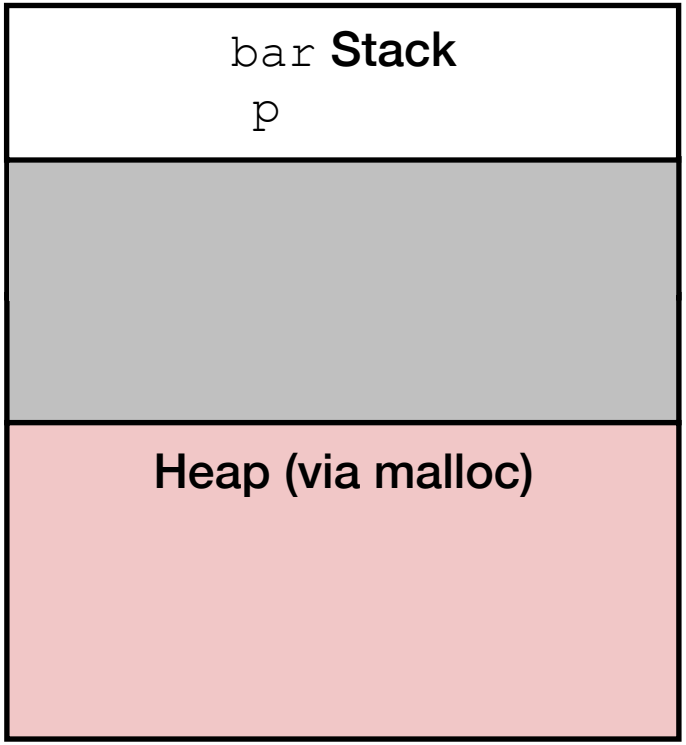

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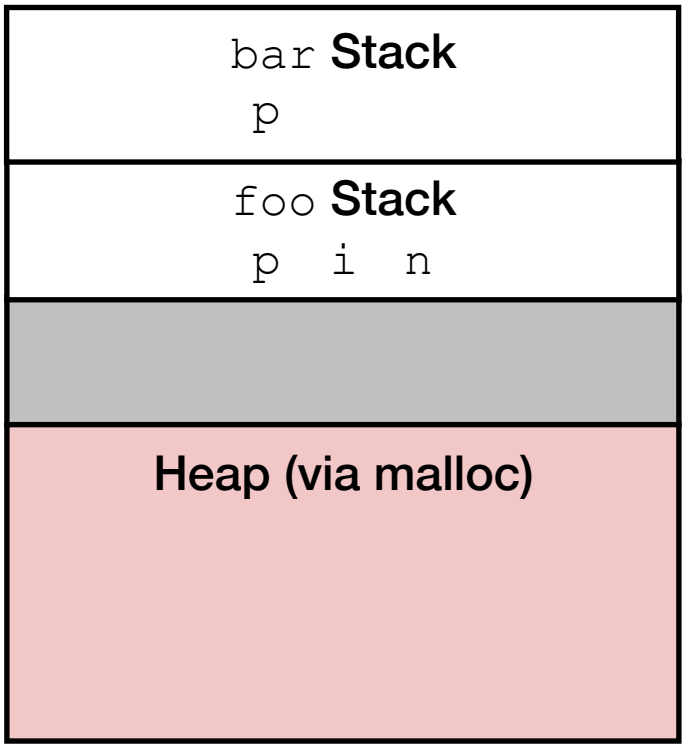

