15-213

"The course that gives CMU its Zip!"

Pentium/Linux Memory System March 17, 2005

Topics

- P6 address translation
- x86-64 extensions
- Linux memory management
- Linux page fault handling
- Memory mapping

Intel P6

(Bob Colwell's Chip, CMU Alumni)

Internal Designation for Successor to Pentium

- **Which had internal designation P5**

Fundamentally Different from Pentium

- **Out-of-order, superscalar operation**

Resulting Processors

- **PentiumPro (1996)**
- **Pentium II (1997)**
  - **L2 cache on same chip**
- **Pentium III (1999)**
  - **The Fish machines**

Current Systems Pentium 4

- **Different operation, but similar memory system**

Legacy Issue

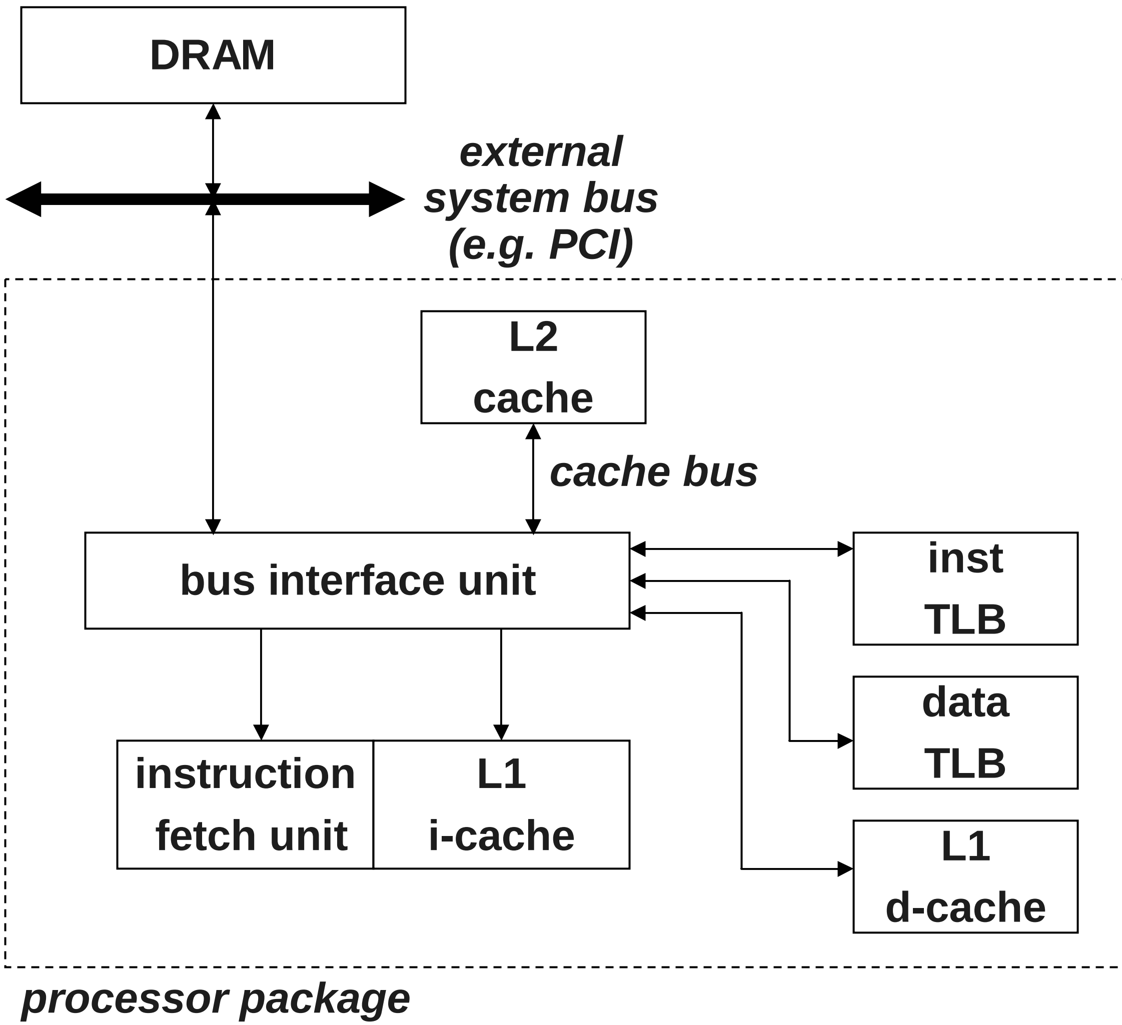
x86 Processors Support Multiple Addressing Schemes

- Segment-based
  - Variable sized blocks
  - Numerous variants
    - » Real mode
    - » Virtual-8086 mode
    - » Protected mode
  - All obsolete
- Page-based
  - Fixed size blocks
  - Virtual address: 32b
  - Physical address: 32b, 40b
  - Page sizes: 4K, 2M, 4M

What Will We Do?

- Look at the common case

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

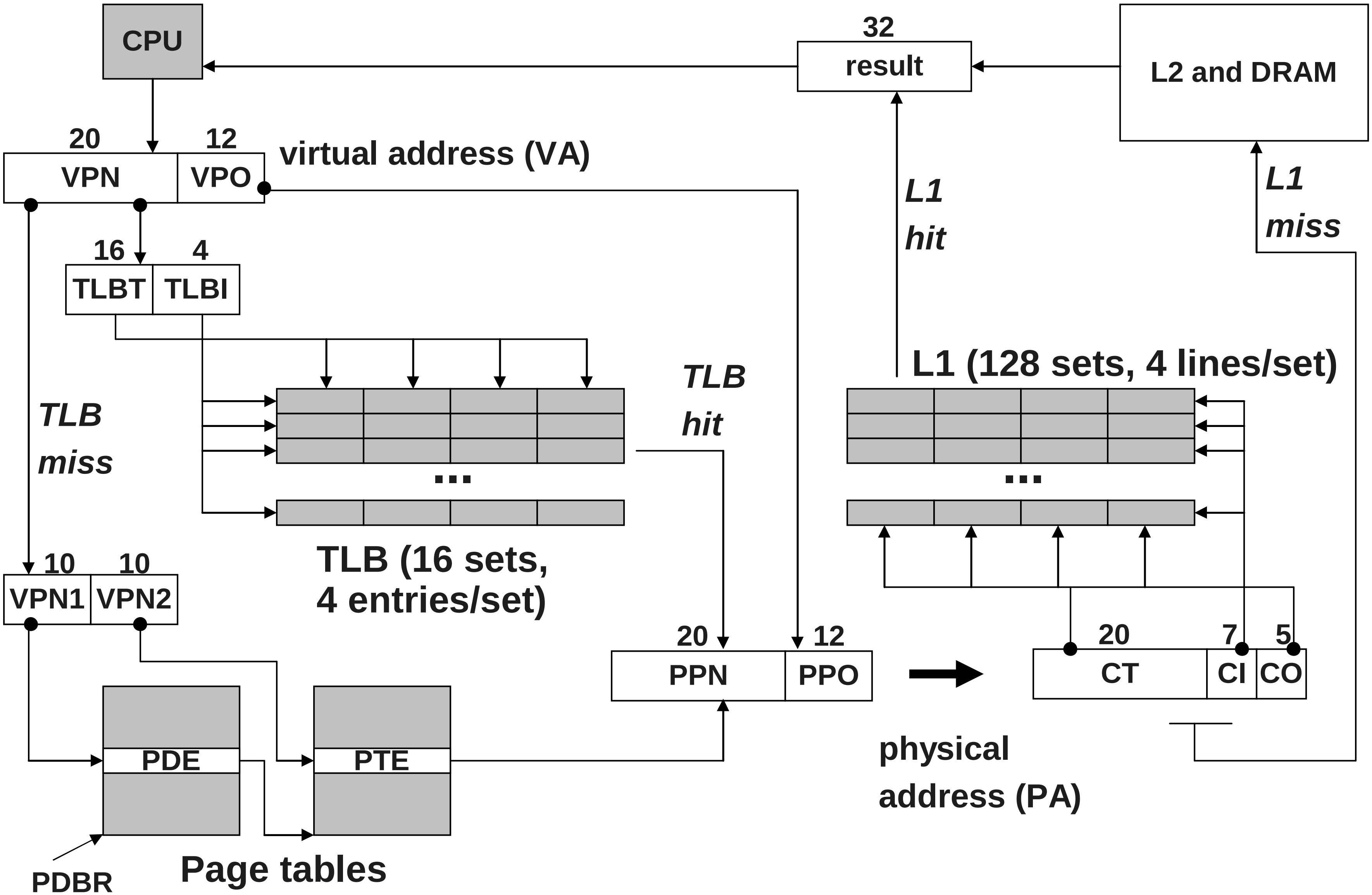
- unified
- 128 KB -- 2 MB

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

Overview of P6 Address Translation



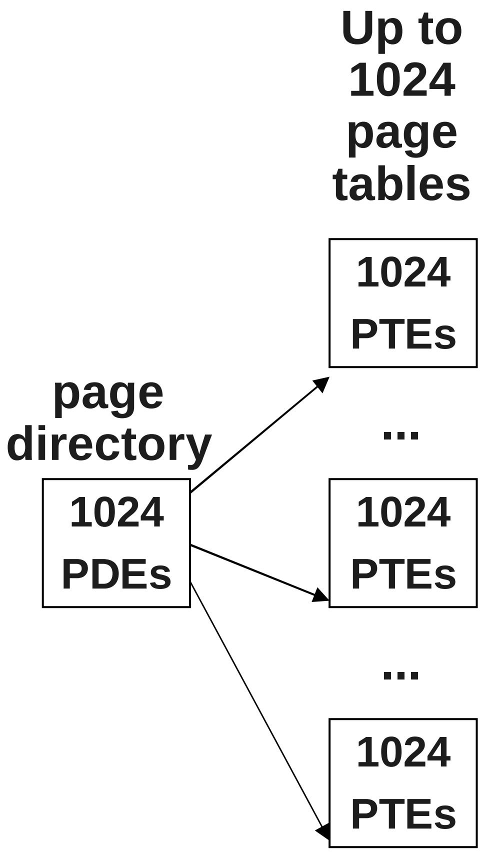
P6 2-level Page Table Structure

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)

31 12	11 9	8	7	6	5	4	3	2	1	0
Page table physical base addr	Avail	G	PS		A	CD	WT	U/S	R/W	P=1

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

<u>Avail</u>: These bits available for system programmers

<u>G</u>: global page (don’t evict from TLB on task switch)

<u>PS</u>: page size 4K (0) or 4M (1)

<u>A</u>: accessed (set by MMU on reads and writes, cleared by software)

<u>CD</u>: cache disabled (1) or enabled (0)

<u>WT</u>: write-through or write-back cache policy for this page table

<u>U/S</u>: user or supervisor mode access

<u>R/W</u>: read-only or read-write access

<u>P</u>: page table is present in memory (1) or not (0)

