15-213

P6/Linux Memory System
April 5, 2001

Topics

- P6 address translation
- Linux memory management
- Linux page fault handling
- memory mapping

Intel P6

Internal Designation for Successor to Pentium

- **Which had internal designation P5**

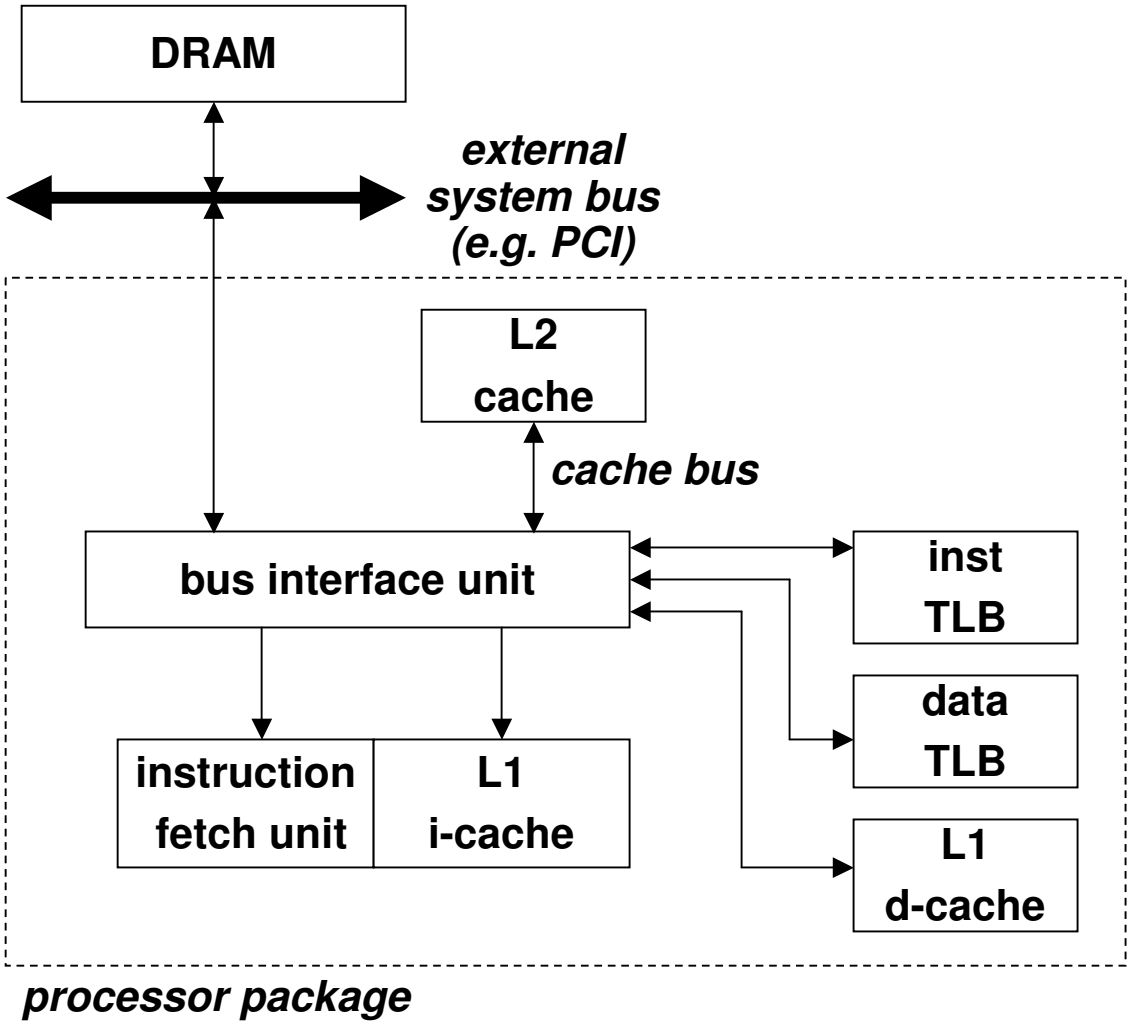
Fundamentally Different from Pentium

- **Out-of-order, superscalar operation**
- **Designed to handle server applications**
  - Requires high performance memory system

Resulting Processors

- **PentiumPro (1996)**
- **Pentium II (1997)**
  - Incorporated MMX instructions
    - » special instructions for parallel processing
  - L2 cache on same chip
- **Pentium III (1999)**
  - Incorporated Streaming SIMD Extensions
    - » More instructions for parallel processing

P6 memory system



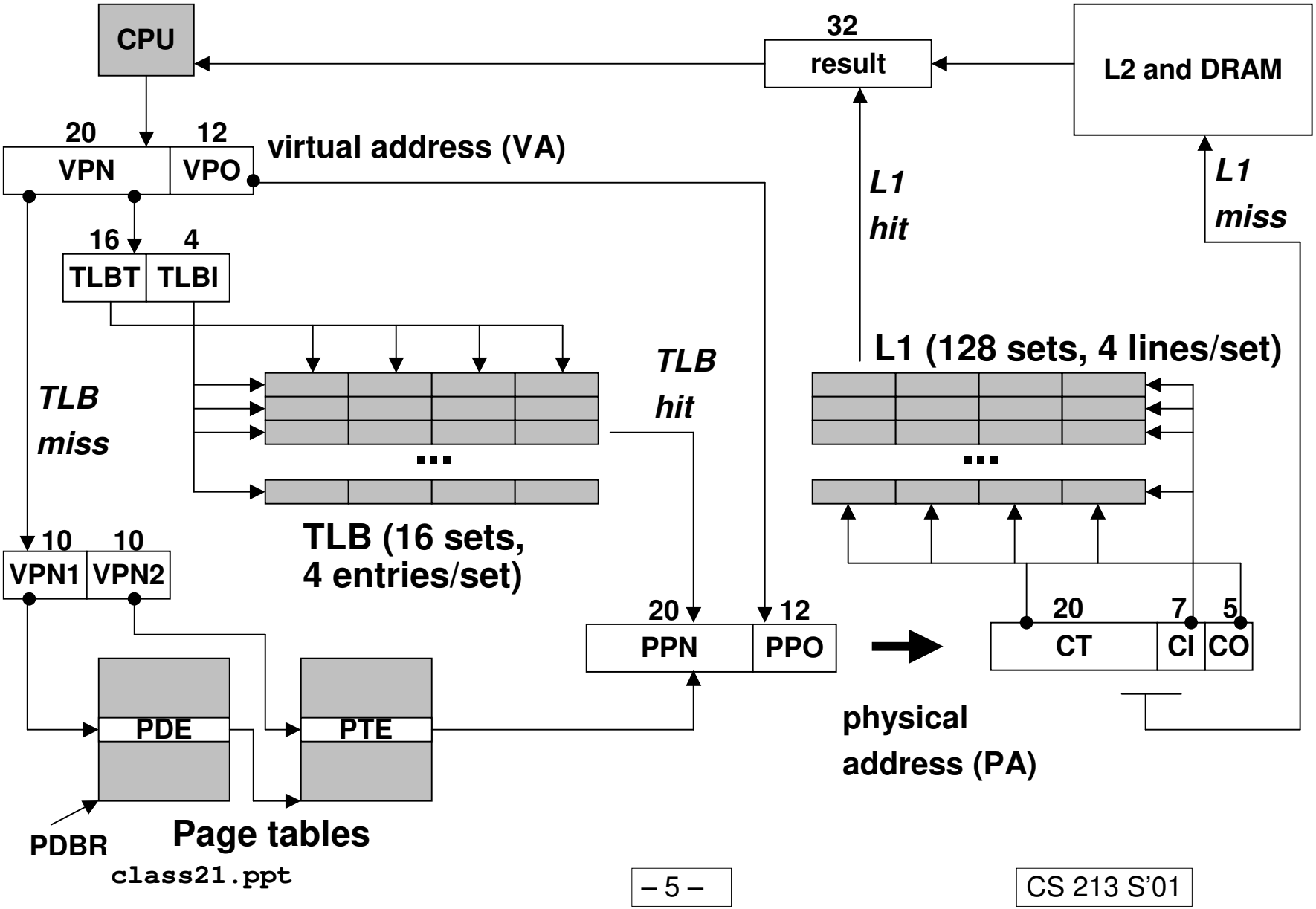
- 32 bit address space
- 4 KB page size
- L1, L2, and TLBs
  - 4-way set associative
- inst TLB
  - 32 entries
  - 8 sets
- data TLB
  - 64 entries
  - 16 sets
- L1 i-cache and d-cache
  - 16 KB
  - 32 B line size
  - 128 sets
- L2 cache
  - unified
  - 128 KB -- 2 MB

Review of abbreviations

Symbols:

- **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
- **Other**
  - PDBR: Page directory base register

Overview of P6 address translation



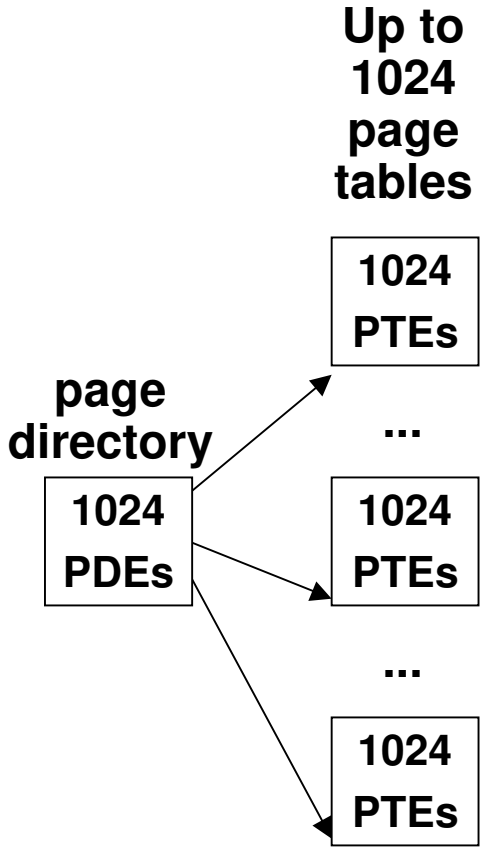
P6 2-level page table structure

Page directory

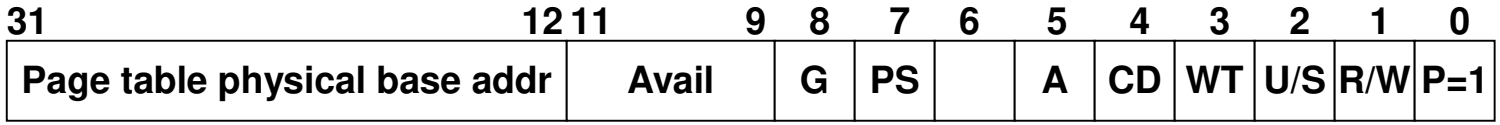
- 1024 4-byte page directory entries (PDEs) that point to page tables
- one page directory per process.
- page directory must be in memory when its process is running
- always pointed to by PDBR

Page tables:

- 1024 4-byte page table entries (PTEs) that point to pages.
- page tables can be paged in and out.



