CMPE110 Lecture 22
Virtual Memory

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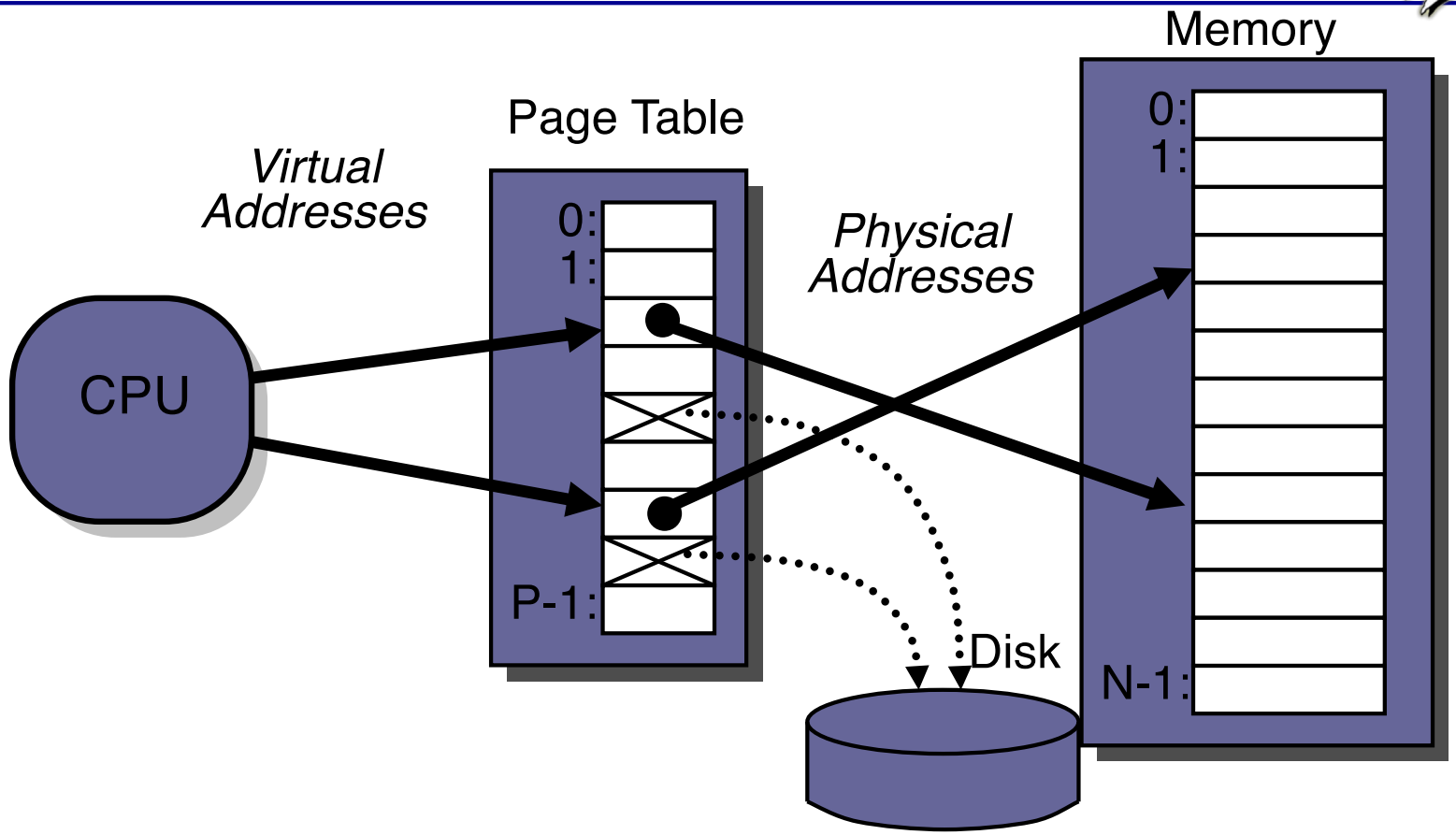
https://canvas.ucsc.edu/courses/19290

Announcements

- Review Lecture on Monday March 11th
  - Given by Peter, Minghao, Saba
  - Propose Topics on Piazza now
  - If we have lots of topics, well poll and select on Friday