31 1	0
Available for OS (page table location in secondary storage)	P=0

P6 Page Table Entry (PTE)

31–12	11–9	8	7	6	5	4	3	2	1	0
Page physical base address	Avail	G	0	D	A	CD	WT	U/S	R/W	P=1

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

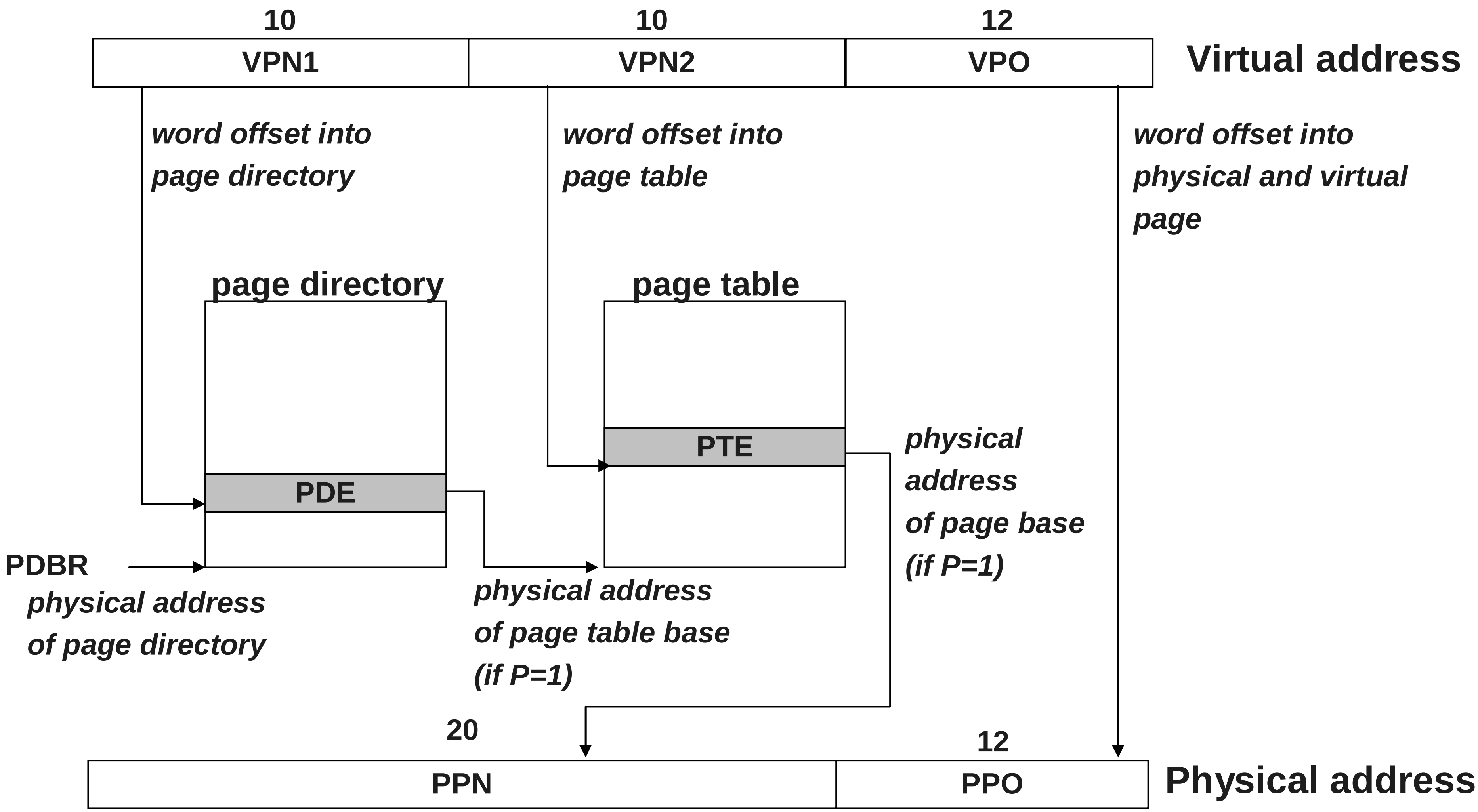
U/S: user/supervisor

R/W: read/write

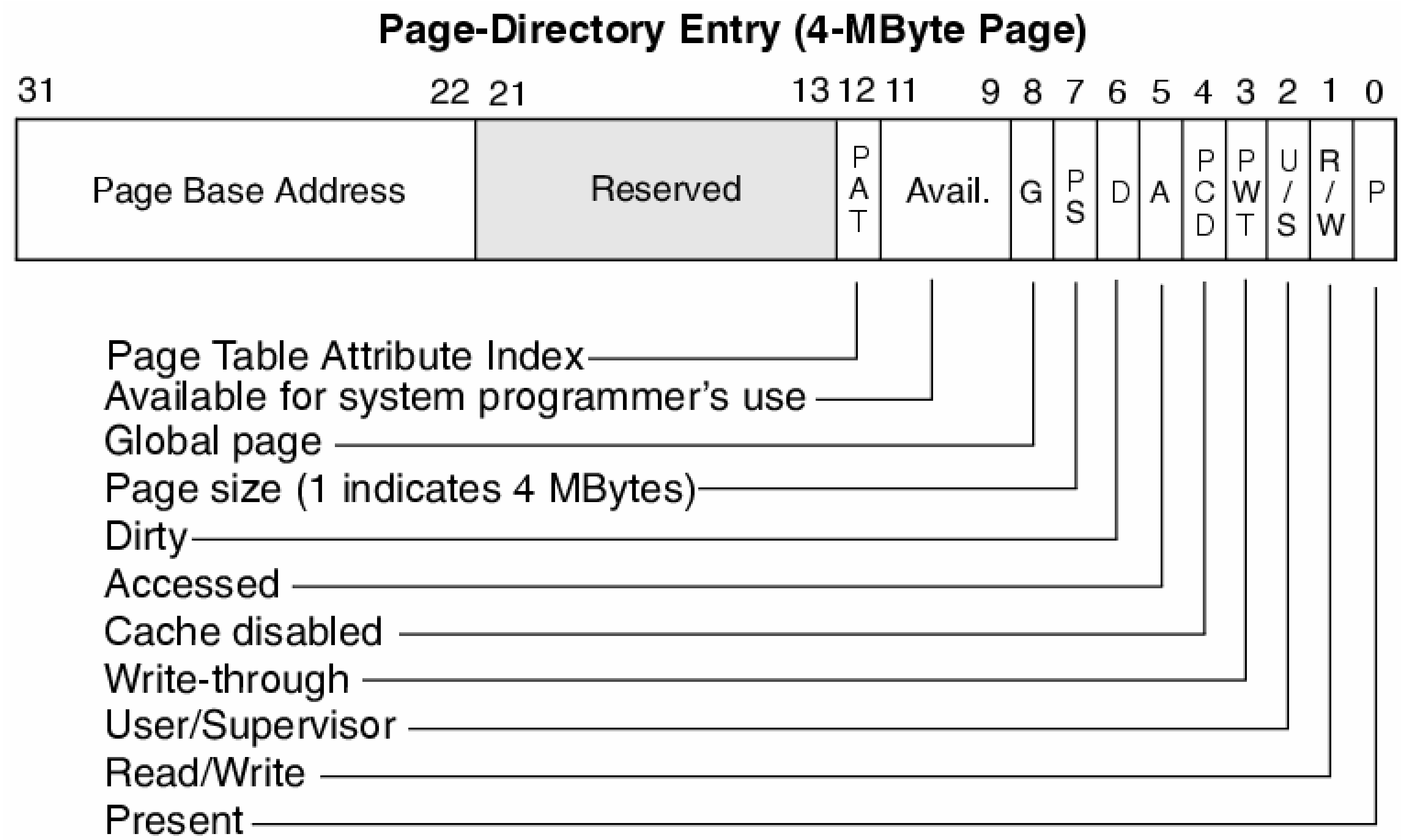
P: page is present in physical memory (1) or not (0)