P6 page directory entry (PDE)



Page table physical base address: 20 most significant bits of physical page table address (forces page tables to be 4KB aligned)

Avail: available for system programmers

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

PS: page size 4K (0) or 4M (1)

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

CD: cache disabled (1) or enabled (0)

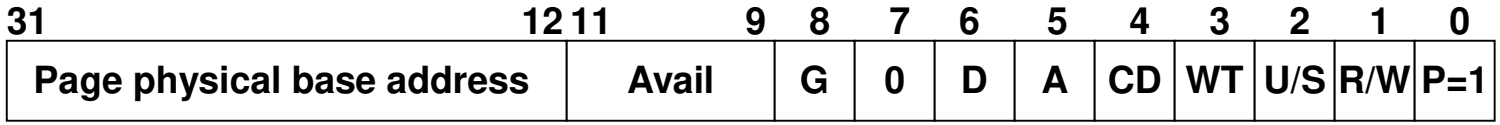
WT: write-through or write-back cache policy for this page table

U/S: user or supervisor mode access

R/W: read-only or read-write access

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

P6 page table entry (PTE)



Page base address: 20 most significant bits of physical page address (forces pages to be 4 KB aligned)

Avail: available for system programmers

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

D: dirty (set by MMU on writes)

A: accessed (set by MMU on reads and writes)

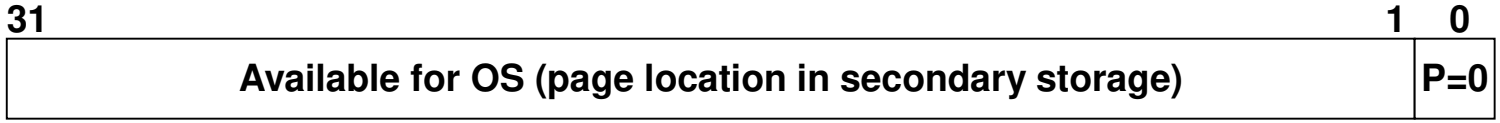
CD: cache disabled or enabled

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

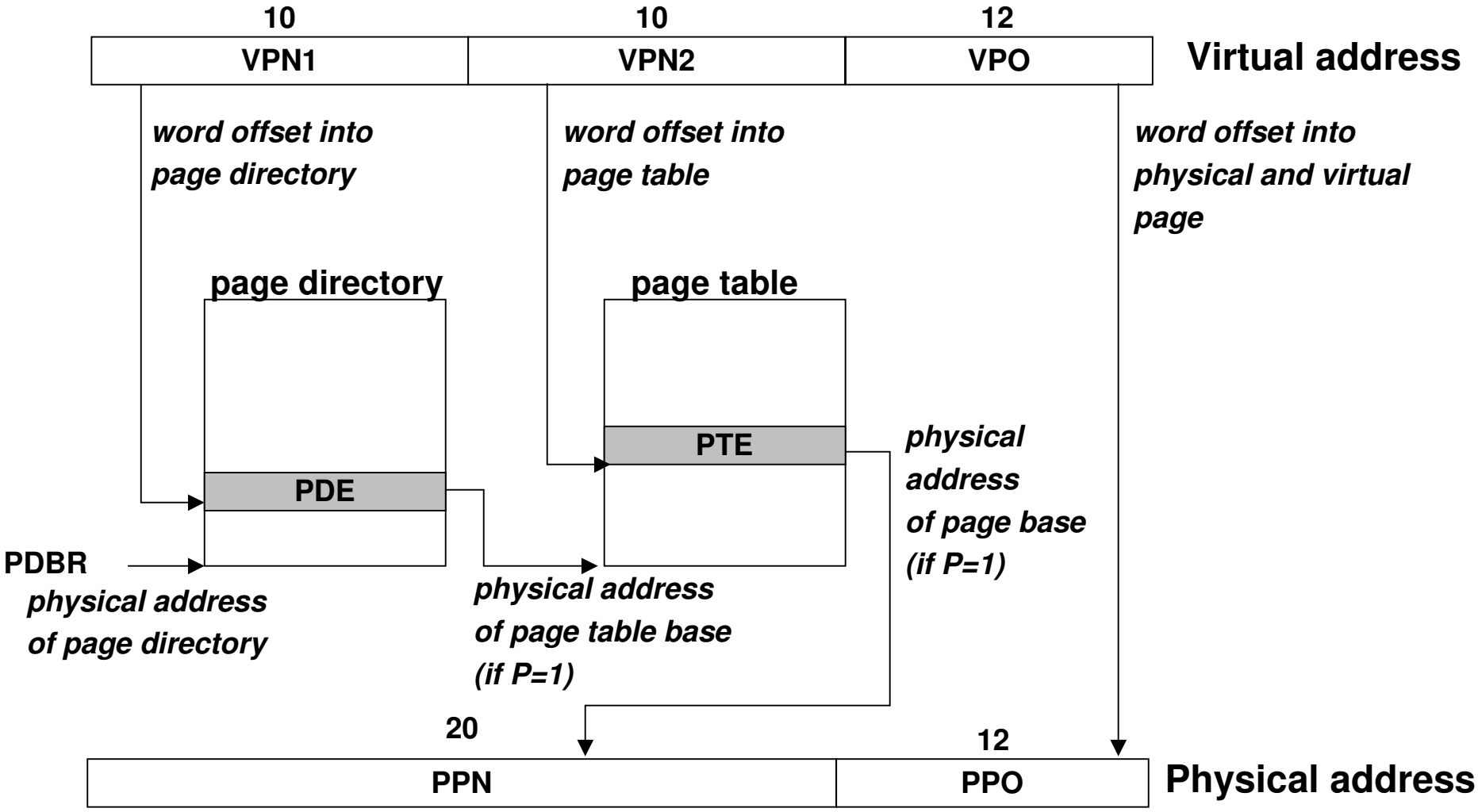
U/S: user/supervisor

R/W: read/write

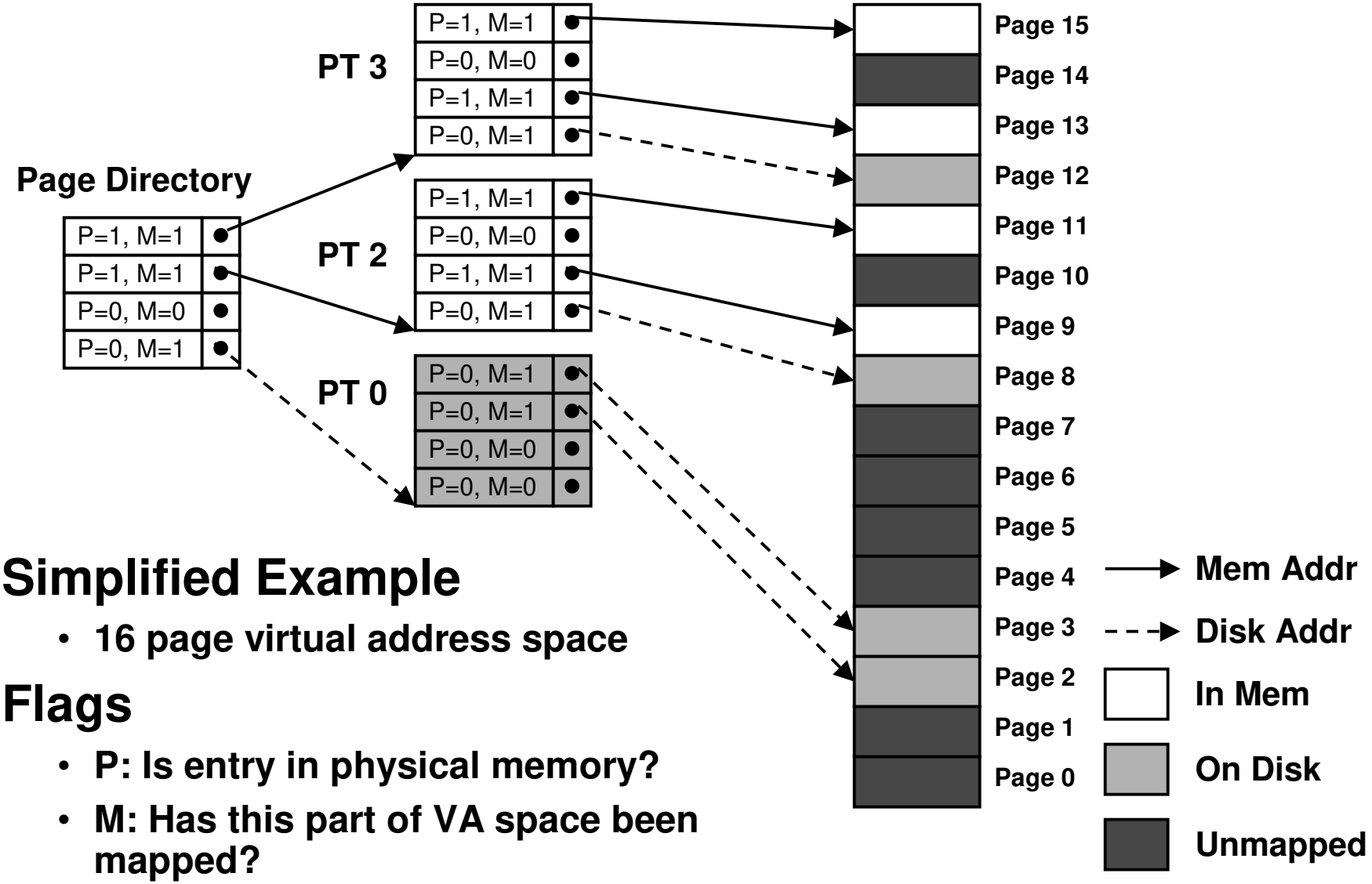
P: page is present in physical memory (1) or not (0)