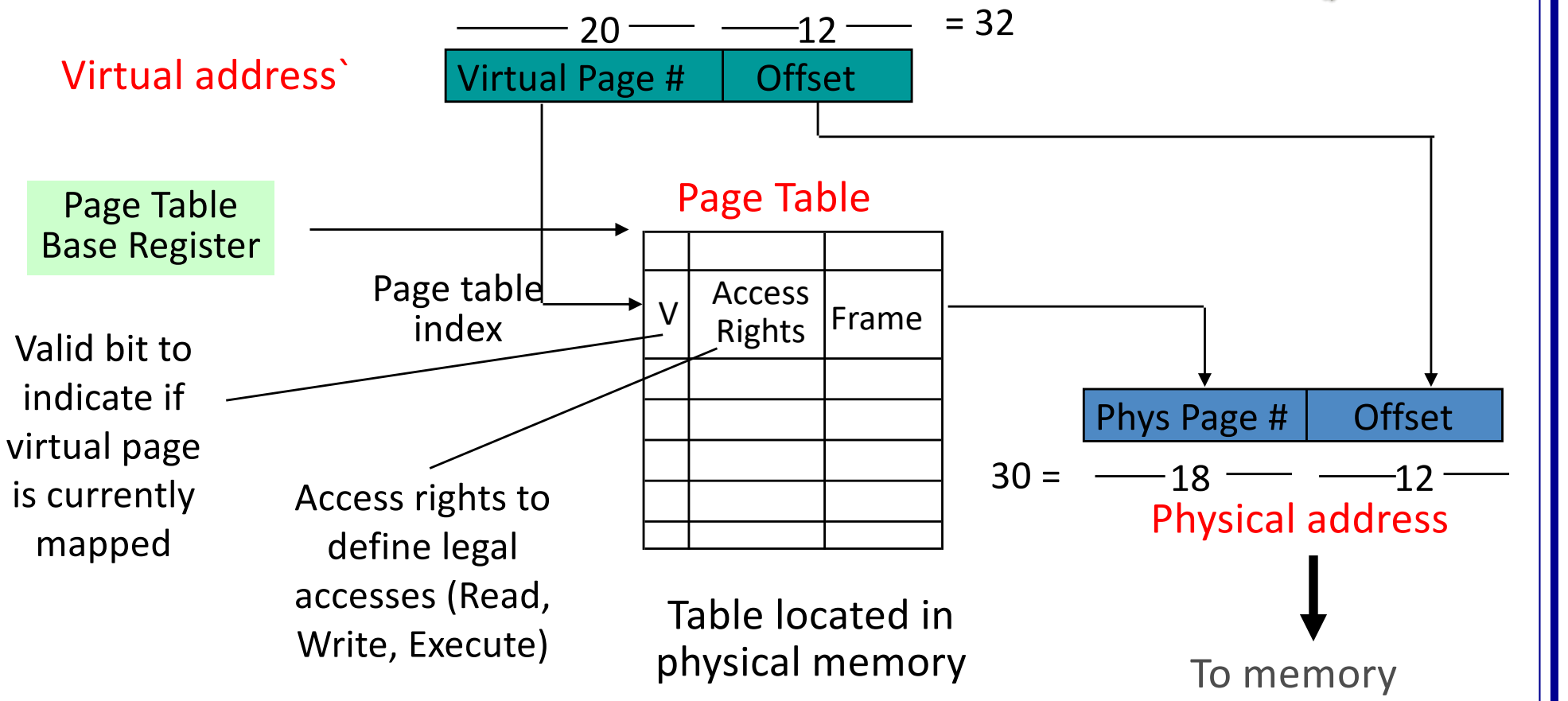
Review

Virtual Memory



- HW translates addresses using an OS-managed lookup table
- Indirection allows redirection and checks!

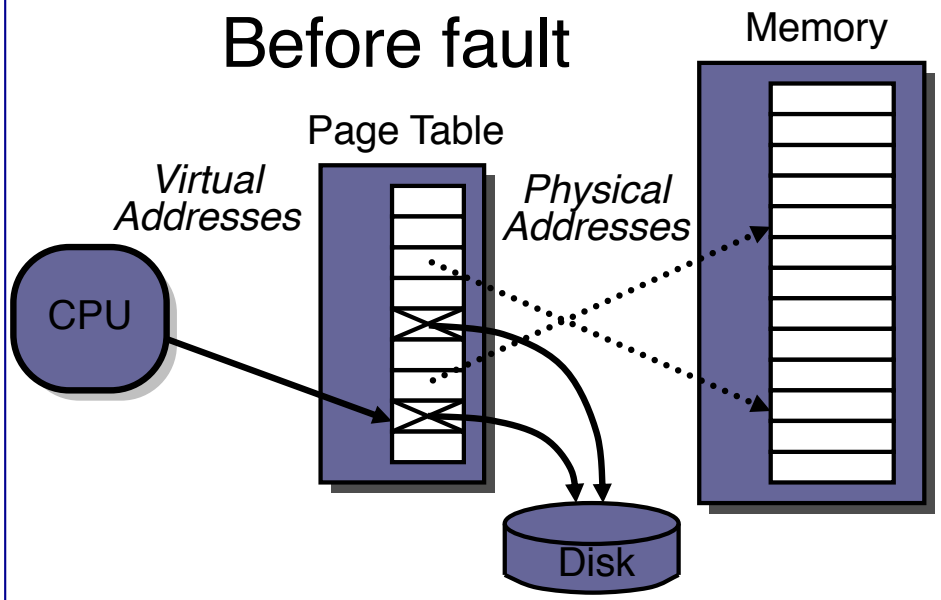
Page Table

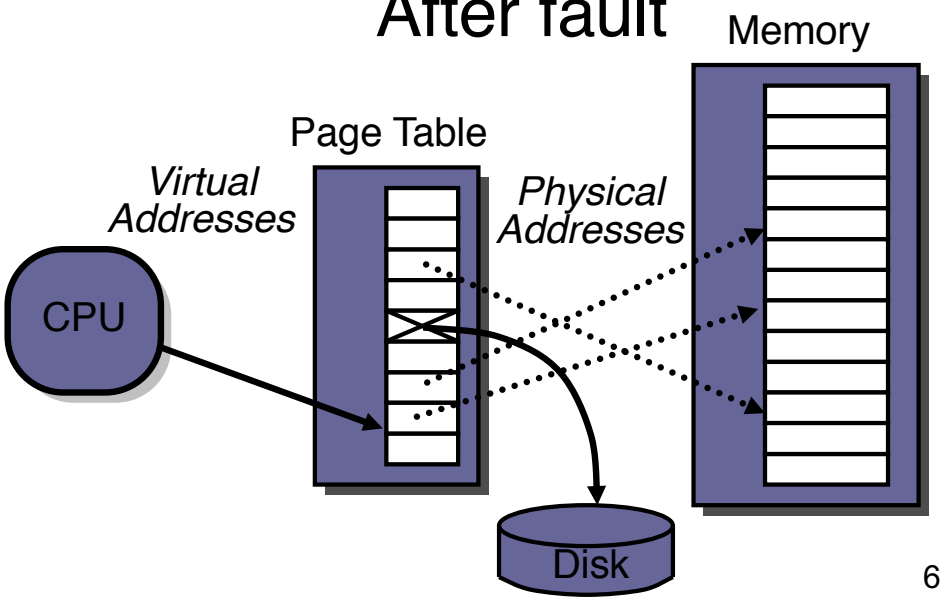


- One page table per process stored in memory
  - Process == instance of program
- One entry per virtual page number

Page Faults

- Page fault → an exception case
  - HW indicates exception cause and problematic address
  - OS handler invoked to move data from disk into memory
    - Current process suspends, others can resume
    - OS has full control over placement
  - When process resumes, repeat load or store