31–1	0
Available for OS (page location in secondary storage)	P=0

How P6 Page Tables Map Virtual Addresses to Physical Ones

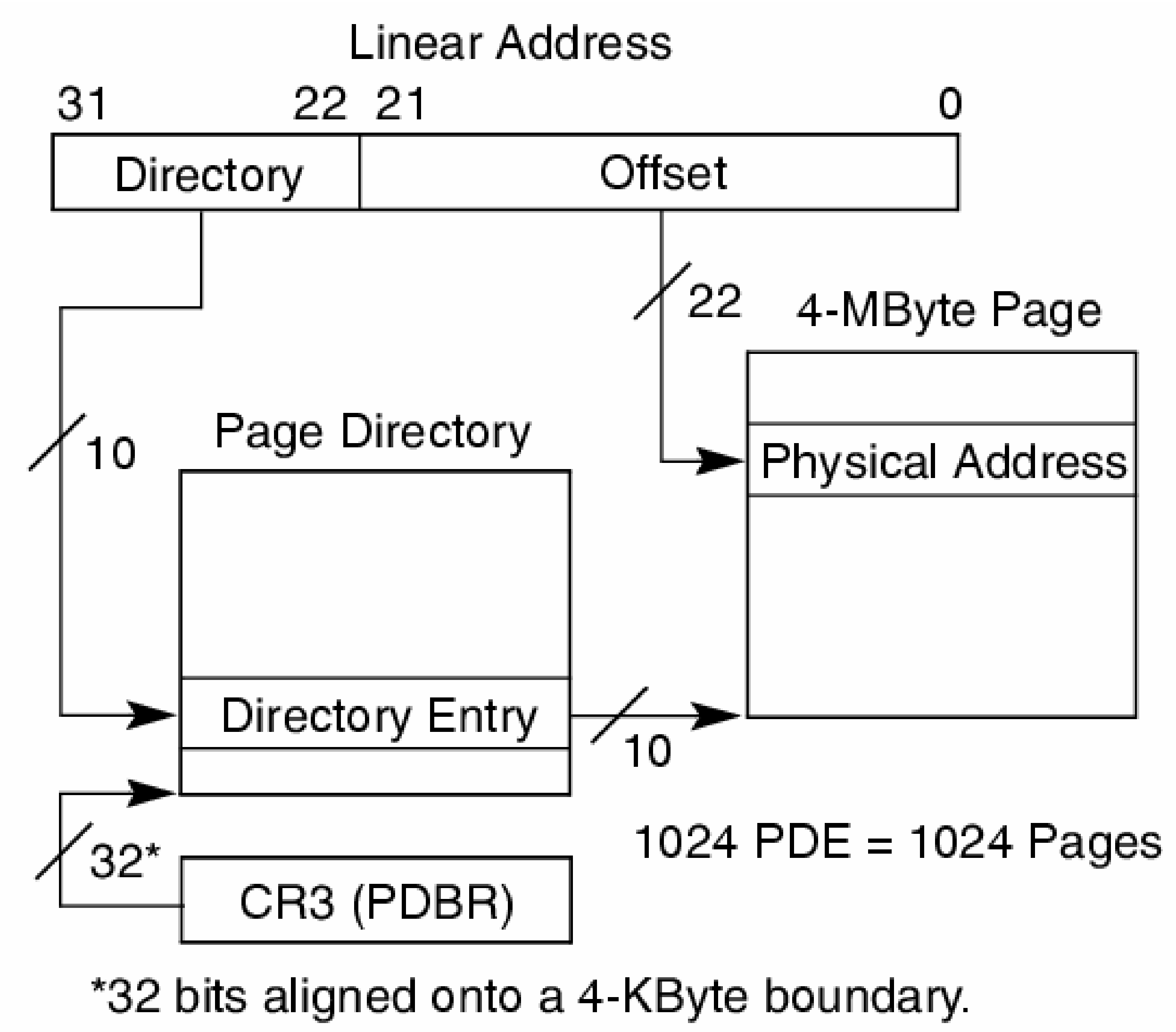


4Mbyte PDE's



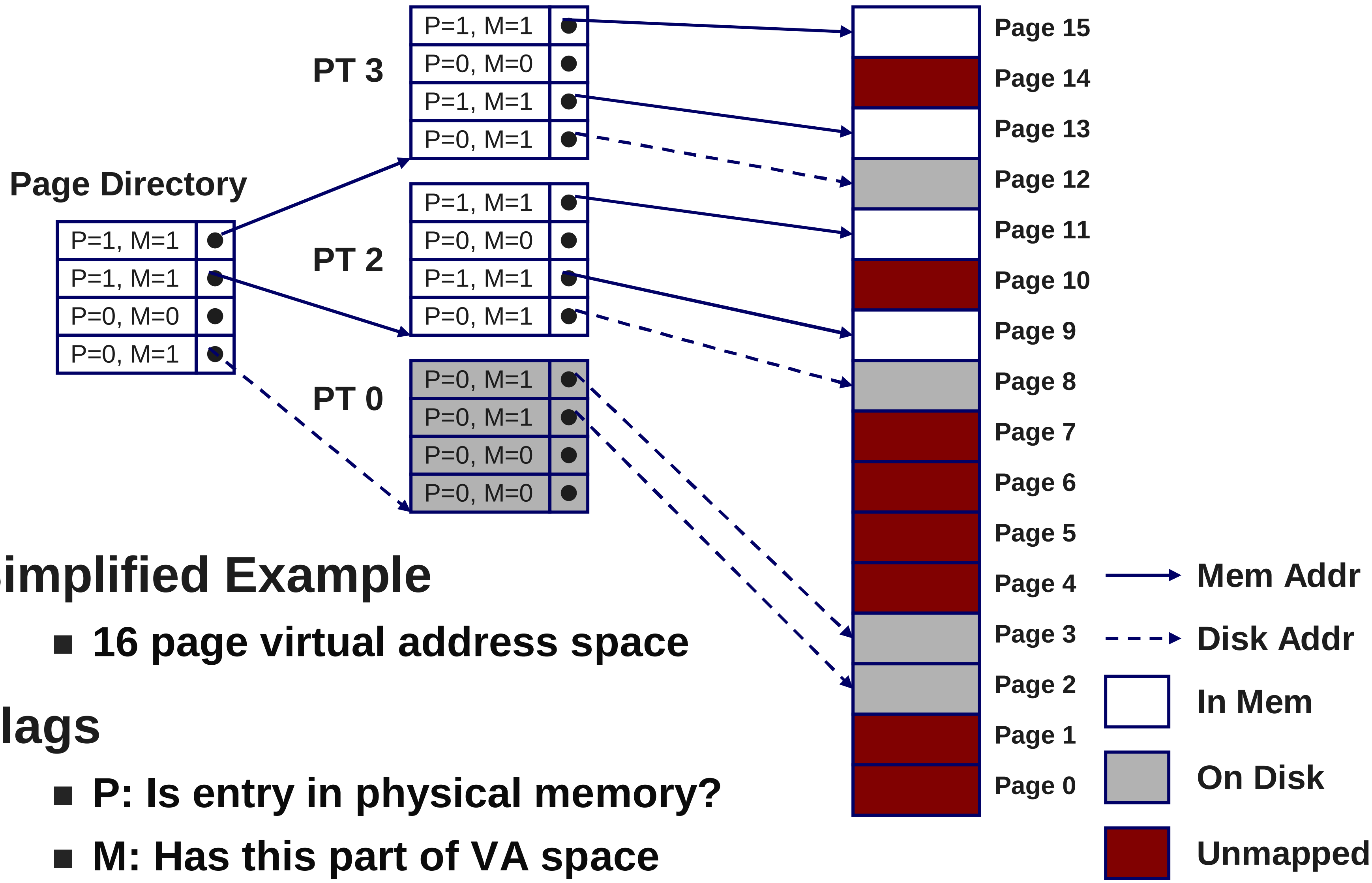
Page-Directory Entry (4-MByte Page)
31
22 21
13 12 11
9 8 7 6 5 4 3 2 1 0
Page Base Address
Reserved
PAT
Avail.
G
PS
D
A
PCD
PWT
U/S
R/W
P
Page Table Attribute Index
Available for system programmer's use
Global page
Page size (1 indicates 4 MBytes)
Dirty
Accessed
Cache disabled
Write-through
User/Supervisor
Read/Write
Present

Support for 4Mbyte Pages



Page Directory occupies single 4KB page **(1024 4-byte entries)**

Representation of VM Address Space



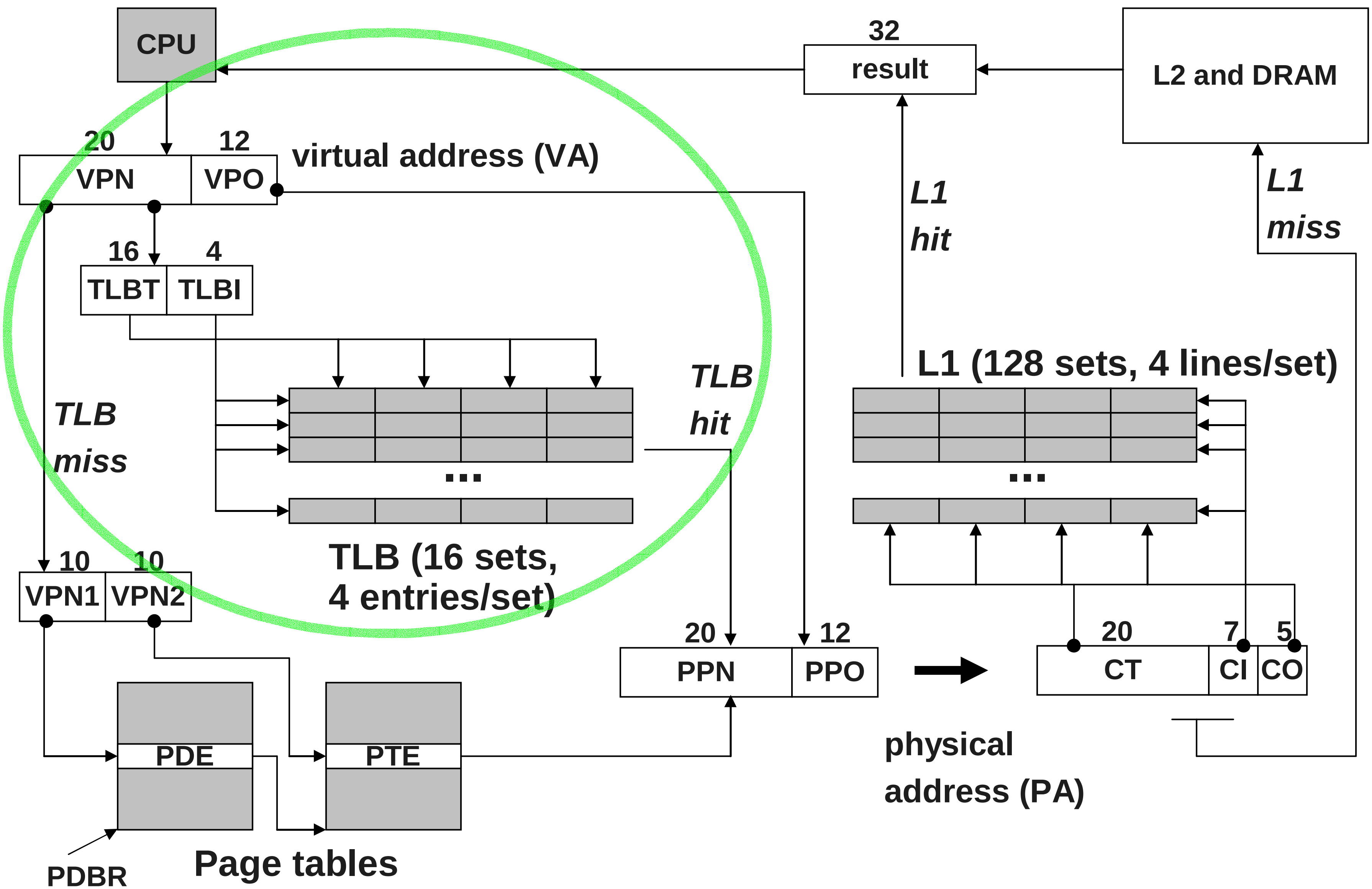
Simplified Example

- 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):