How P6 page tables map virtual addresses to physical ones



Representation of Virtual Address Space



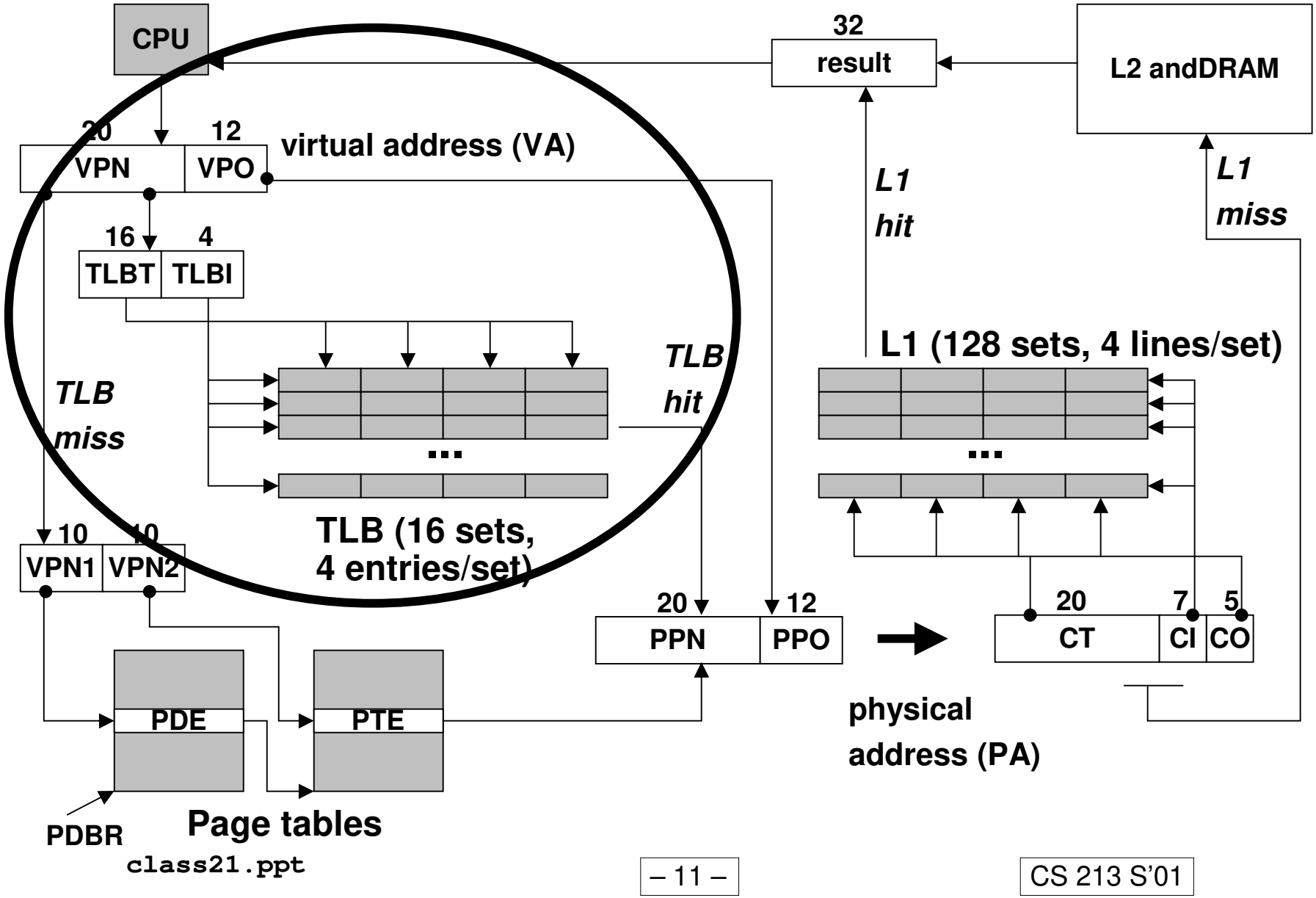
Simplified Example

- 16 page virtual address space

Flags

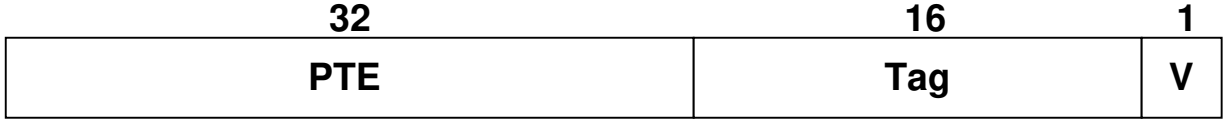
- P: Is entry in physical memory?
- M: Has this part of VA space been mapped?

P6 TLB translation



P6 TLB

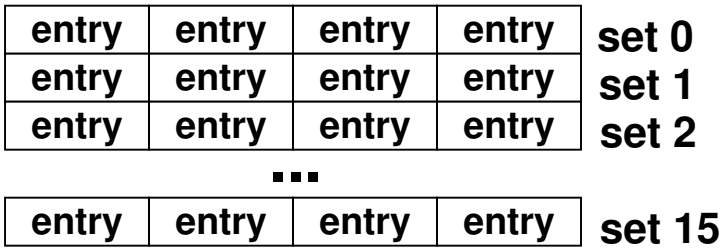
TLB entry (not all documented, so this is speculative):



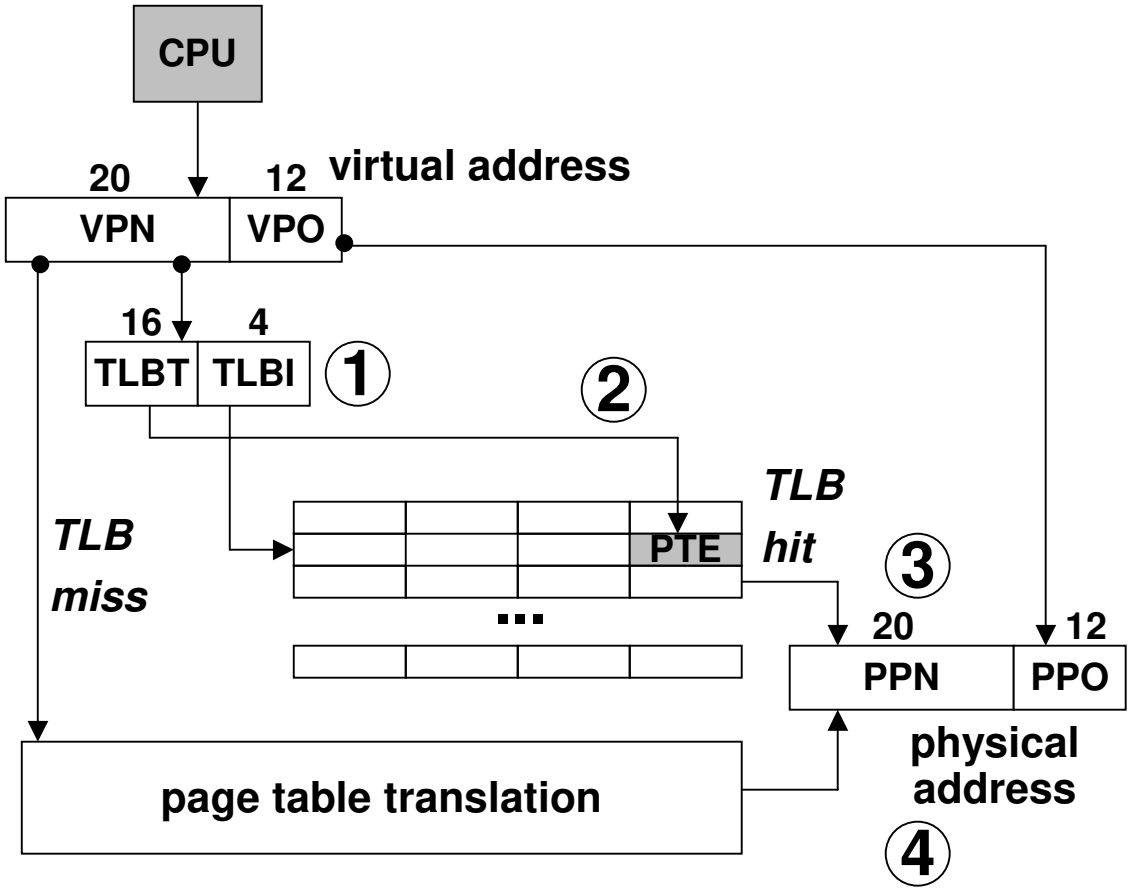
- V: indicates a valid (1) or invalid (0) TLB entry
- tag: disambiguates entries cached in the same set
- PTE: page table entry