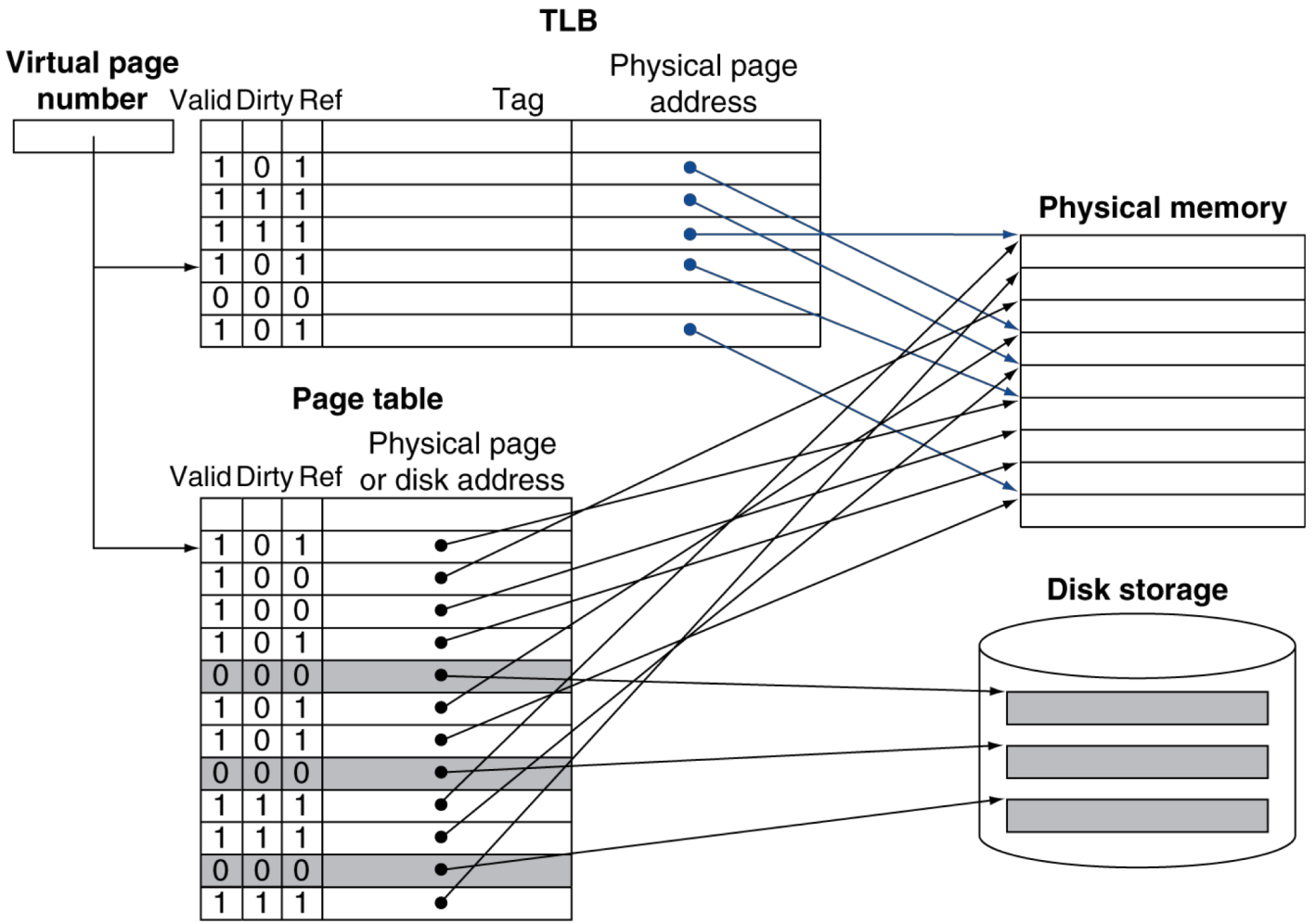
Wait, How About Performance?

- Virtual memory is great but
- We just doubled the memory accesses
  - A load requires an access to the page table first
  - Then an access to the actual data
- How can we do translation fast?
  - Without an additional memory access?

Translation Look-aside Buffer

- TLB = a hardware cache just for translation entries
  - A hardware cache specializing in page table entries
- Key idea: locality in accesses → locality in translations
- TLB design: similar issues to all caches
  - Basic parameters: capacity, associativity replacement policy
  - Basic optimizations: instruction/data TLBs, multi-level TLBs, …
  - Misses may be handled by HW or SW
    - x86: hardware services misses
    - MIPS: software services misses through exception

TLB Organization



TLB Entries

- Each TLB entry stores a page table entry (PTE)
- TLB entry data → PTE entry fields
  - Physical page numbers
  - Permission bits (RXW)
  - Other PTE information (dirty bit, etc)
- The TLB entry metadata
  - Tag: portion of virtual page # not used to index the TLB
    - Depends on the TLB associativity
  - Valid bit
  - LRU bits
    - If TLB is associative and LRU replacement is used

Example TLB

- TLB entry design
  - Addresses are 32 bits with 4 KB pages (12 bit offset)
  - TLB has 64 entries, 4-way set associative
  - Each entry is 42 bits wide:

16	6	6	20	1	1	1	1
Virtual Page Tag	PID	0	Physical Frame	N	D	V	G

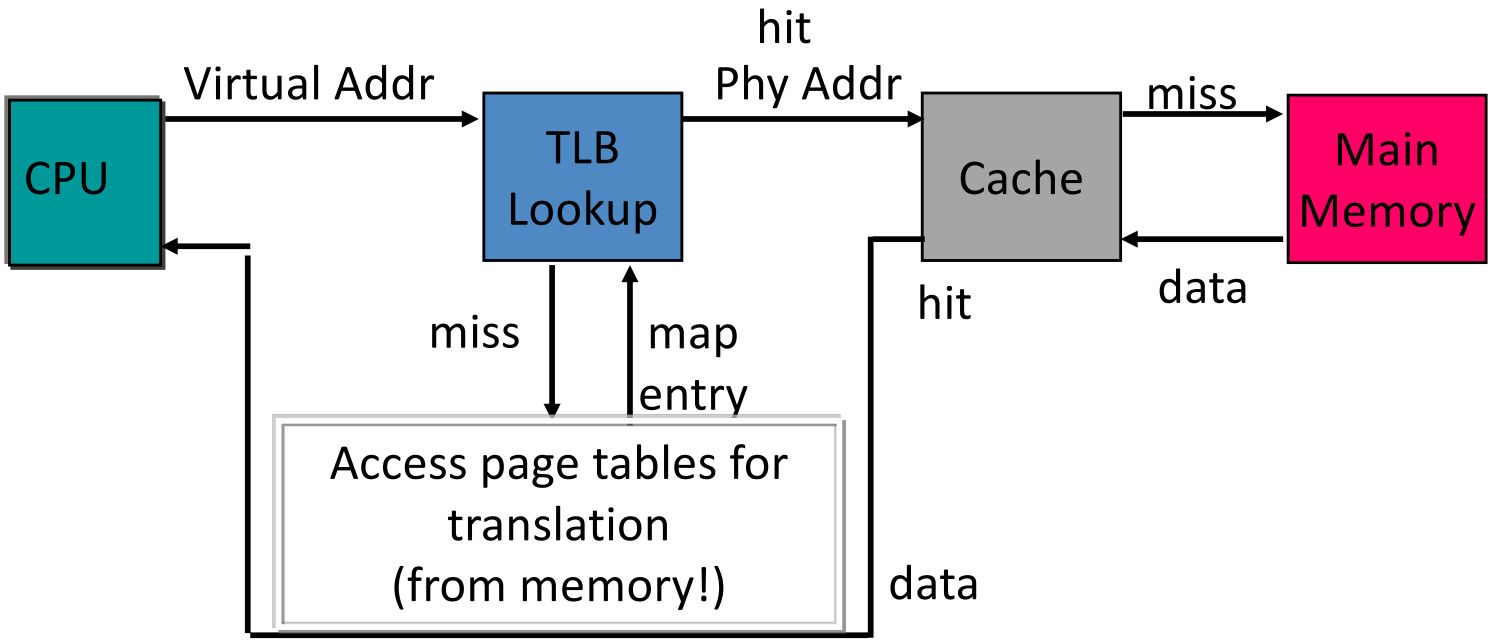
PID	Process ID
N	Do not cache memory address (optional)
D	Dirty bit
V	Valid bit
G	Global (valid regardless of PID)