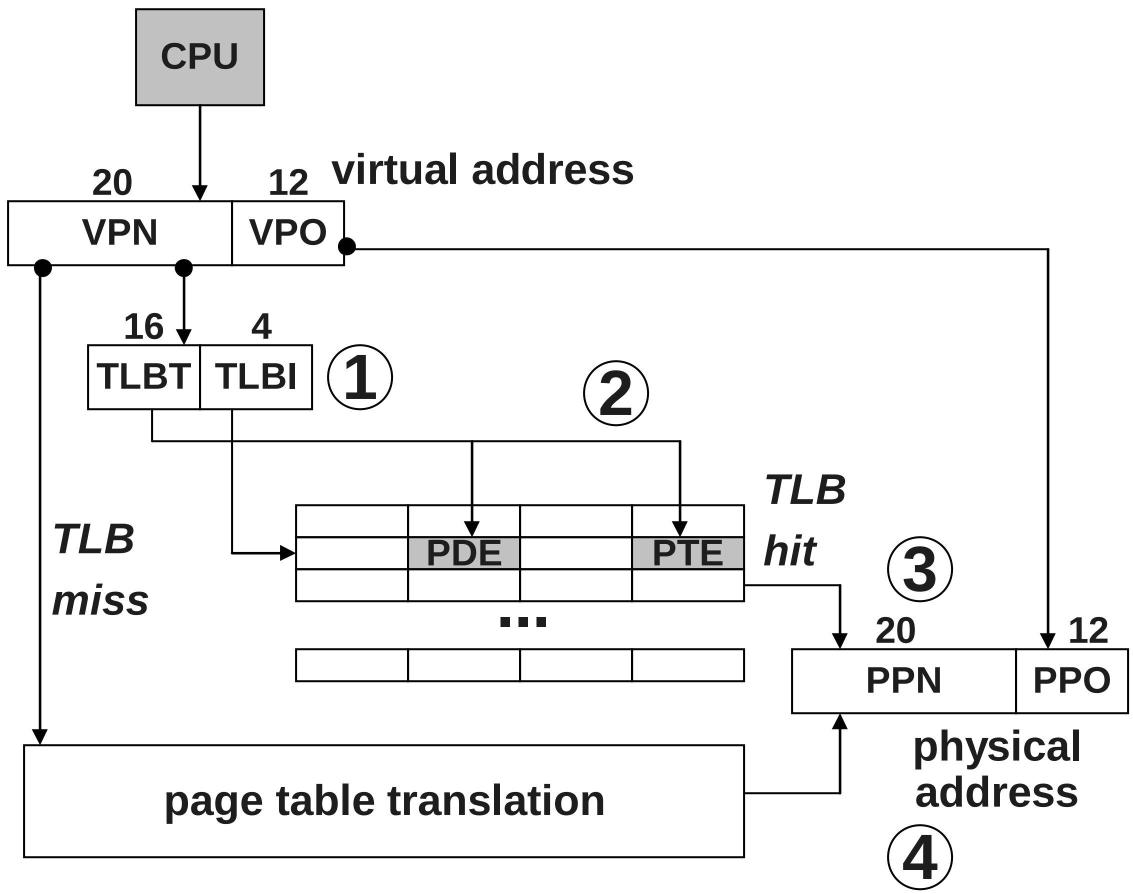
32	16	1	1
PDE/PTE	Tag	PD	V

- V: indicates a valid (1) or invalid (0) TLB entry
- PD: is this entry a PDE (1) or a PTE (0)?
- tag: disambiguates entries cached in the same set
- PDE/PTE: page directory or page table entry

- **Structure of the data TLB:**
  - 16 sets, 4 entries/set

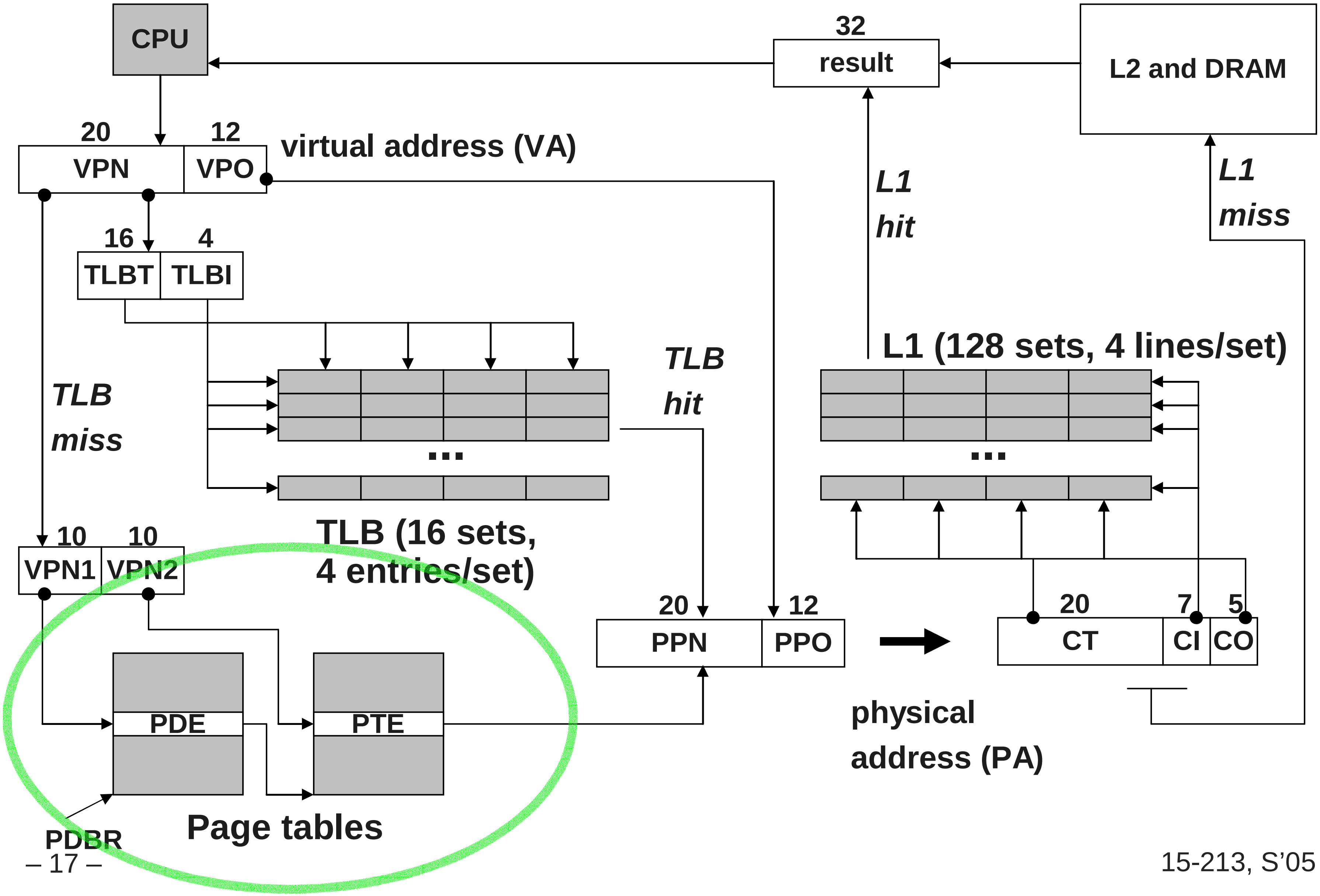
entry	entry	entry	entry	set 0
entry	entry	entry	entry	set 1
entry	entry	entry	entry	set 2
...				
entry	entry	entry	entry	set 15

Translating with the P6 TLB

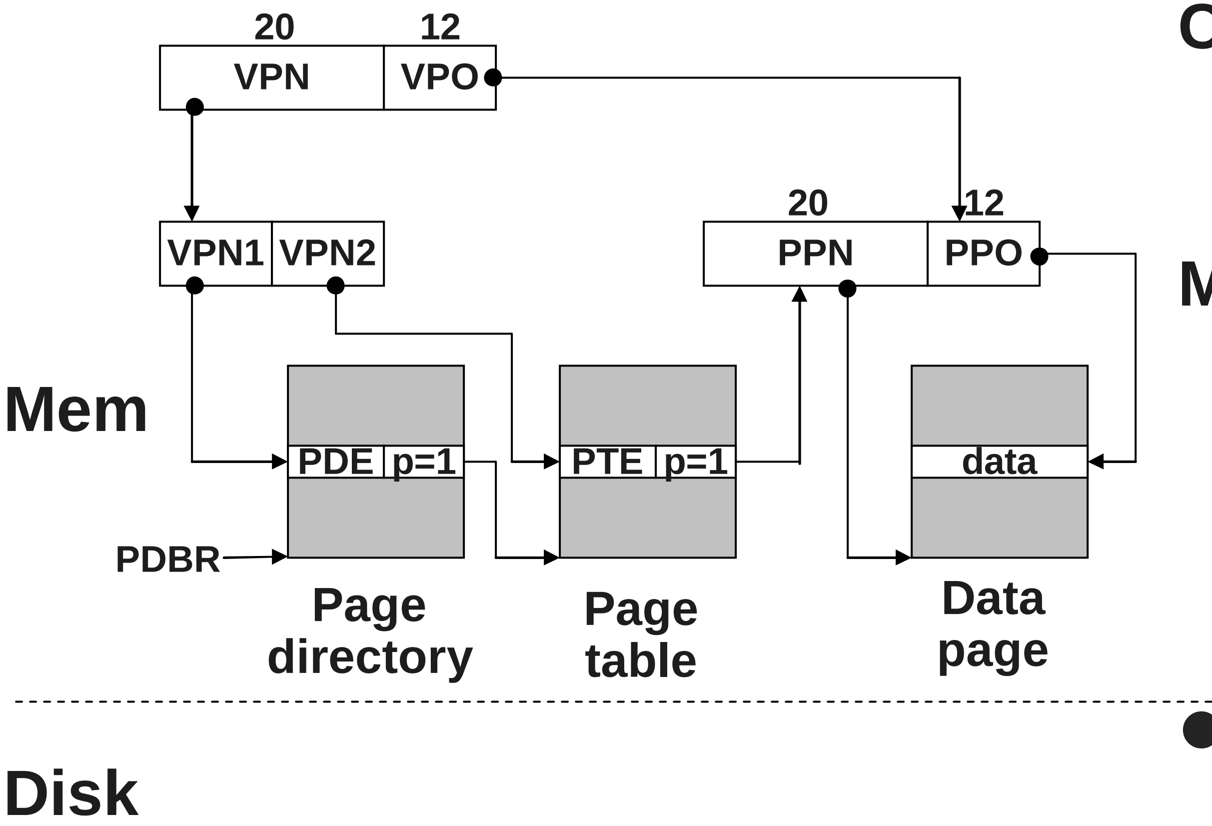


1. Partition VPN into TLBT and TLBI.
2. Is the PTE for VPN cached in set TLBI?
3. <u>Yes</u>: then build physical address.
4. <u>No</u>: then read PTE (and PDE if not cached) from memory and build physical address.