• Structure of the data TLB

- 16 sets, 4 entries/set

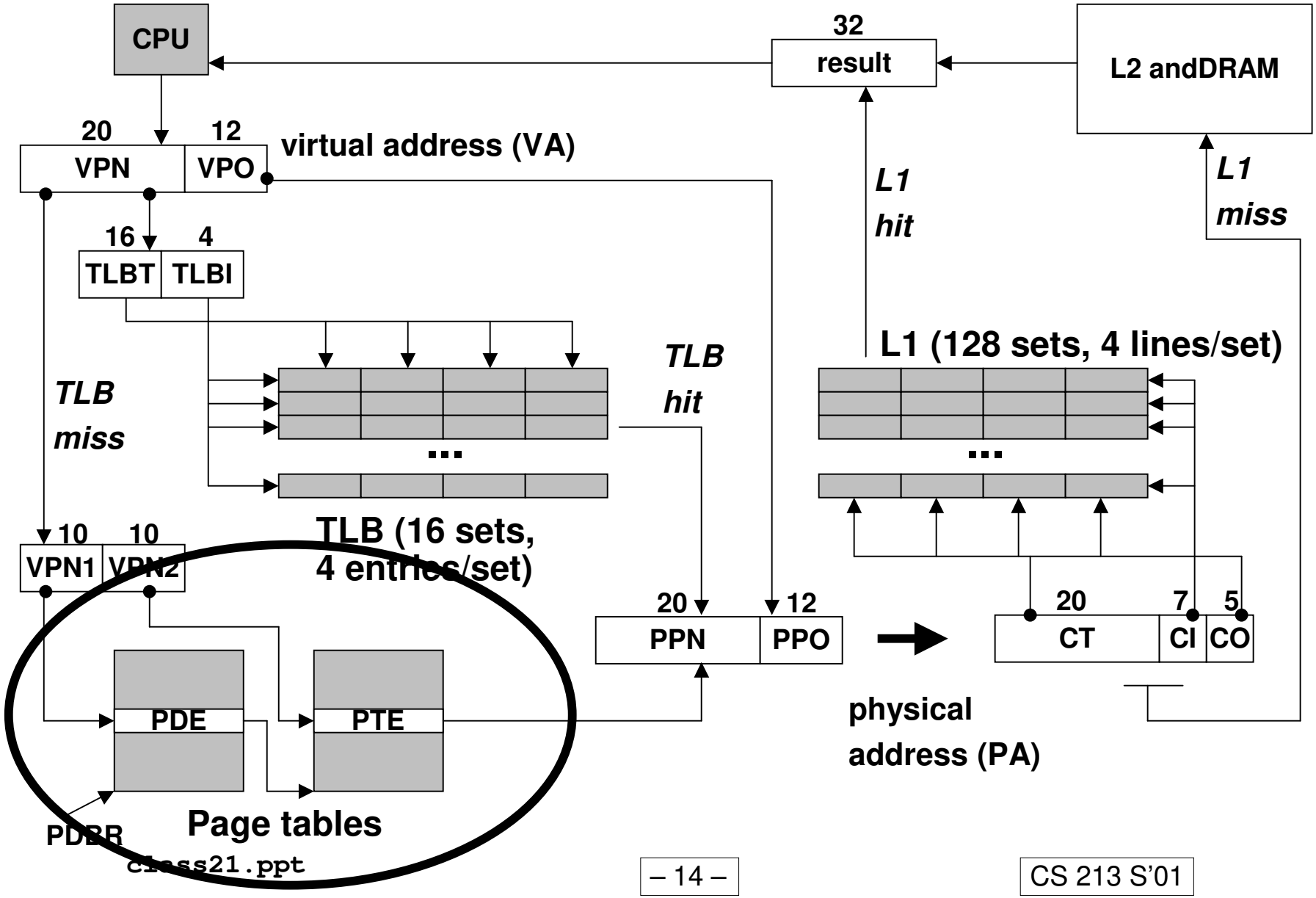


Translating with the P6 TLB

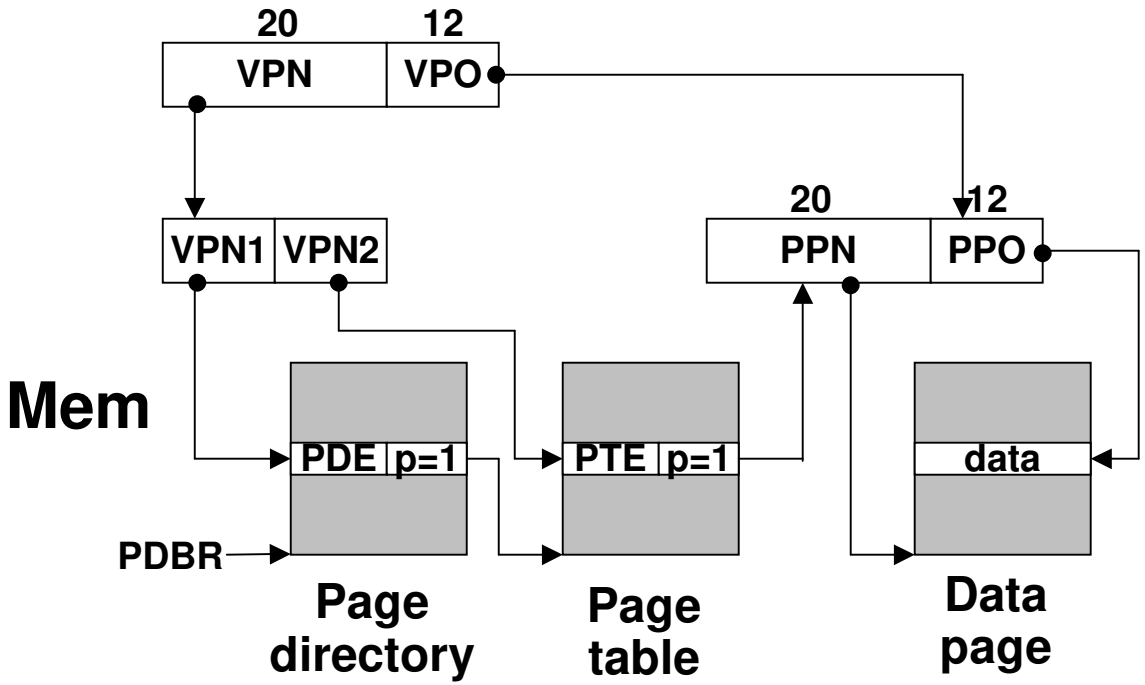


1. Partition VPN into TLBT and TLBI.
2. Is the PTE for VPN cached in set TLBI?
   - 3. Yes: then build physical address.
4. No: then read PTE (and PDE if not cached) from memory and build physical address.

P6 page table translation



Translating with the P6 page tables (case 1/1)



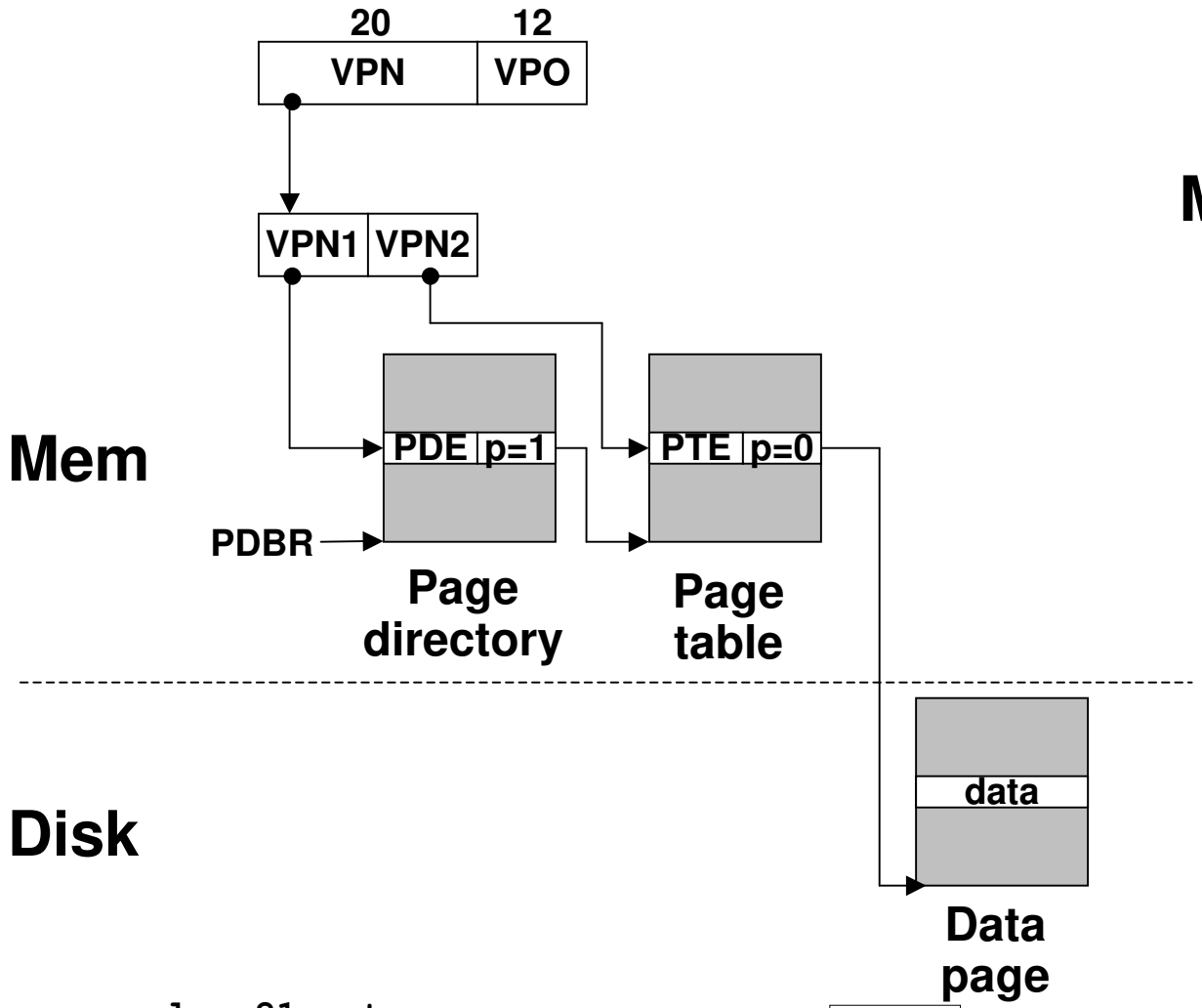
Case 1/1: page table and page present.