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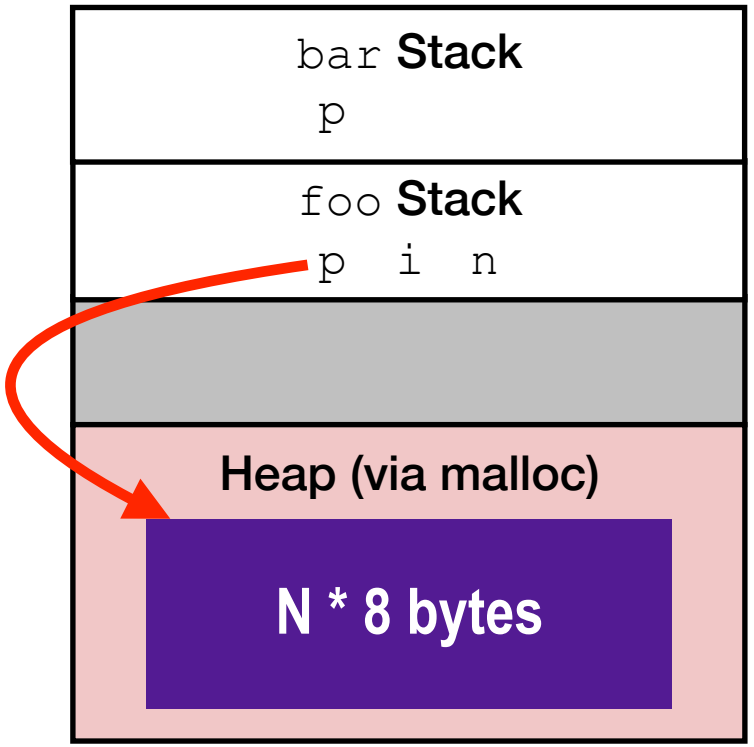

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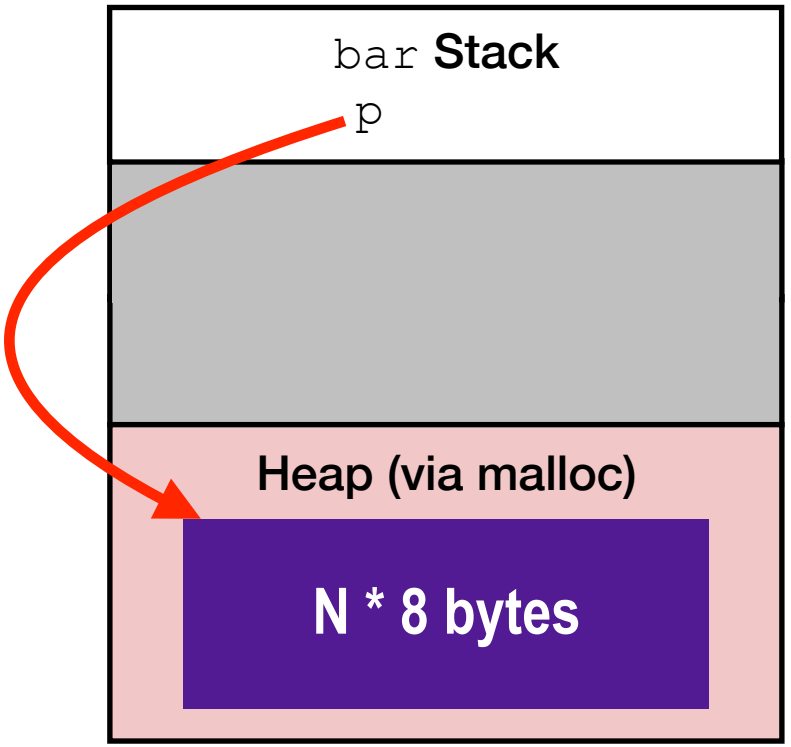

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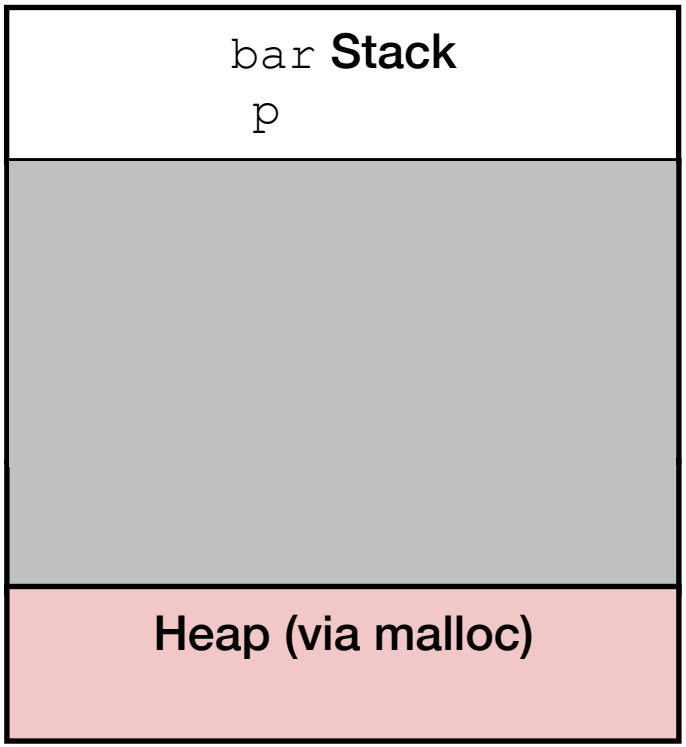