P6 Page Table Translation



Translating with the P6 Page Tables (case 1/1)



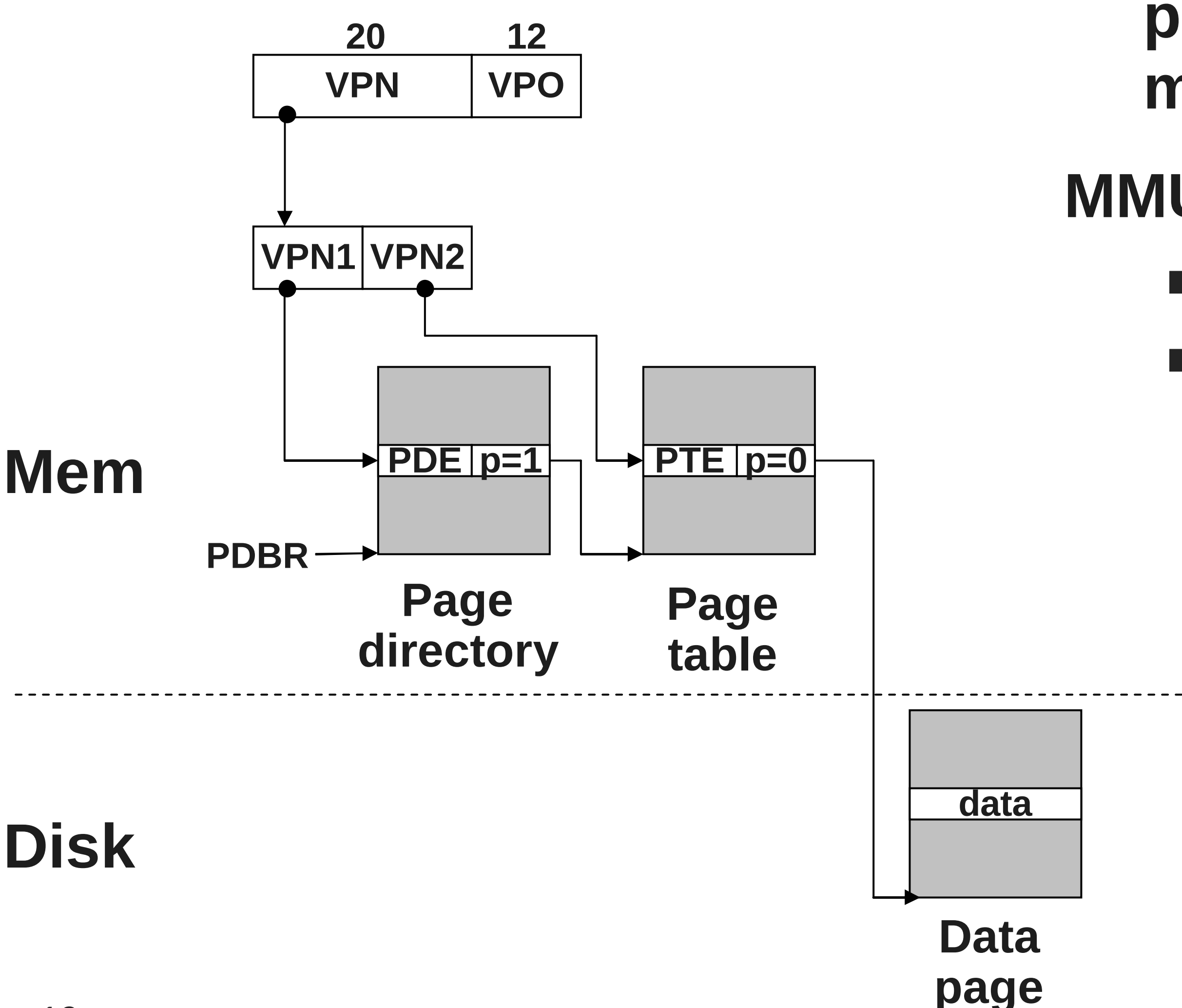
Case 1/1: page table and page present.

MMU Action:

- MMU builds physical address and fetches data word.

- OS action
  - none

Translating with the P6 Page Tables (case 1/0)

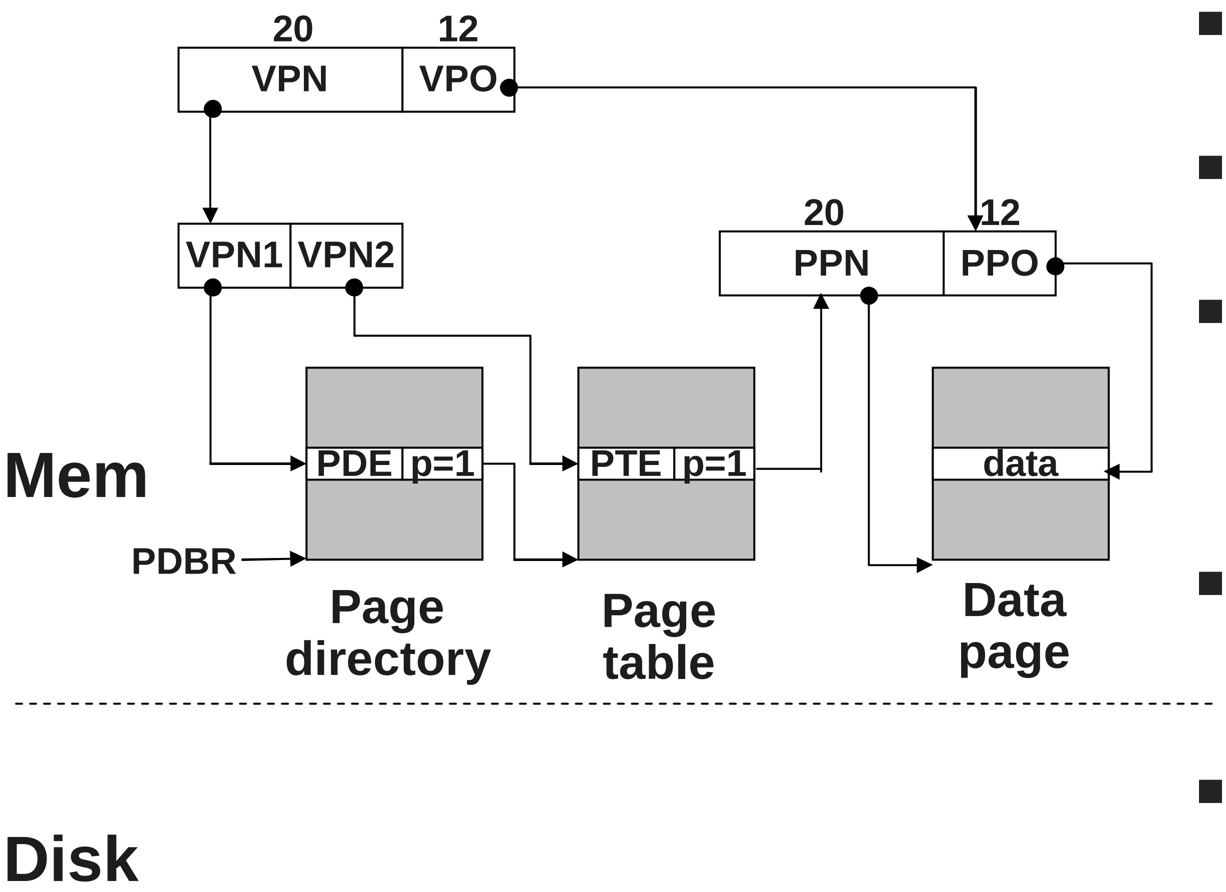


Case 1/0: page table present but page missing.

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

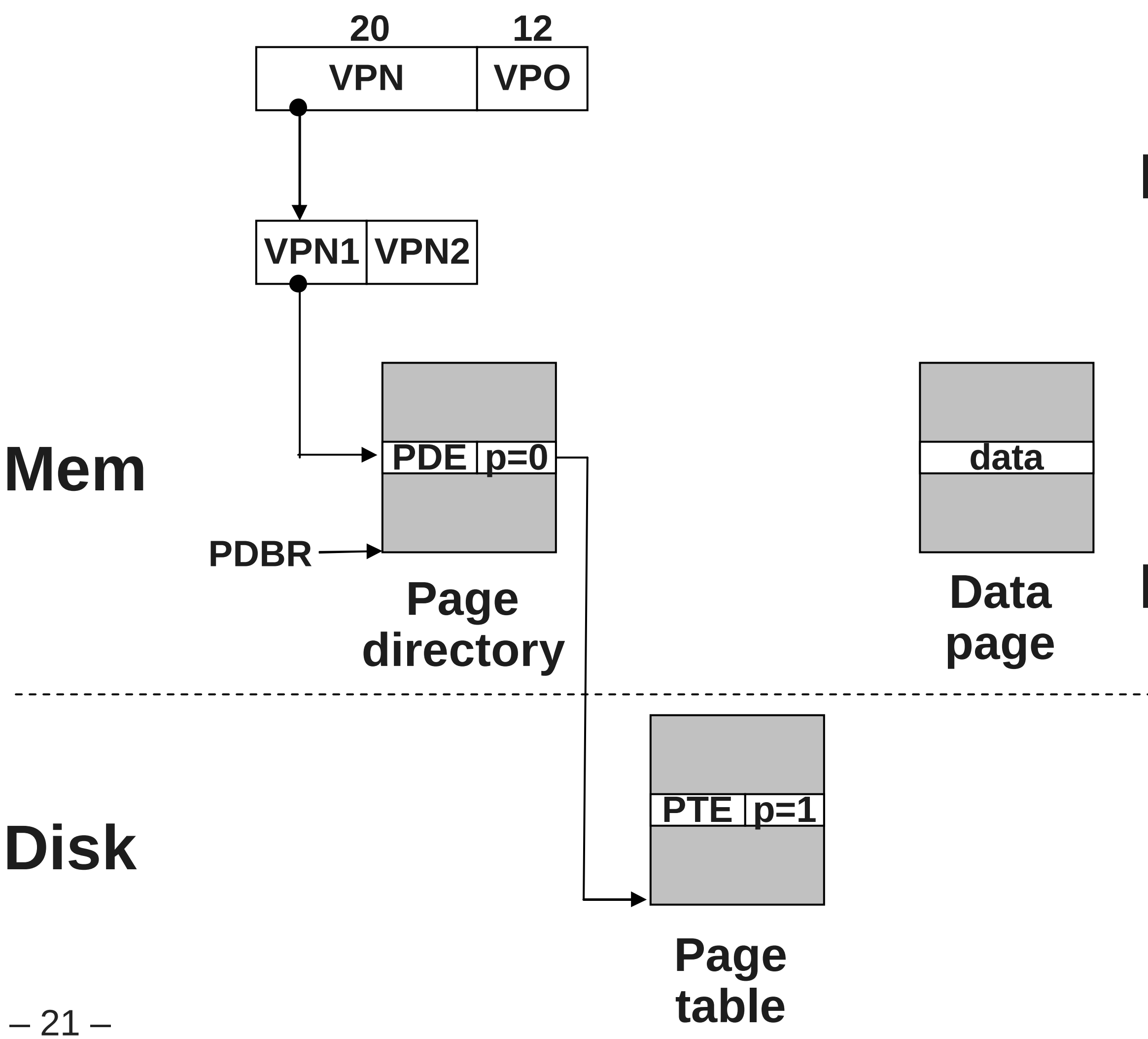
Translating with the P6 Page Tables (case 1/0, cont)



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.