MMU Action:

- MMU build physical address and fetch data word.

- OS action
  - none

Translating with the P6 page tables (case 1/0)

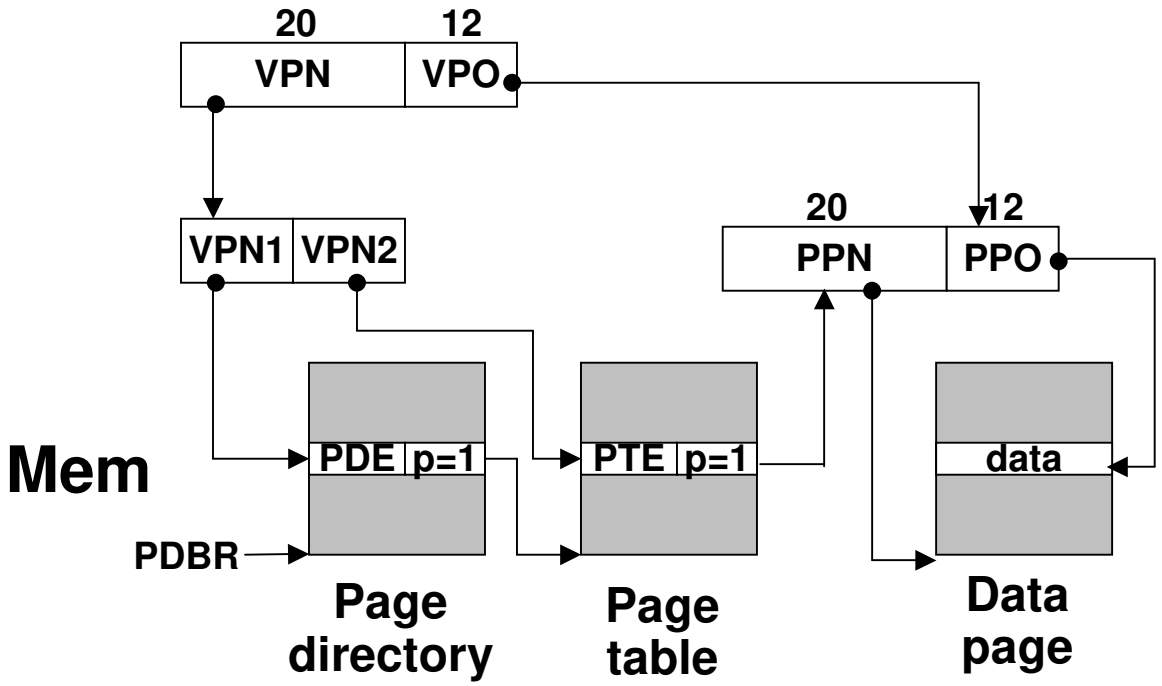


Case 1/0: page table present but page missing.

MMU Action:

- **page fault exception**
- **handler receives the following args:**
  - VA that caused fault
  - fault caused by non-present page or page-level protection violation
  - read/write
  - user/supervisor

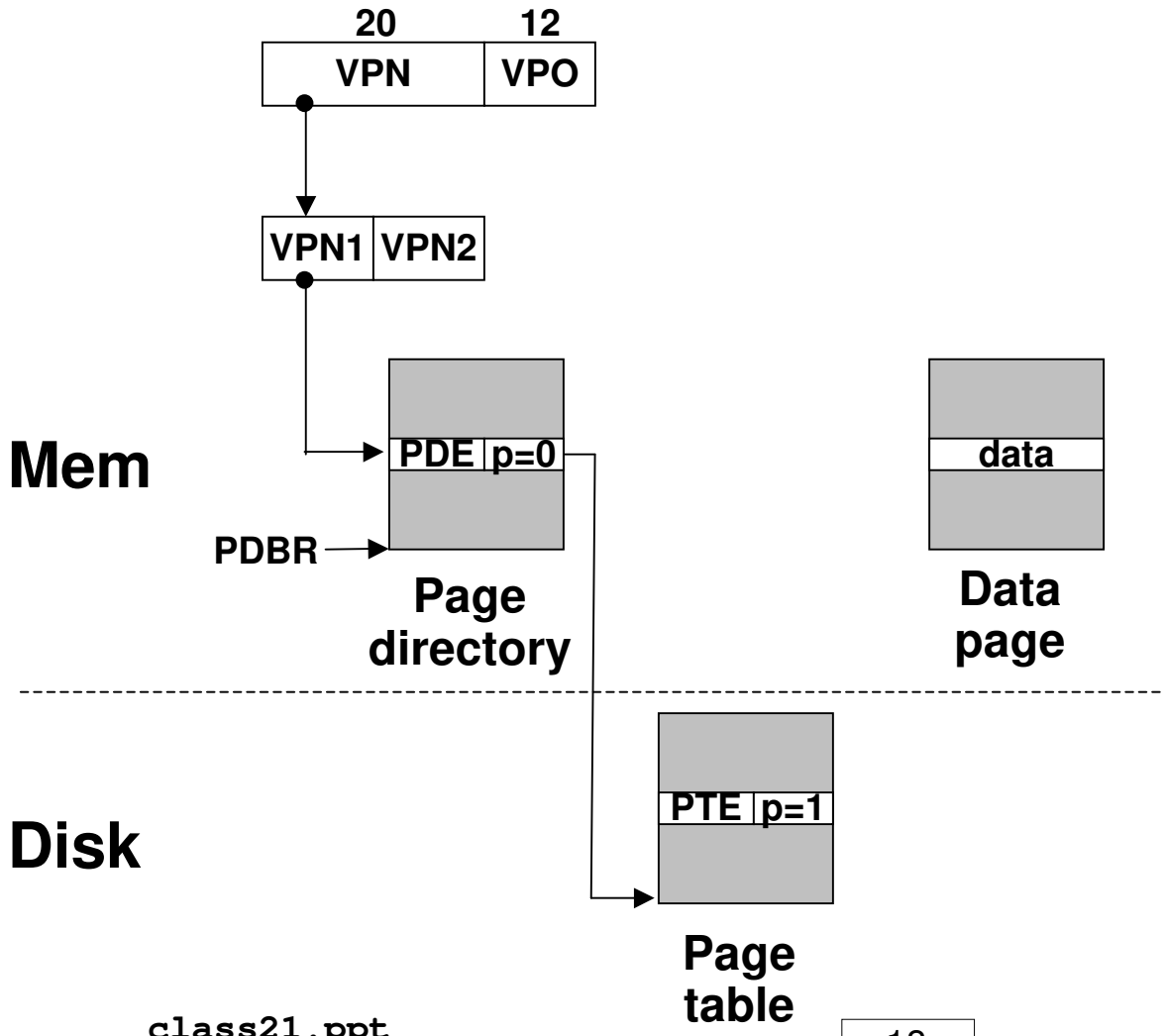
Translating with the P6 page tables (case 1/0, cont)



OS Action:

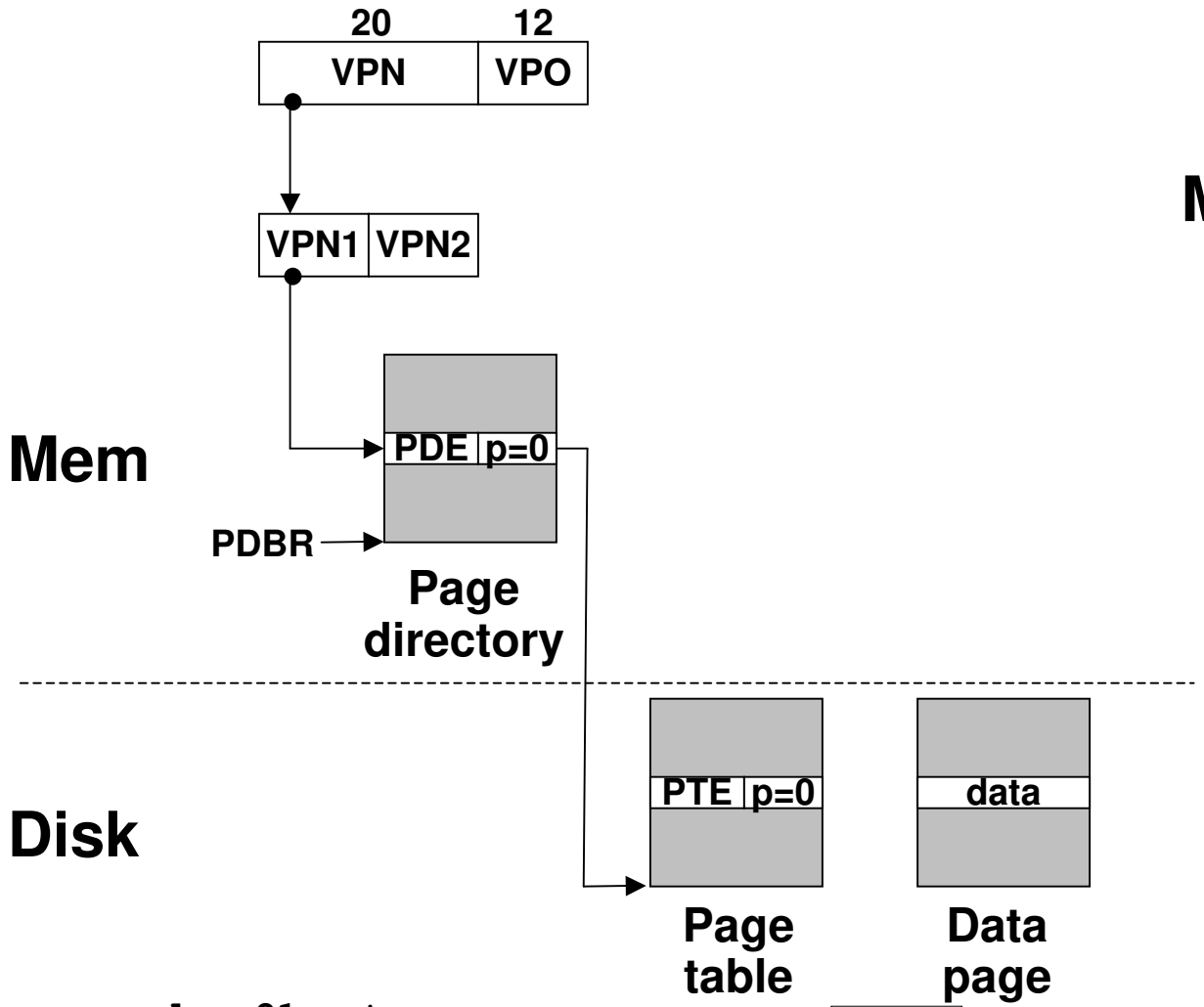
- Check for a legal virtual address.
- Read PTE through PDE.
- Find free physical page (swapping out current page if necessary)
- Read virtual page from disk and copy to virtual page
- Restart faulting instruction by returning from exception handler.