TLB Caveats: Context Switching

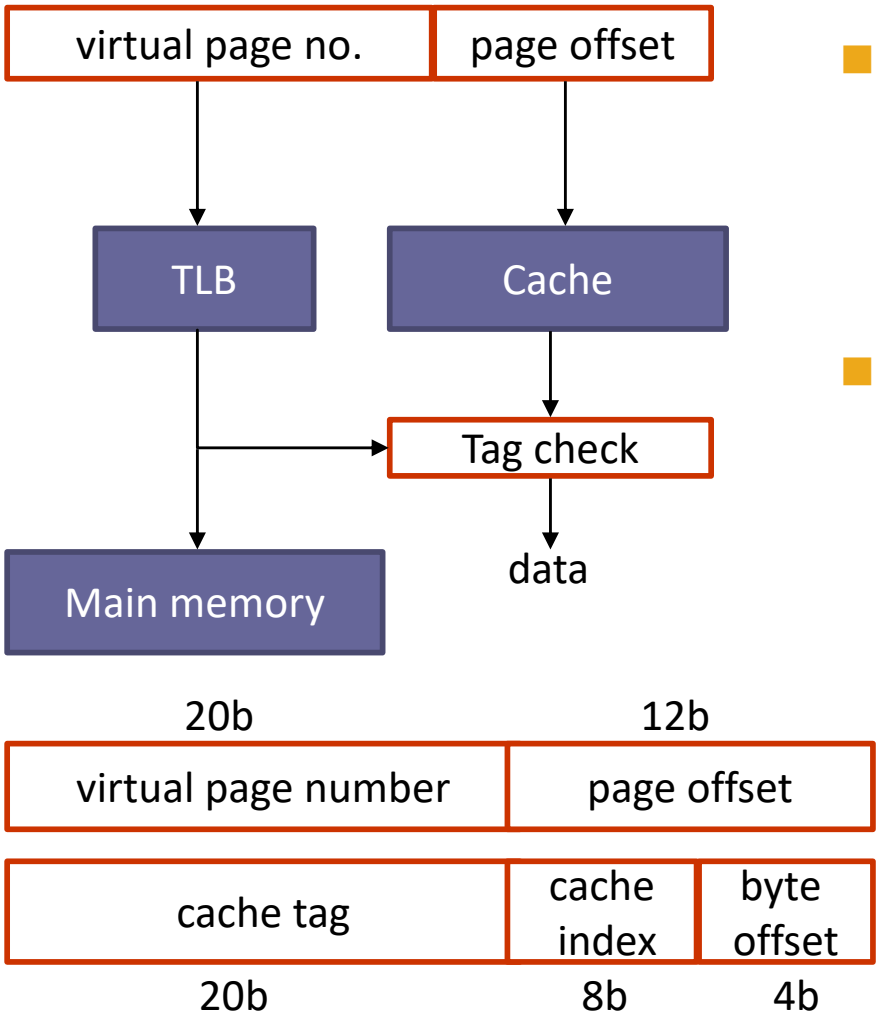
- What happens to TLB when switching between processes?
- The OS must flush the entries in the TLB
  - Large number of TLB misses after every switch
- Alternatively, use a process ID each TLB entry
  - PID or ASID
  - Allows entries from multiple programs to co-exist
  - Gradual replacement

TLB & Memory Hierarchies

- Basic process
  - Use TLB to get VA → PA
  - Use PA to access caches and DRAM
- Question: can you ever access the TLB and the cache in parallel?



Virtually Indexed, Physically Tagged Caches



- Translation & cache access in parallel
  - Start access to cache with page offset
  - Tag check used physical address
- Only works when
  - VPN bits not needed for cache lookup
  - Cache Size ≤ Page Size * Associativity
    - I.e. Set Size ≤ Page Size
  - Ok, we want L1 to be small anyway

Virtual Memory and Caches

TLB	Cache	DRAM	Possible?
hit	miss	hit	
miss	hit	hit	
miss	miss	hit	
miss	miss	miss	
hit	miss	miss	
hit	hit	miss	
miss	hit	miss	

TLB Caveats: Limited Reach

- 64 entry TLB with 4KB pages maps 256 KB
  - Smaller than many L3 caches in most systems
  - TLB miss rate > L2 miss rate!
- Potential solutions
  - Larger pages
  - Multilevel TLBs (just like multi-level caches)

Page Size Tradeoff

Larger pages

Pros: smaller page tables, fewer page faults and more efficient transfer with larger applications, improved TLB coverage

Cons: higher internal fragmentation

Smaller pages

Pros: improved time to start small processes with fewer pages, internal fragmentation is low (important for small programs)

Cons: high overhead in large page tables

General trend toward larger pages

1978: 512 B, 1984: 4 KB, 1990: 16 KB, 2000: 64 KB, 2010: 4MB

Multiple Page Sizes

Many machines support multiple page sizes

- SPARC: 8KB, 64KB, 1 MB, 4MB
- MIPS R4000: 4KB – 16 MB
- x86: 4KB, 4MB, 1GB

Page size dependent upon application

- OS kernel uses large pages
- Most user applications use smaller pages

Issues

- Software complexity
- TLB complexity
  - How do you do match VPN if not sure about the page size?

Final Problem: Page Table Size

Page table size is proportional to size of address space

- x86 example: virtual addresses are 32 bits, pages are 4 KB
- Total number of pages: $2^{32} / 2^{12} = 1$ Million
- Page Table Entry (PTE) are 32 bits wide
- Total page table size is therefore 1M × 4 bytes = 4 MB
  - But, only a small fraction of those pages are actually used!