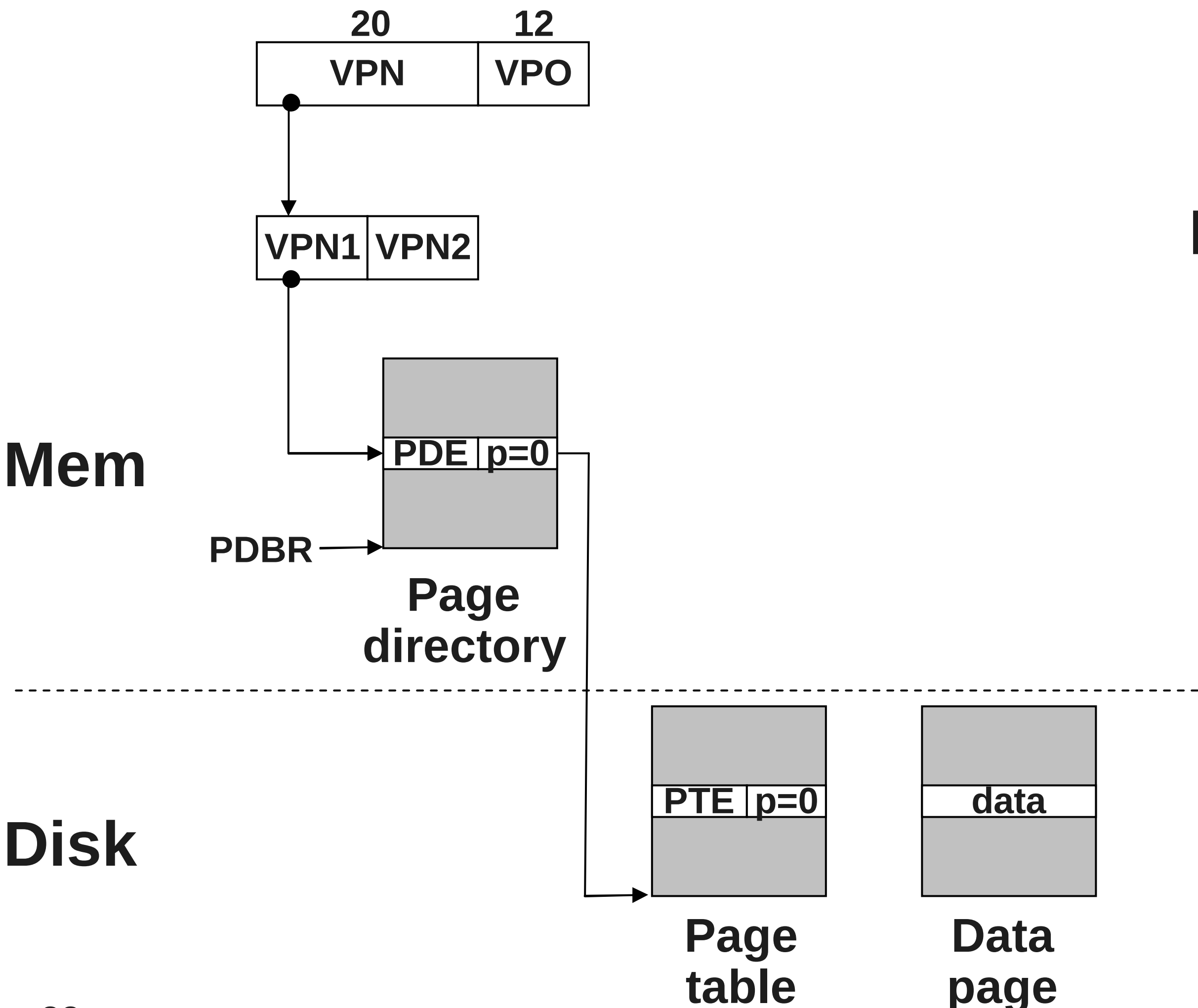
Introduces consistency issue.

- 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)

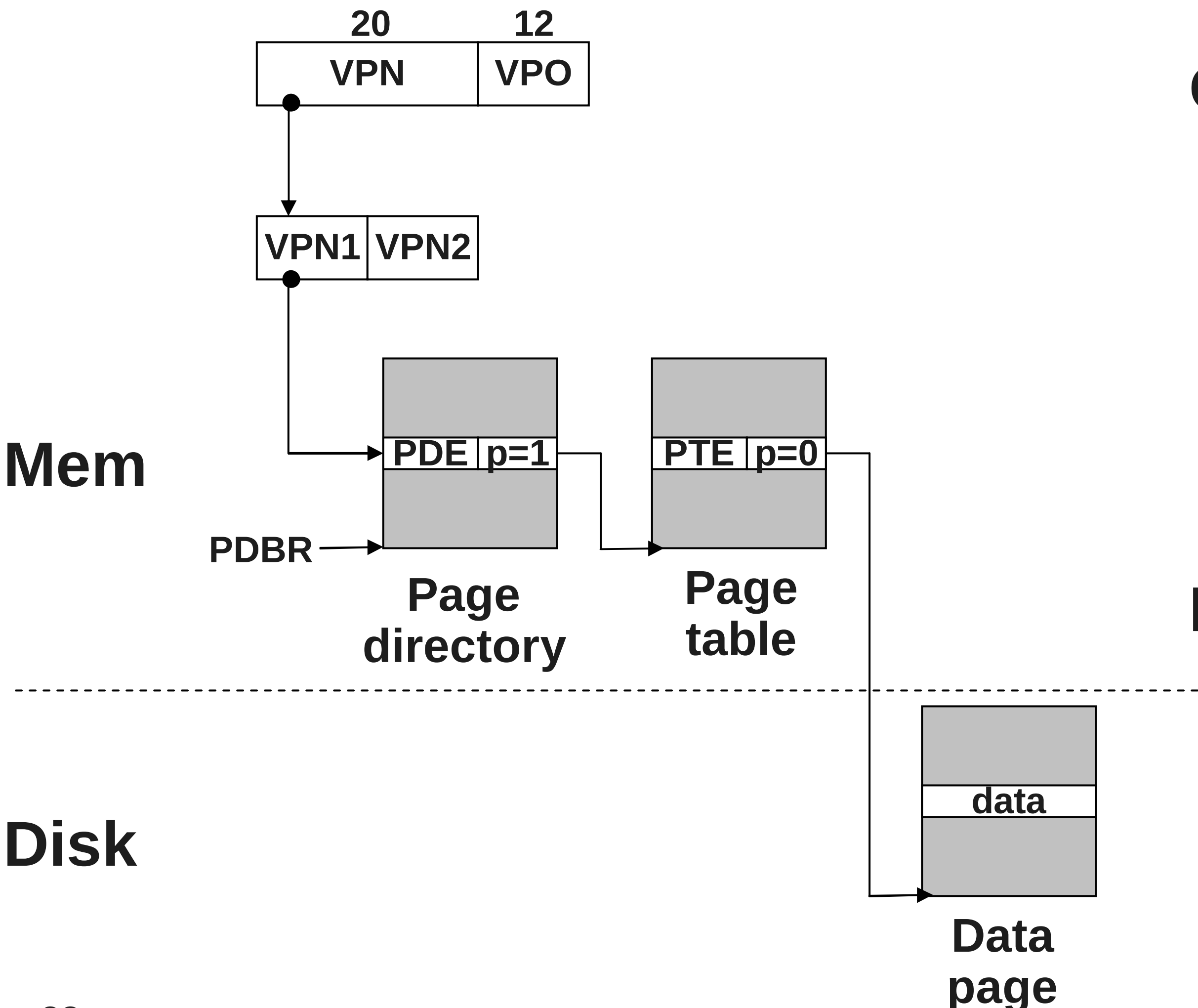


Case 0/0: page table and page missing.

MMU Action:

- page fault exception

Translating with the P6 Page Tables (case 0/0, cont)

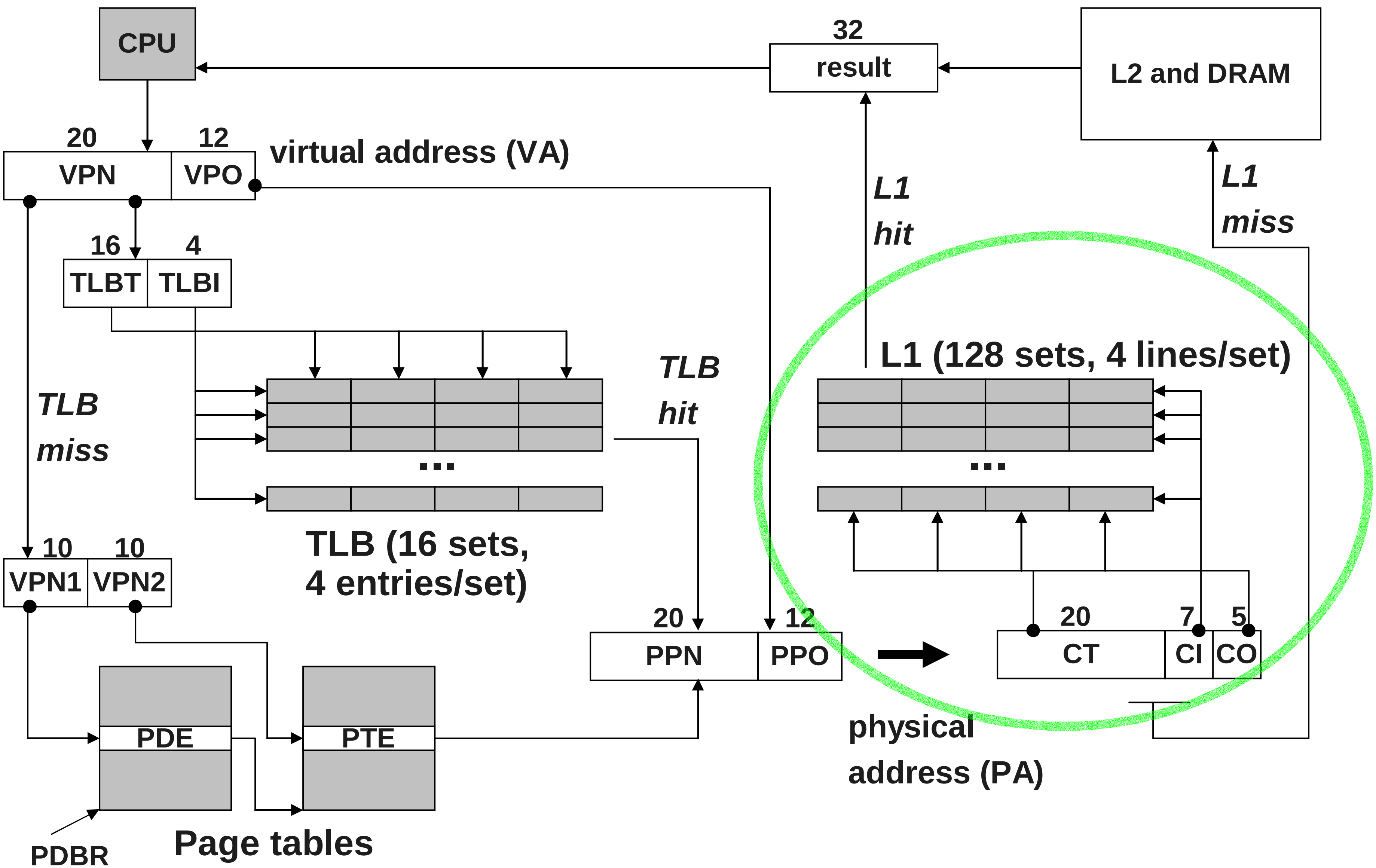


OS action:

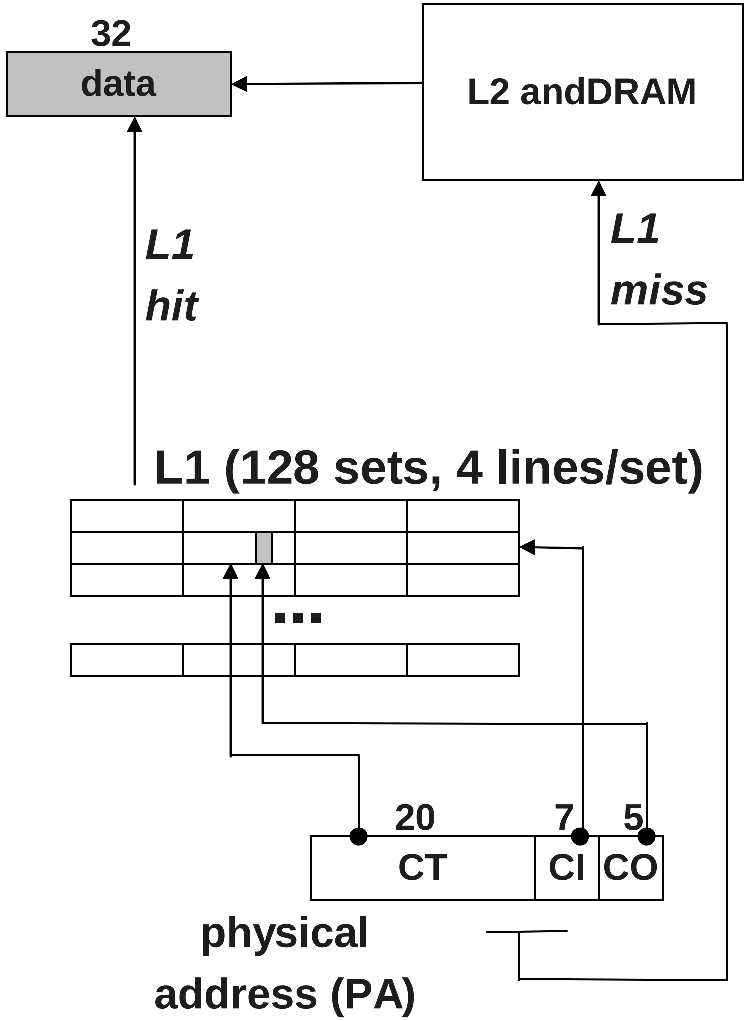
- swap in page table.
- restart faulting instruction by returning from handler.

Like case 0/1 from here on.

P6 L1 Cache Access

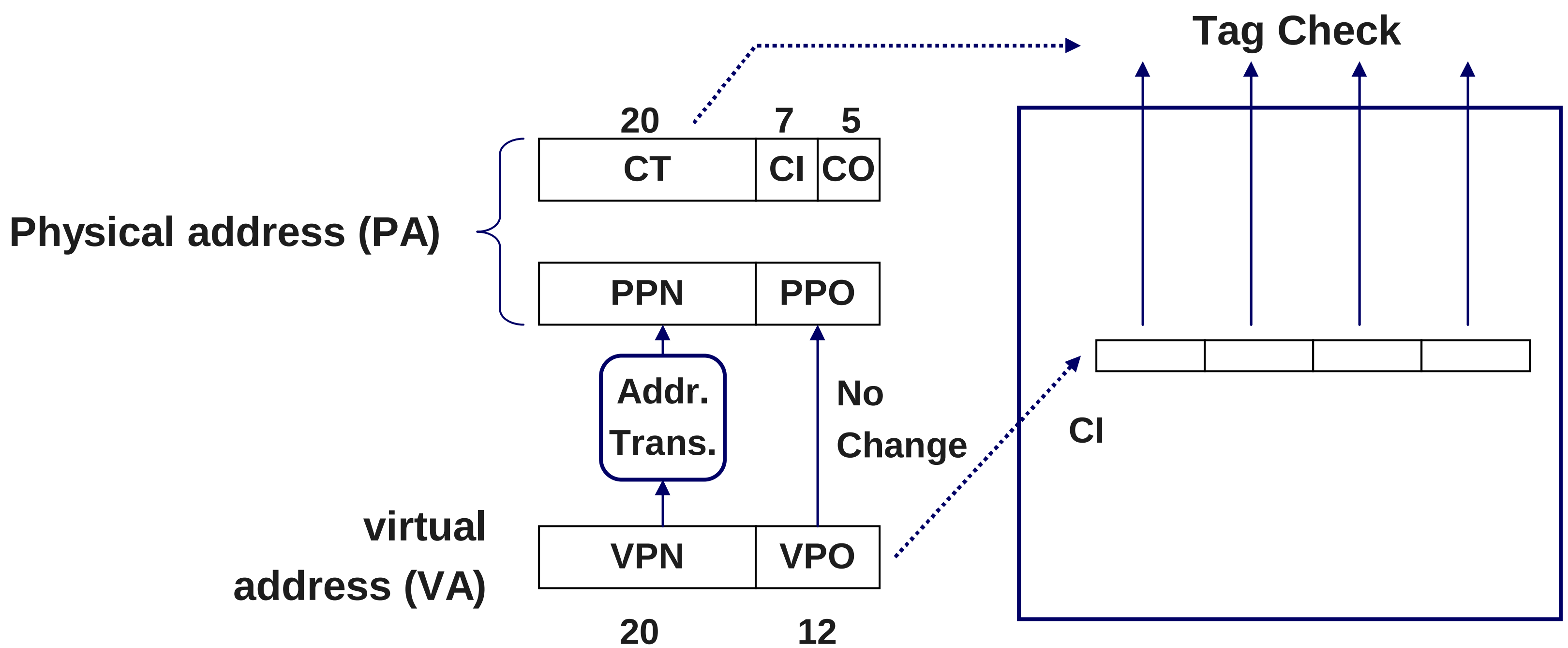


L1 Cache Access



- 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 taking place
- Then check with CT from physical address
- "Virtually indexed, physically tagged"
- Cache carefully sized to make this possible

x86-64 Paging

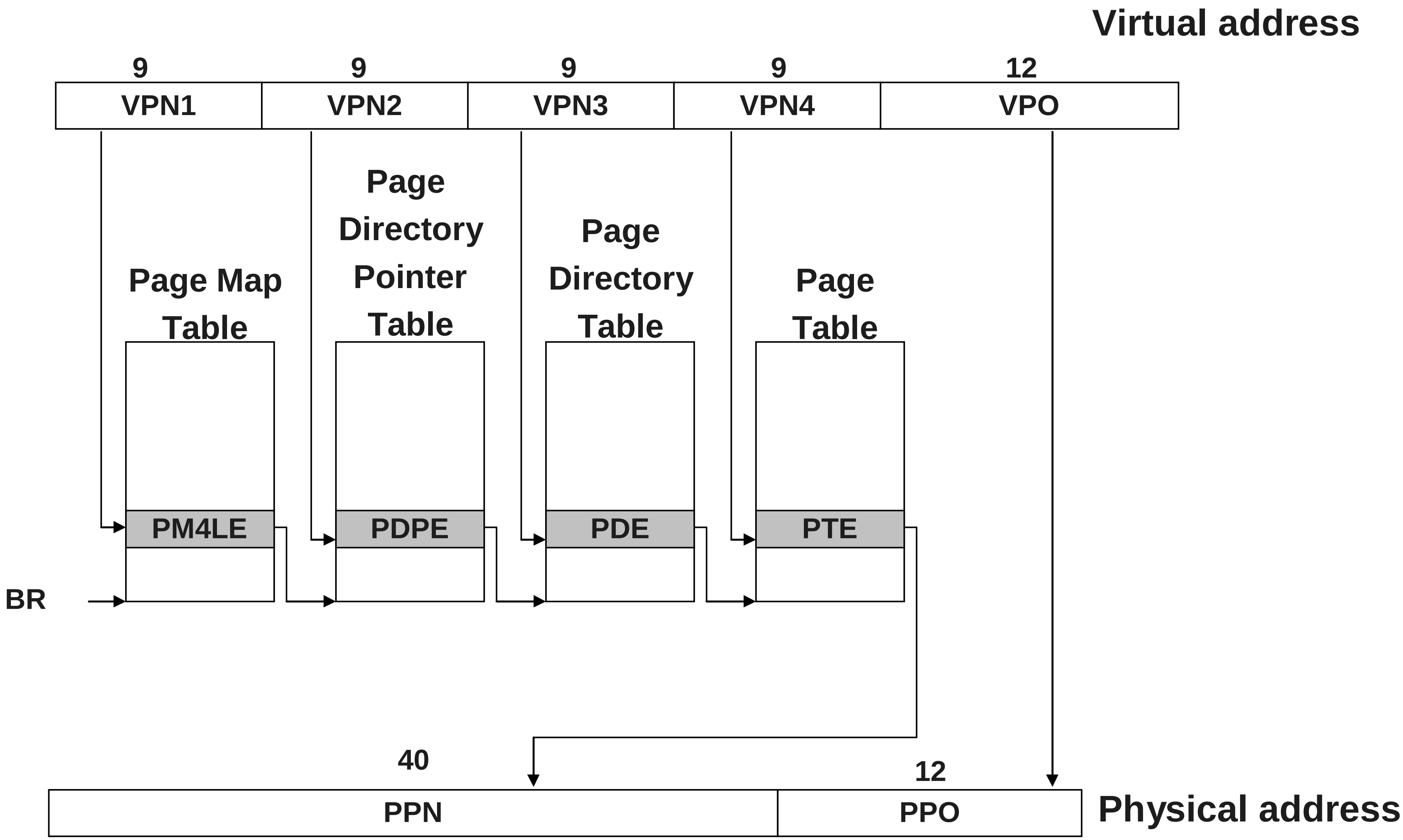
Origin

- AMD's way of extending x86 to 64-bit instruction set
- Intel has followed with "EM64T"