Translating with the P6 page tables (case 0/1)



- **Case 0/1: page table missing but page present.**
- **Introduces consistency issue.**
  - **potentially every page out requires update of disk page table.**
- **Linux disallows this**
  - **if a page table is swapped out, then swap out its data pages too.**

Translating with the P6 page tables (case 0/0)

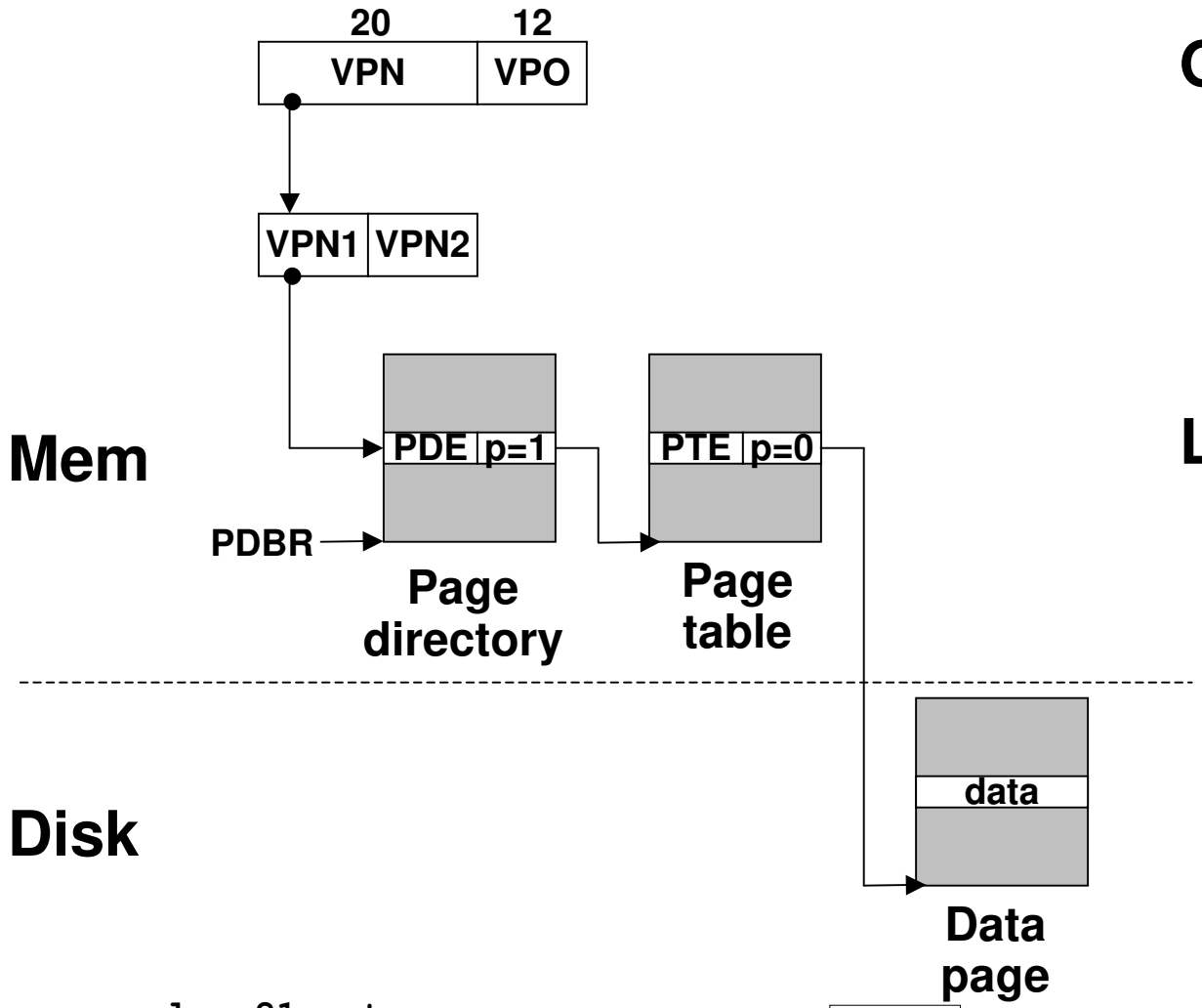


Case 0/0: page table and page missing.

MMU Action:

- **page fault exception**

Translating with the P6 page tables (case 0/0, cont)

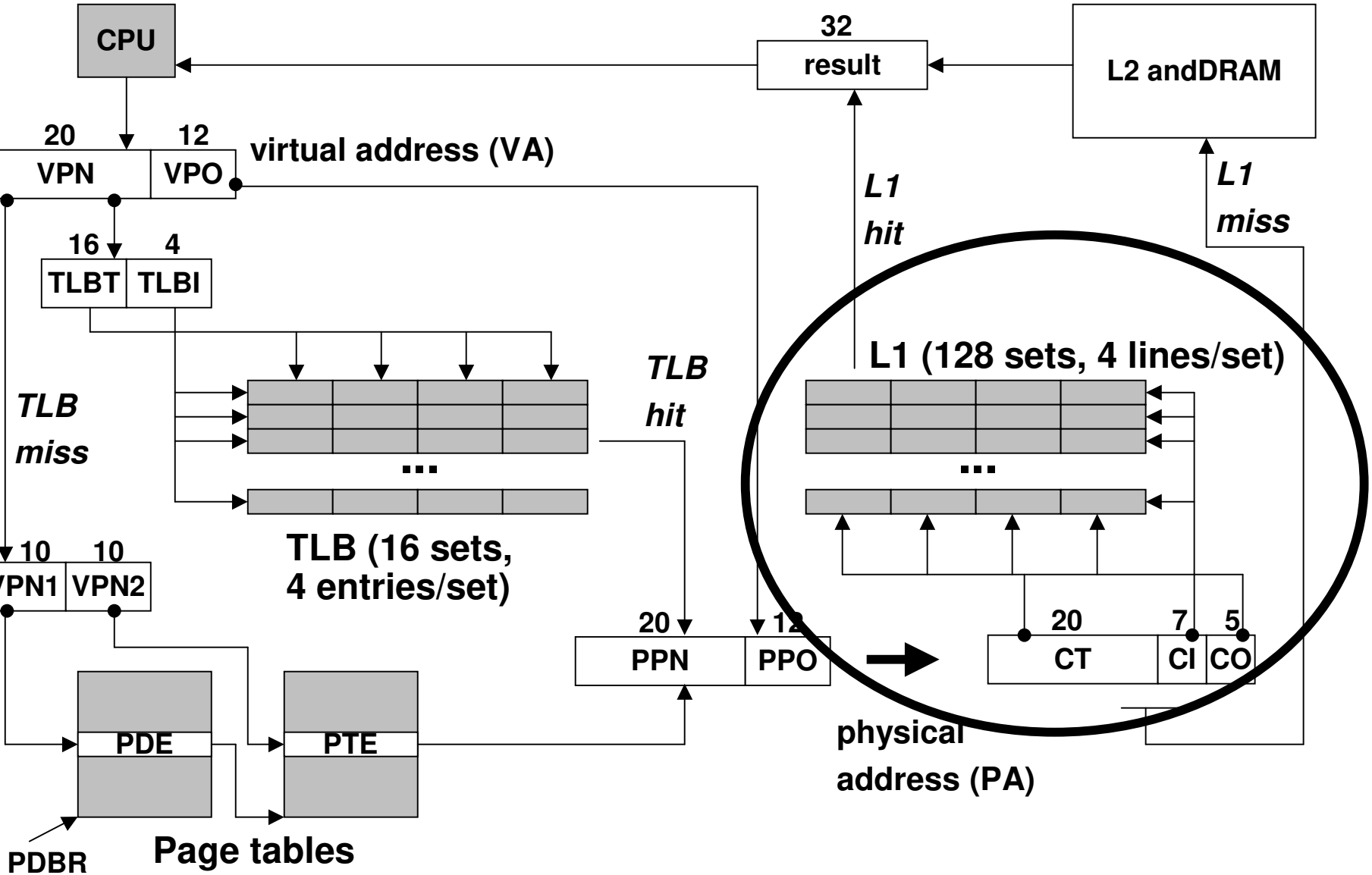


OS action:

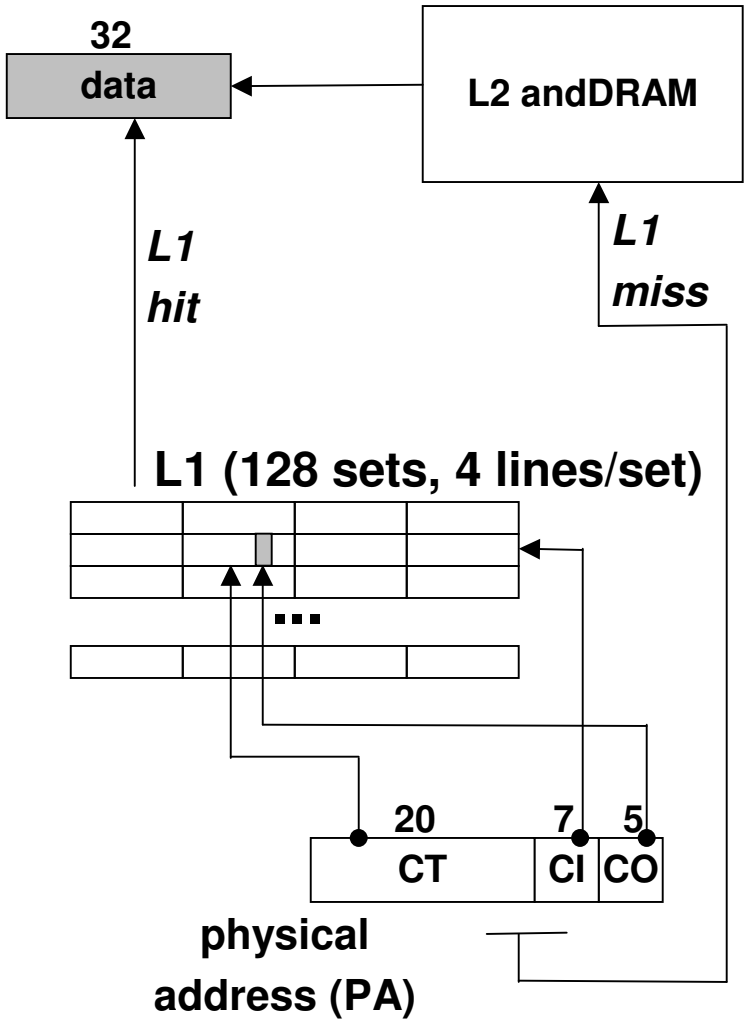
- **swap in page table.**
- **restart faulting instruction by returning from handler.**

Like case 0/1 from here on.

P6 L1 cache access

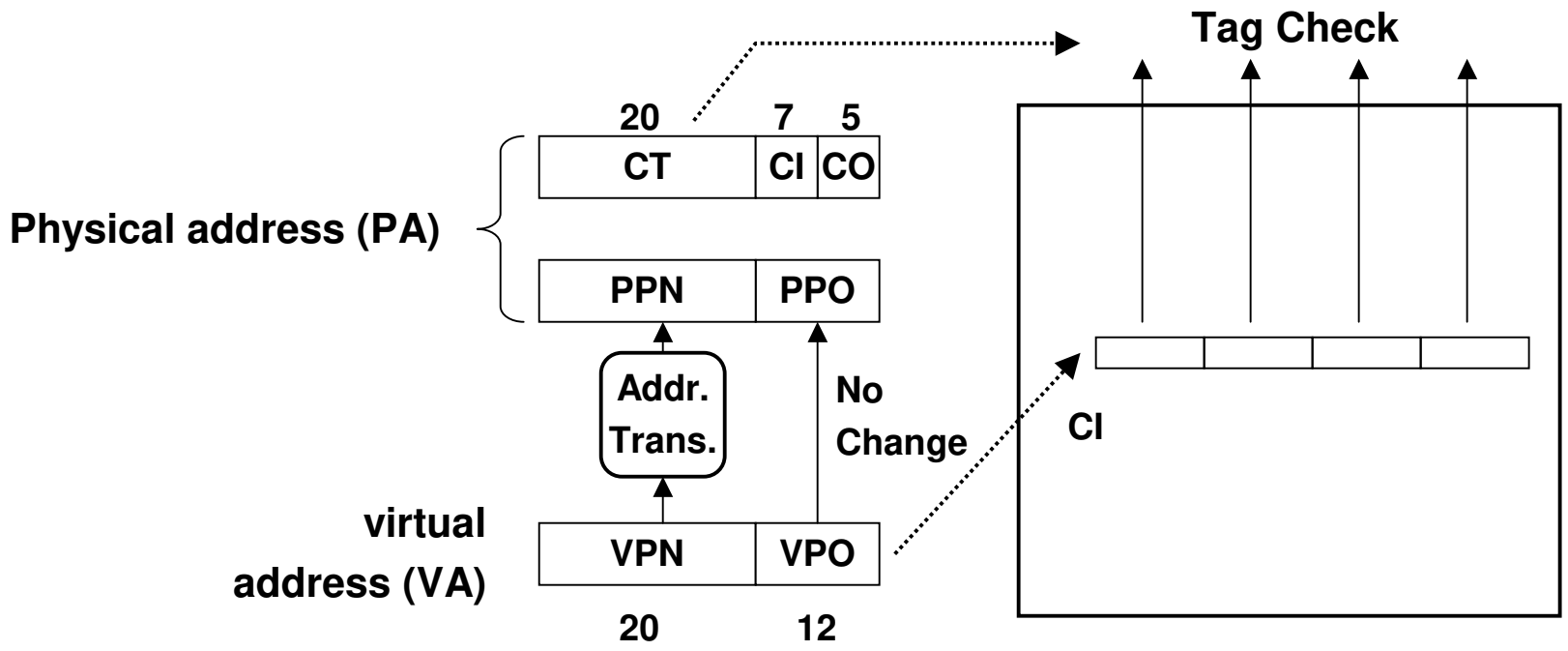


L1 cache access



- Partition physical address into CO, CI, and CT.
- Use CT to determine if line containing word at address PA is cached in set CI.
- If no: check L2.
- If yes: extract word at byte offset CO and return to processor.

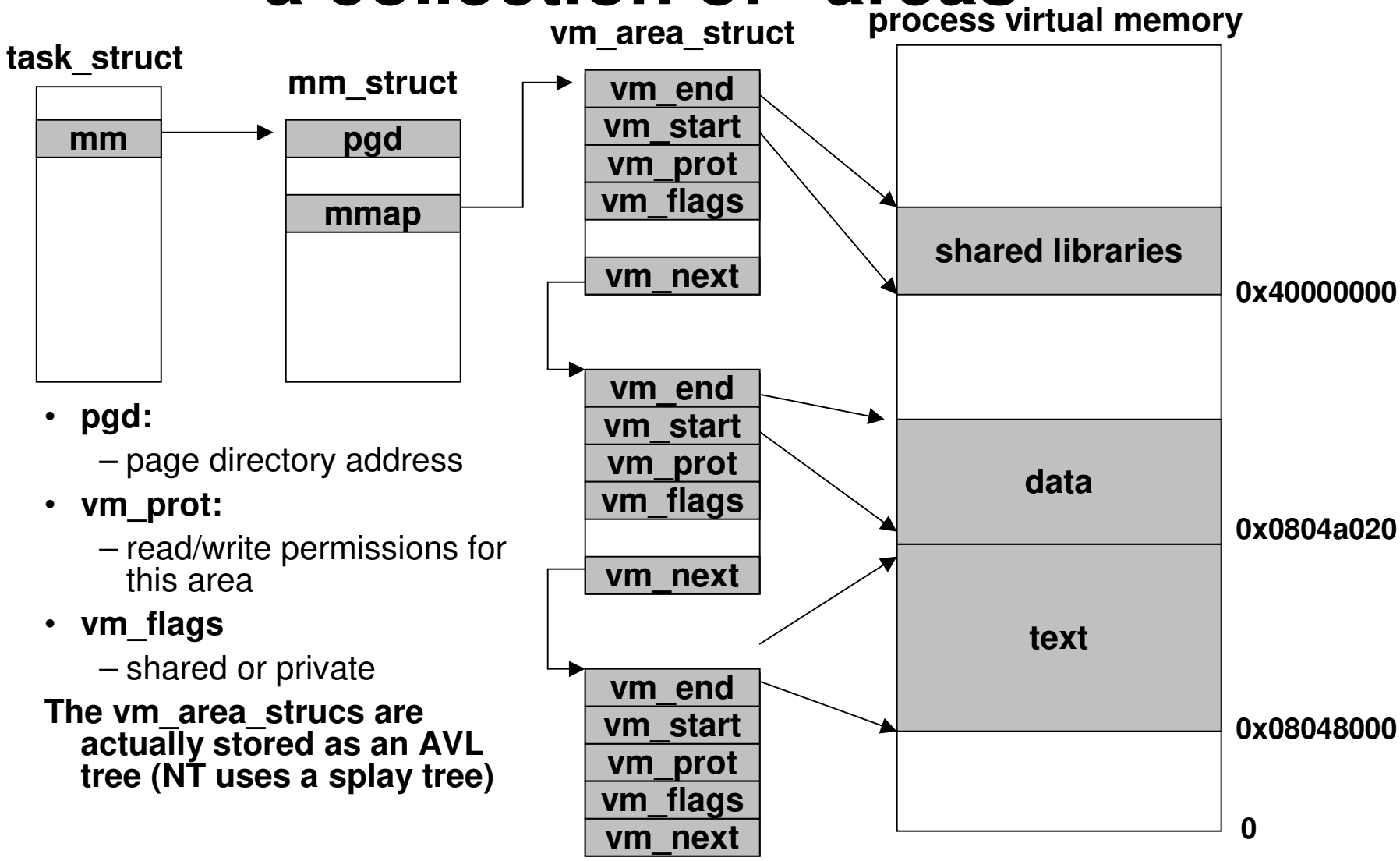
Speeding Up L1 Access



Observation

- Bits that determine CI identical in virtual and physical address
- Can index into cache while address translation being performed
- Then check with CT from physical address
- "Virtually indexed, physically tagged"