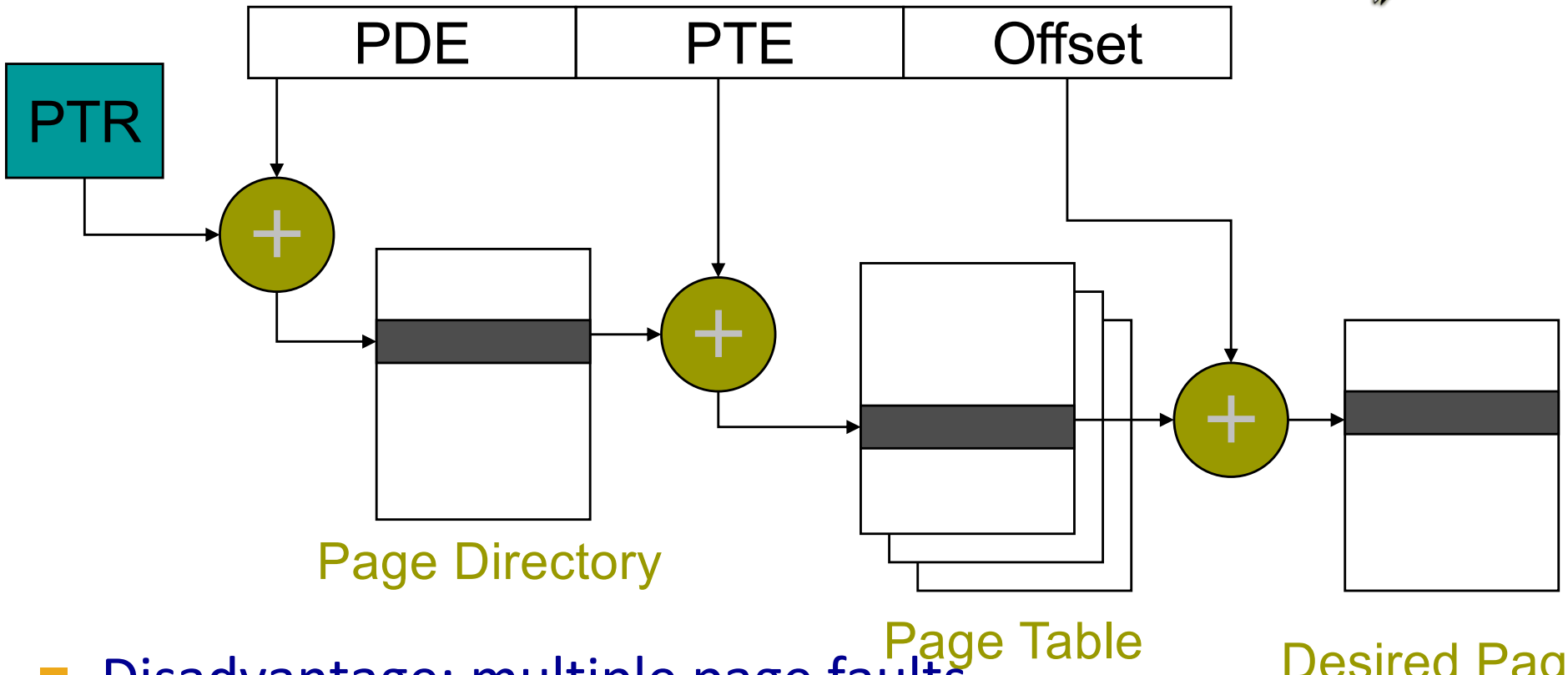
Why is this a problem?

- The page table must be resident in memory (why?)
- What happens for the 64-bit version of x86?
- What about running multiple programs?

Solution: Multi-Level Page Tables

- Use a hierarchical page table structure
- Example: Two levels
  - First level: directory entries
  - Second level: actual page table entries
- Only top level must be resident in memory
- Remaining levels can be in memory, on disk, or unallocated
  - Unallocated if corresponding ranges of the virtual address space are not used

Two-level Page Tables



- Disadvantage: multiple page faults
  - Accessing a PTE page table can cause a page fault
  - Accessing the actual page can cause a second page fault
  - TLB plays an even more important role

Putting it All Together

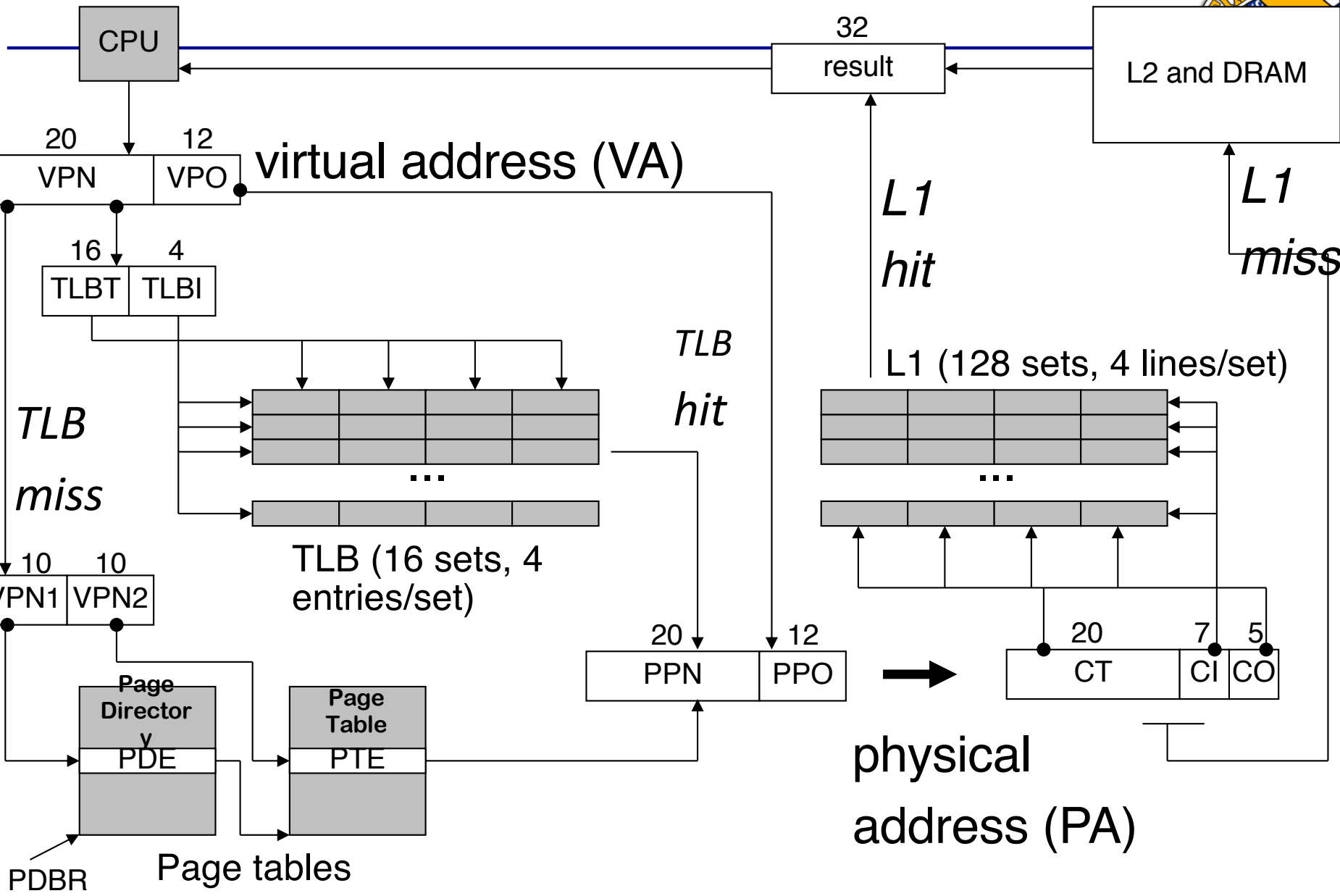
Example: Intel P6 Processor

- 32 bit address space with 4KB pages
- 2-level cache hierarchy
  - L1 I/D: 16KB, 4-way, 128 sets, 32B blocks
  - L2: 128KB – 2MB
- TLBs
  - I-TLB: 32 entries, 4-way, 8 sets
  - D-TLB: 64 entries, 4-way, 16 sets
  - 32 entries, 8 sets