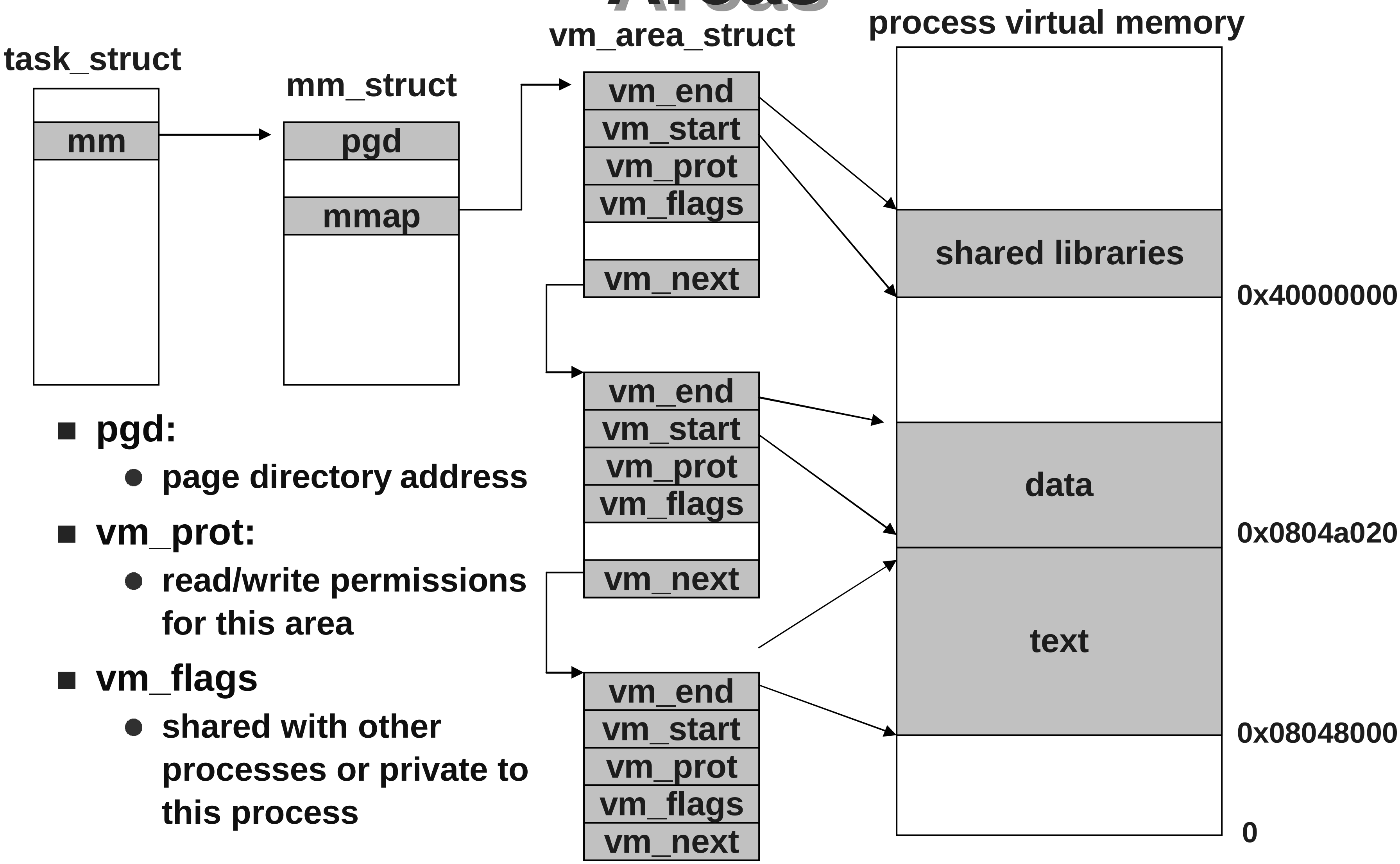
Requirements

- 48 bit virtual address
  - 256 terabytes (TB)
  - Not yet ready for full 64 bits
- 52 bit physical address
  - Requires 64-bit table entries
- 4KB page size
  - Only 512 entries per page

x86-64 Paging

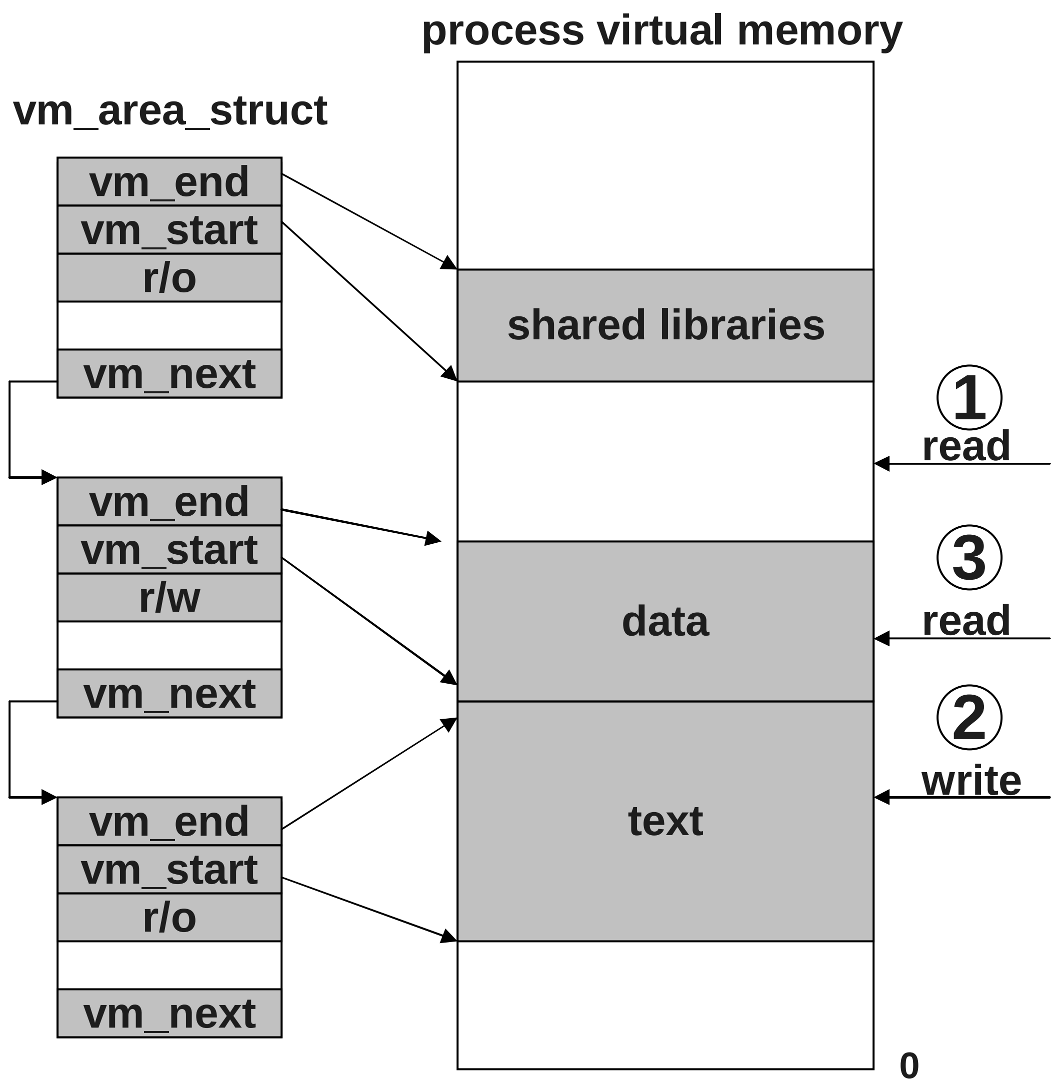


Linux Organizes VM as Collection of "Areas"



- **pgd:**
  - page directory address
- **vm_prot:**
  - read/write permissions for this area
- **vm_flags**
  - shared with other processes or private to this process

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)

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)
```

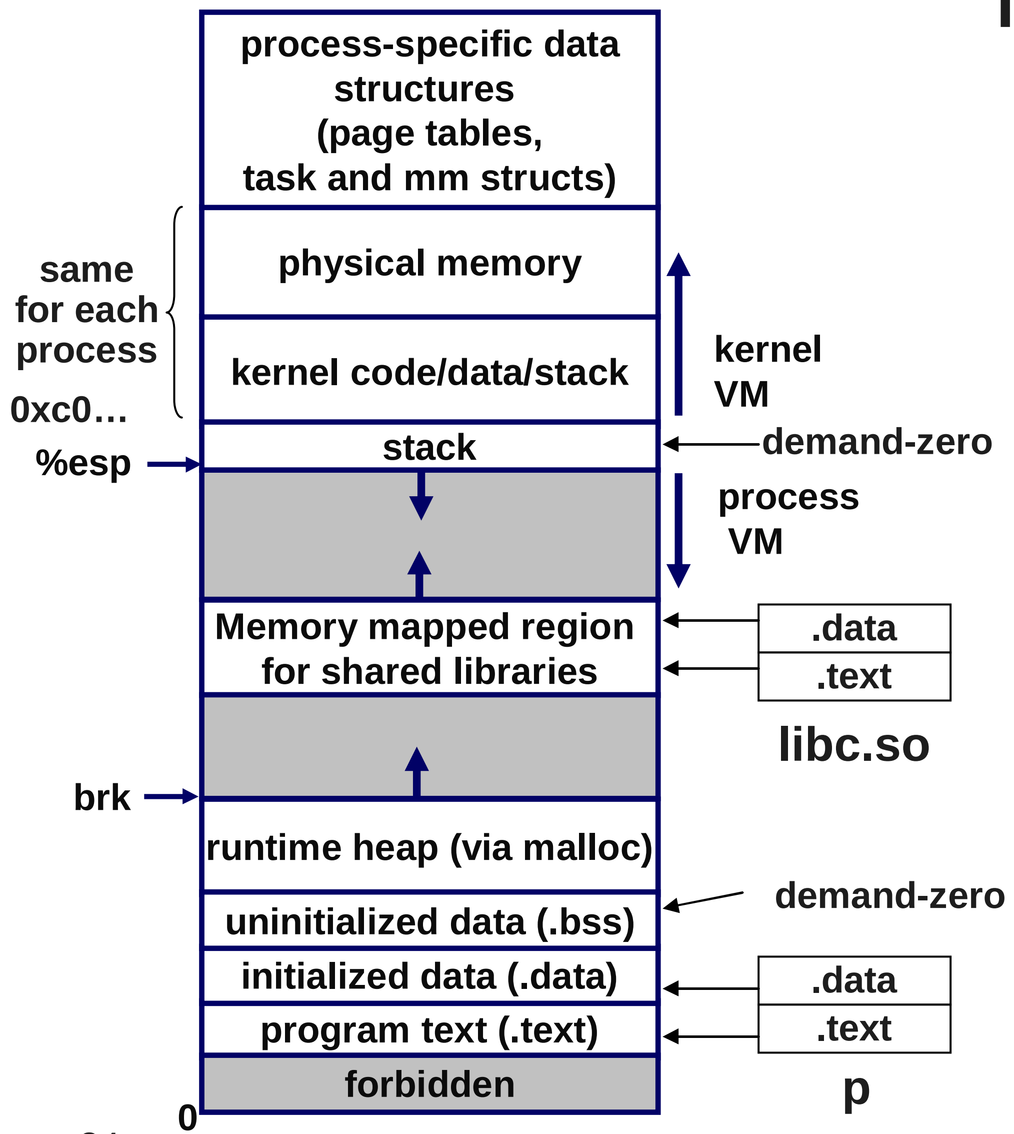
- map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start` (usually 0 for don't care).
  - `prot`: MAP_READ, MAP_WRITE
  - `flags`: MAP_PRIVATE, MAP_SHARED
- return a pointer to the mapped area.
- Example: fast file copy
  - useful for 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 & 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() Revisited

How does OS know when a page can be deallocated?

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 (mostly) 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)