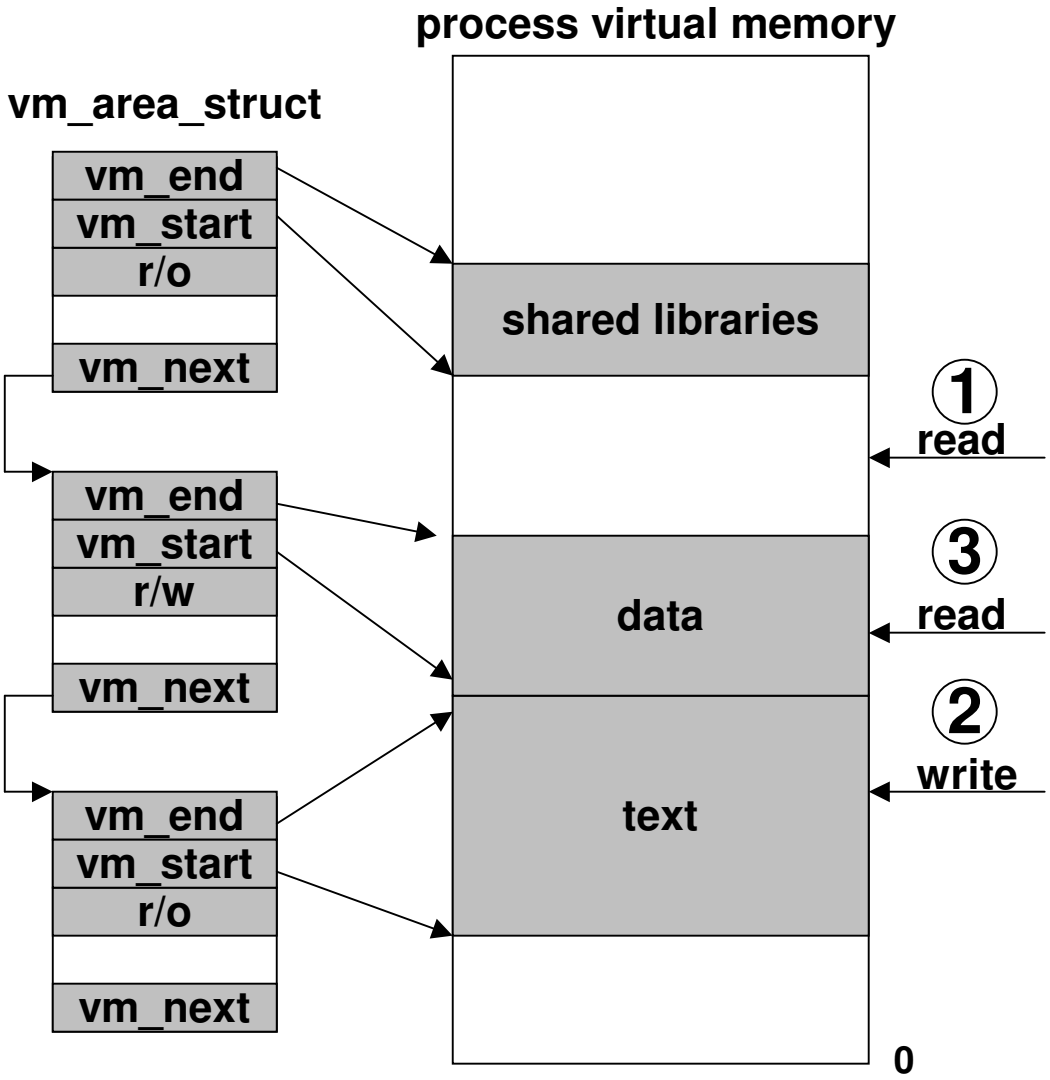
Linux organizes VM as a collection of "areas"



- **pgd:**
  - page directory address
- **vm_prot:**
  - read/write permissions for this area
- **vm_flags**
  - shared or private

The vm_area_strucs are actually stored as an AVL tree (NT uses a splay tree)

Linux page fault handling



Is the VA legal?

- i.e. is it in an area defined by a vm_area_struct?
- if not then signal segmentation violation (e.g. (1))

Is the operation legal?

- i.e., can the process read/write this area?
- if not then signal protection violation (e.g., (2))

If OK, handle fault

- e.g., (3)
- What to do will depend on the region.

Memory mapping

Creation of new VM *area* done via "memory mapping"

- **create new vm_area_struct and page tables for area**
- **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
  - nothing (e.g., bss)
    - » initial page bytes are zeros
- **dirty pages are swapped back and forth between a special swap file.**

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)
```

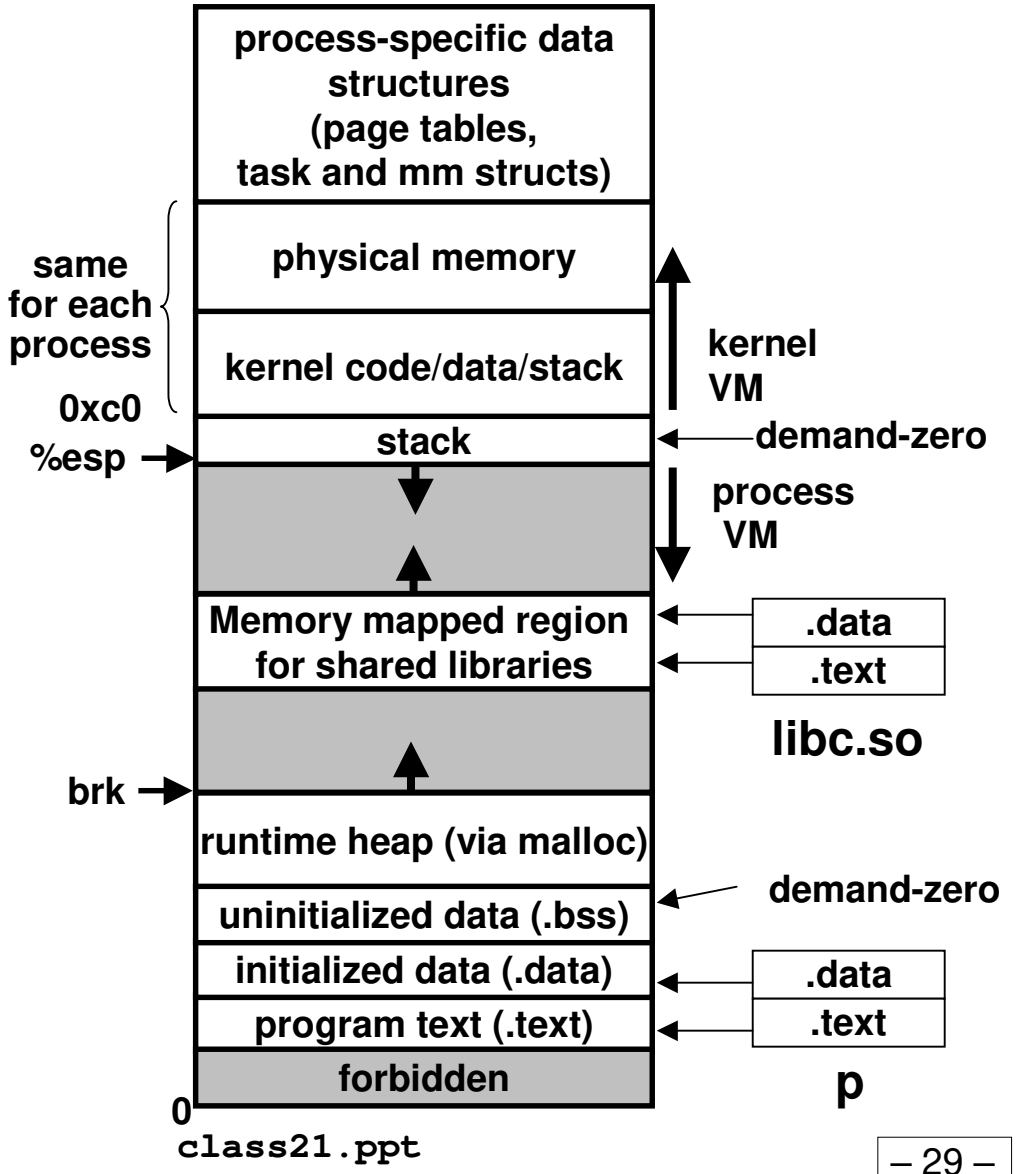
- **map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start` (usually 0 for don't care).**
  - prot: MAP_READ, MAP_WRITE
  - flags: MAP_PRIVATE, MAP_SHARED
- **return a pointer to the mapped area.**
- **Example: fast file copy**
  - useful for applications like Web servers that need to quickly copy files.
  - mmap allows file transfers without copying into user space.

mmap() example: fast file copy

```
#include <unistd.h>
#include <sys/mman.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

/*
 * mmap.c - a program that uses mmap
 * to copy itself to stdout
 */
int main() {
  struct stat stat;
  int i, fd, size;
  char *bufp;

  /* open the file and get its size*/
  fd = open("./mmap.c", O_RDONLY);
  fstat(fd, &stat);
  size = stat.st_size;
```

```
/* map the file to a new VM area */
  bufp = mmap(0, size, PROT_READ,
    MAP_PRIVATE, fd, 0);

  /* write the VM area to stdout */
  write(1, bufp, size);
}
```

Exec() revisited



To run a new program p in the current process using exec():

- **free vm_area_struct's and page tables for old areas.**
- **create new vm_area_struct's and page tables for new areas.**
  - stack, bss, data, text, shared libs.
  - text and data backed by ELF executable object file.
  - bss and stack initialized to zero.
- **set PC to entry point in .text**
  - Linux will swap in code and data pages as needed.

Fork() revisted

To create a new process using fork:

- **make copies of the old process's mm_struct, vm_area_struct's, and page tables.**
  - at this point the two processes are sharing all of their pages.
  - How to get separate spaces without copying all the virtual pages from one space to another?
    - » "copy on write" technique.
- **copy-on-write**
  - make pages of writeable areas read-only
  - flag vm_area_struct's for these areas as private "copy-on-write".
  - writes by either process to these pages will cause page faults.
    - » fault handler recognizes copy-on-write, makes a copy of the page, and restores write permissions.
- **Net result:**
  - copies are deferred until absolutely necessary (i.e., when one of the processes tries to modify a shared page).

Memory System Summary

Cache Memory

- **Purely a speed-up technique**
- **Behavior invisible to application programmer and OS**
- **Implemented totally in hardware**

Virtual Memory

- **Supports many OS-related functions**
  - Process creation
    - » Initial
    - » Forking children
  - Task switching
  - Protection
- **Combination of hardware & software implementation**
  - Software management of tables, allocations
  - Hardware access of tables
  - Hardware caching of table entries (TLB)