Abbreviations

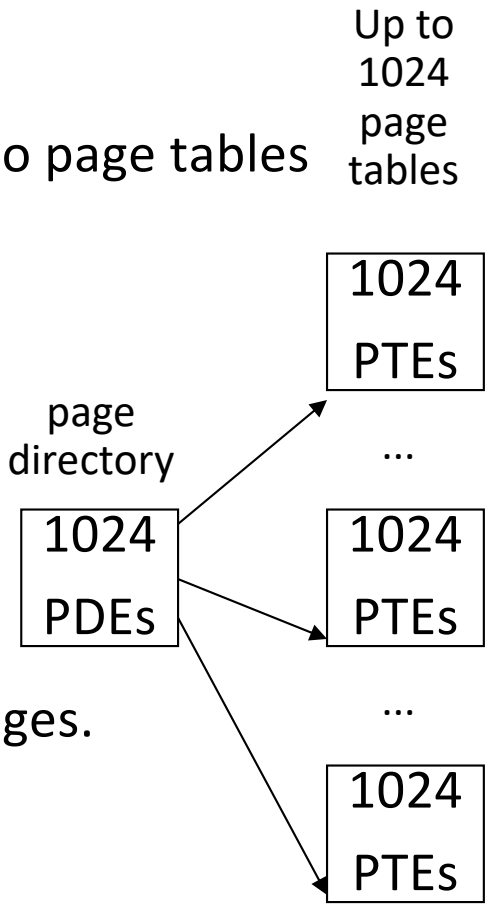
- MMU
  - Memory management unit: controls TLB, handles TLB misses
- Components of the virtual address (VA)
  - TLBI: TLB index
  - TLBT: TLB tag
  - VPO: virtual page offset
  - VPN: virtual page number
- Components of the physical address (PA)
  - PPO: physical page offset (same as VPO)
  - PPN: physical page number
  - CO: byte offset within cache line
  - CI: cache index
  - CT: cache tag

Overview of P6 Address Translation



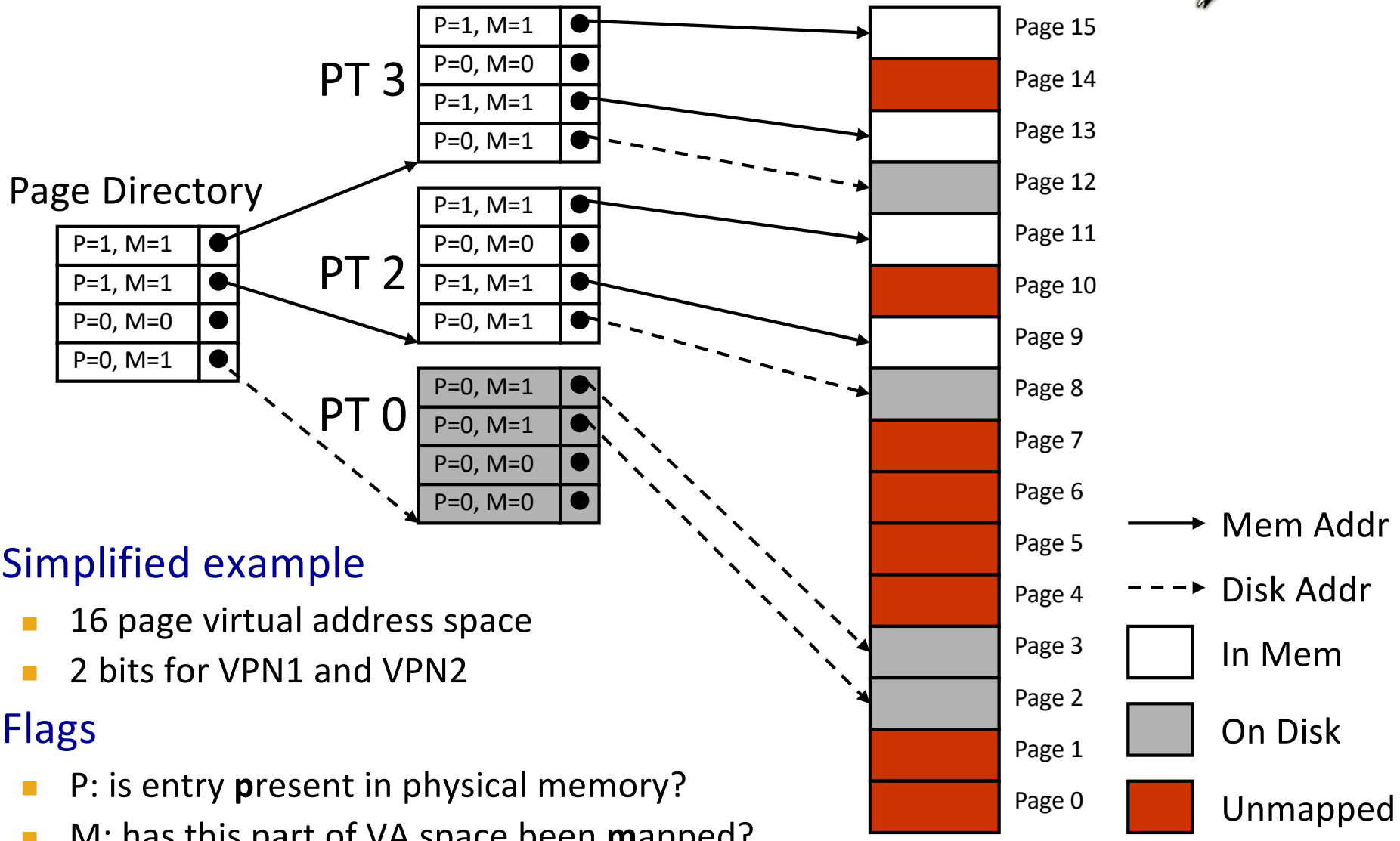
P6 2-level Page Table Structure

- Page directory
  - One page directory per process.
  - 1024 4-byte page directory entries (PDEs) that point to page tables
  - Page directory must be in memory if process running
  - Always pointed to by PDBR