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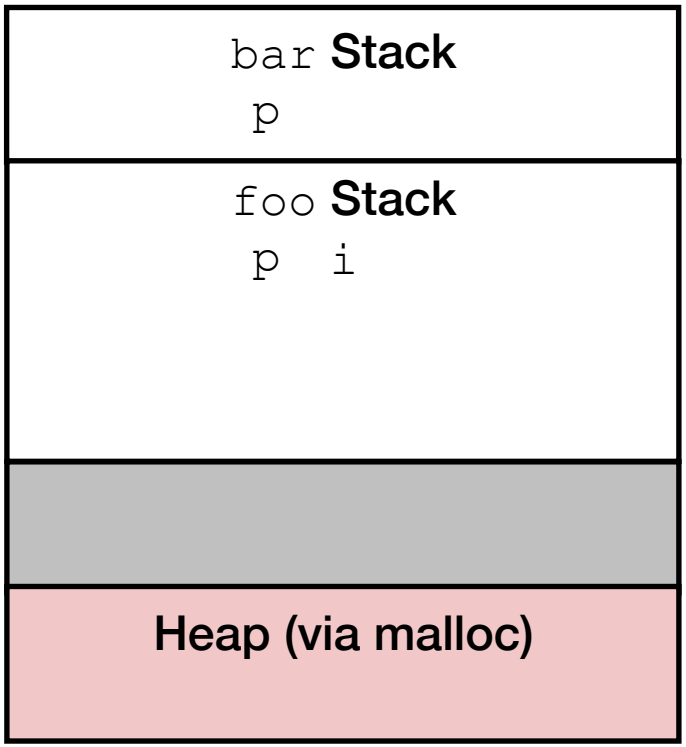

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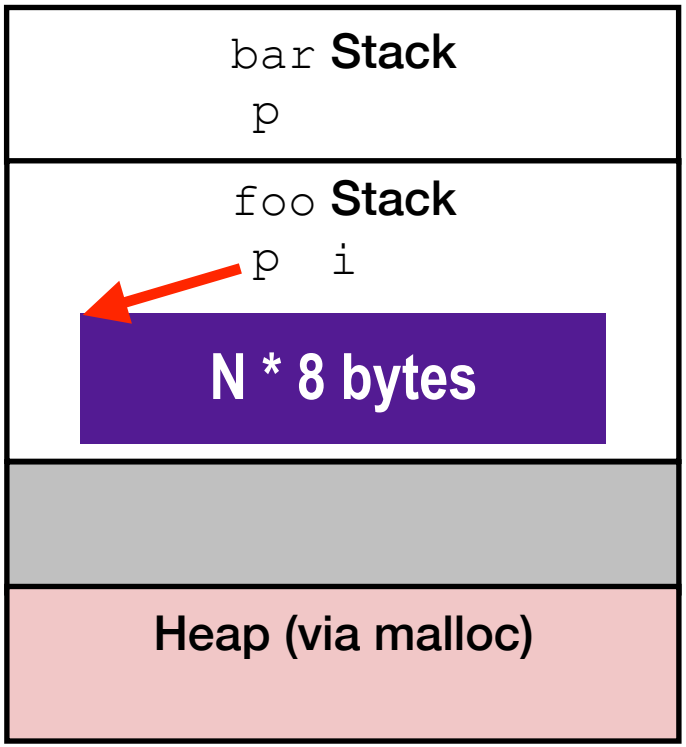

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