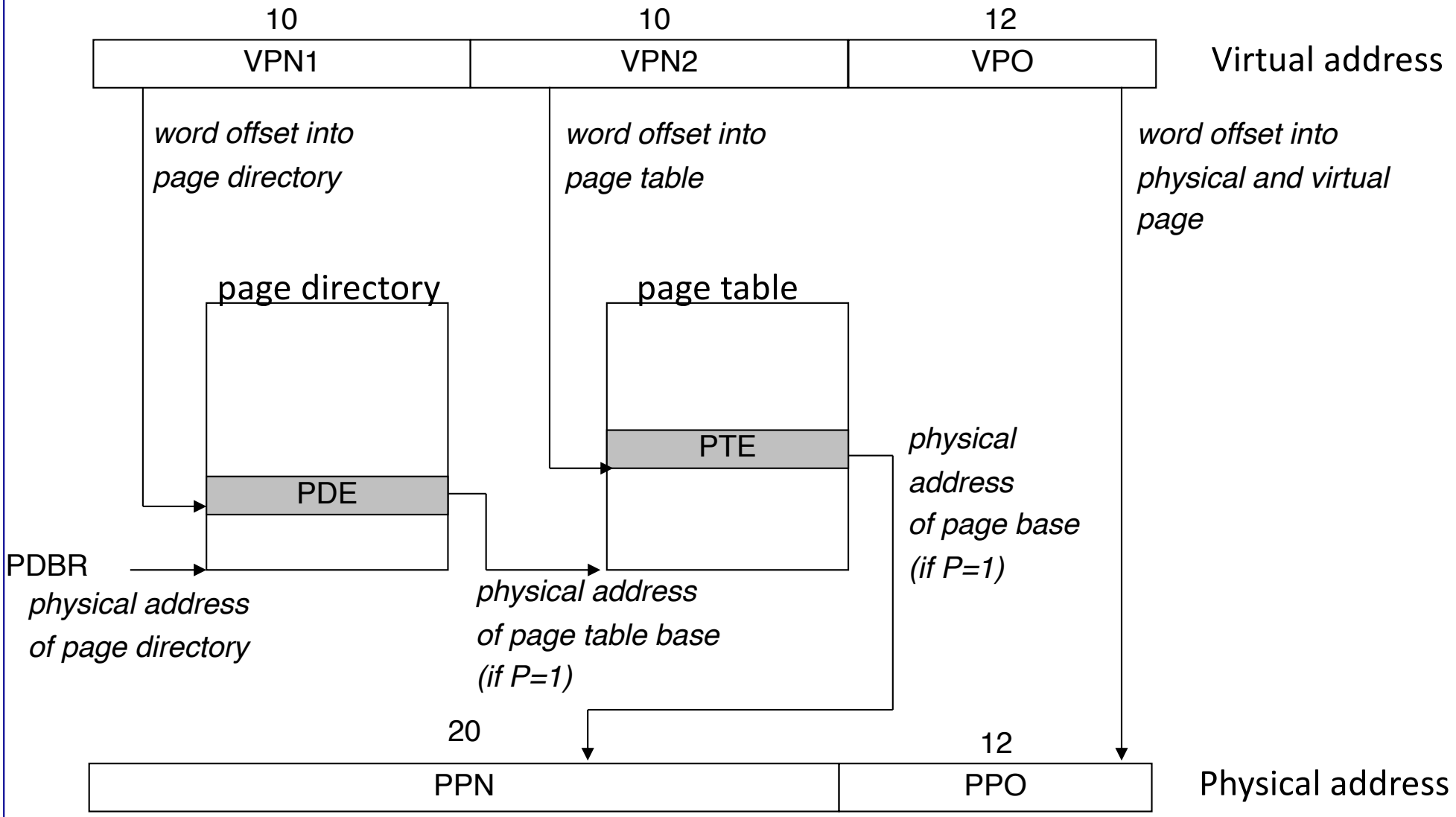
- Page tables
  - 1024 4-byte page table entries (PTEs) that point to pages.
  - Page tables can be paged in and out

Representation of Virtual Address Space



- Simplified example
  - 16 page virtual address space
  - 2 bits for VPN1 and VPN2
- Flags
  - P: is entry **p**resent in physical memory?
  - M: has this part of VA space been **m**apped?

P6 Translation



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

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)

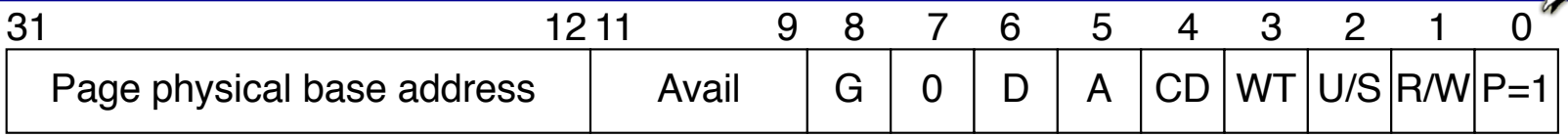
WT: write-through or write-back cache policy for this page table

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)

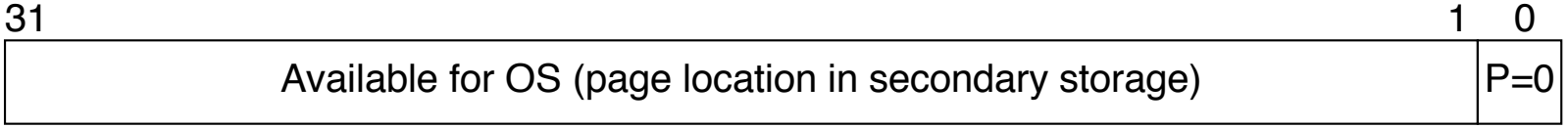
CD: cache disabled or enabled

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

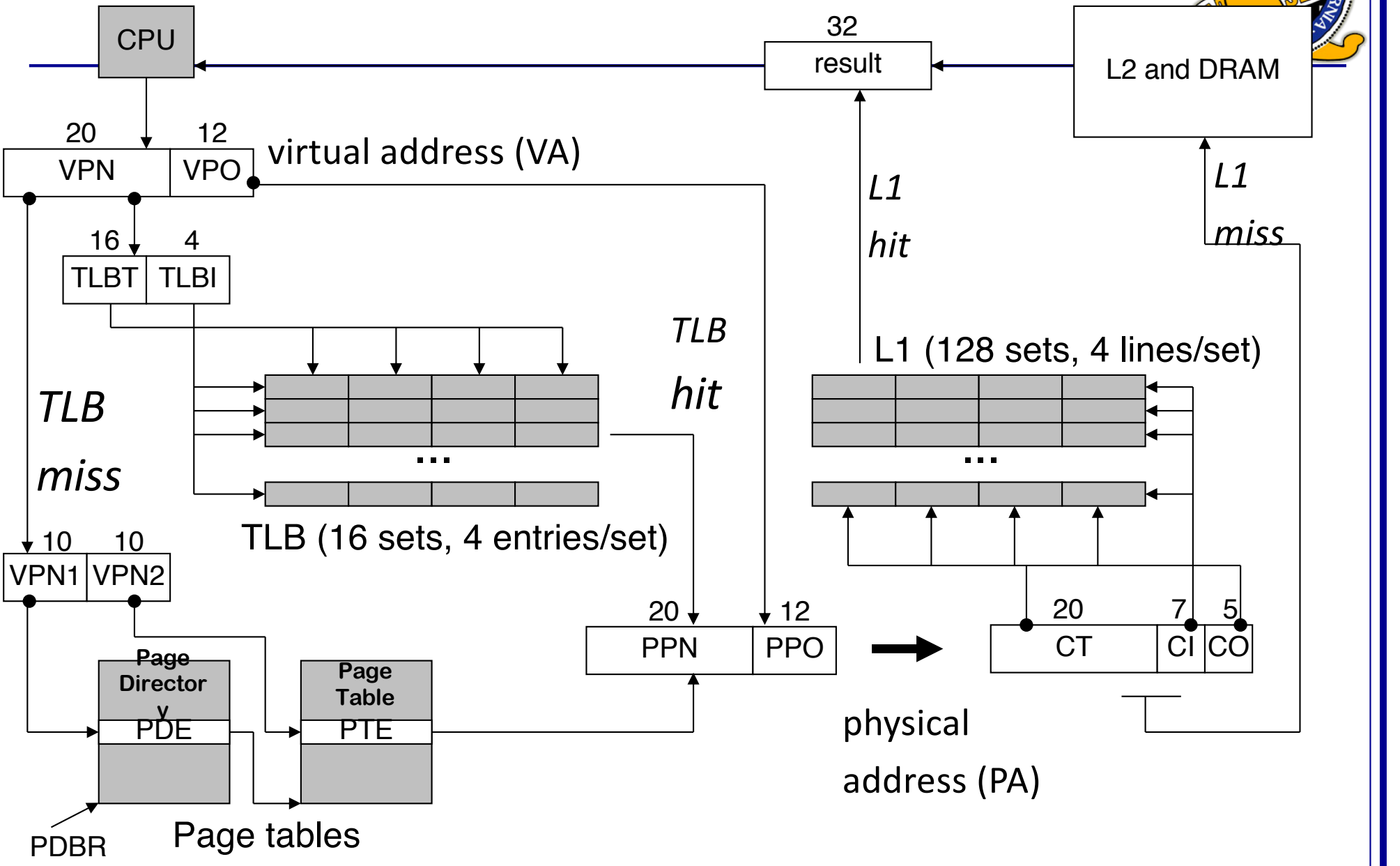
U/S: user/supervisor

R/W: read/write

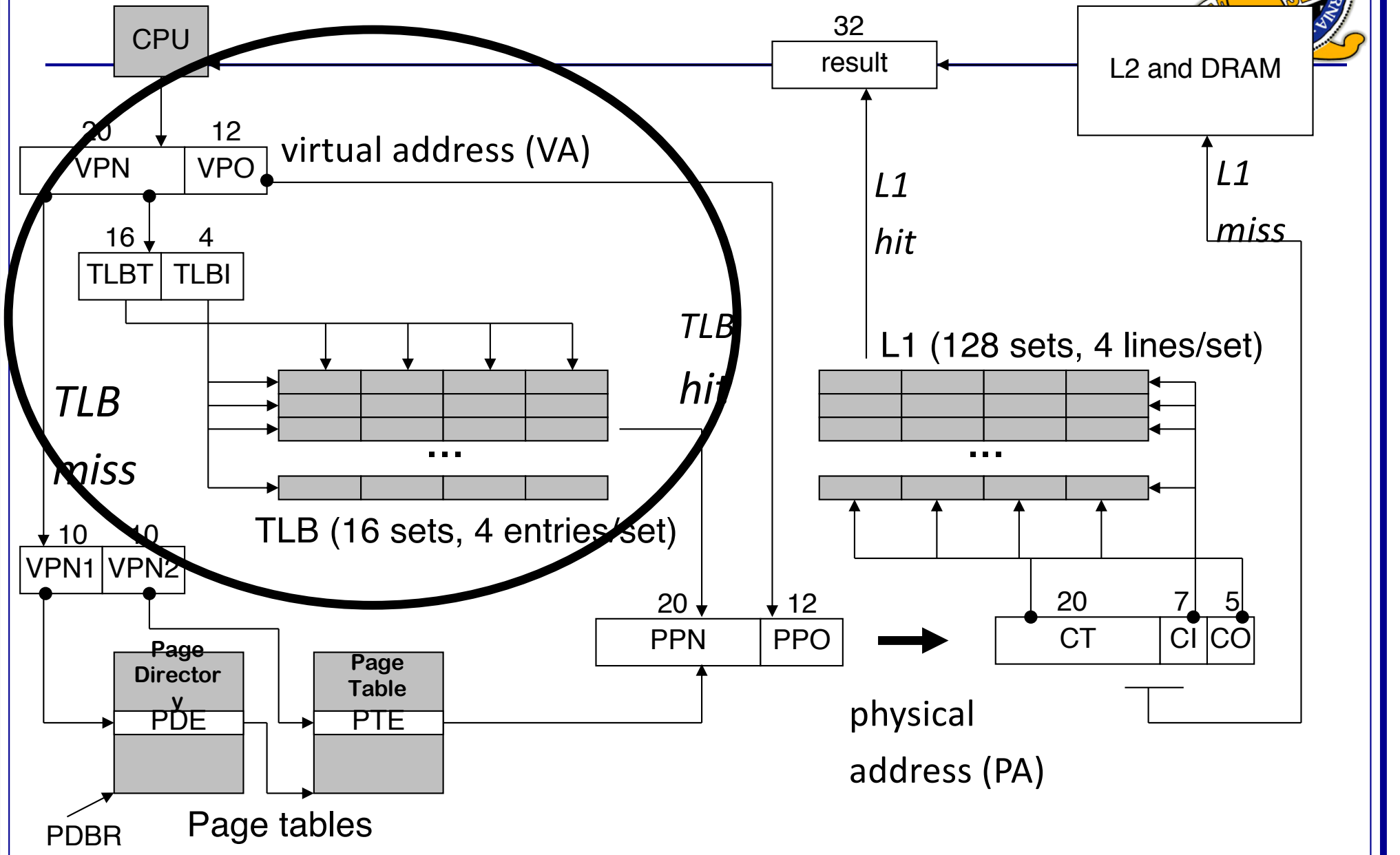
P: page is present in physical memory (1) or not (0)



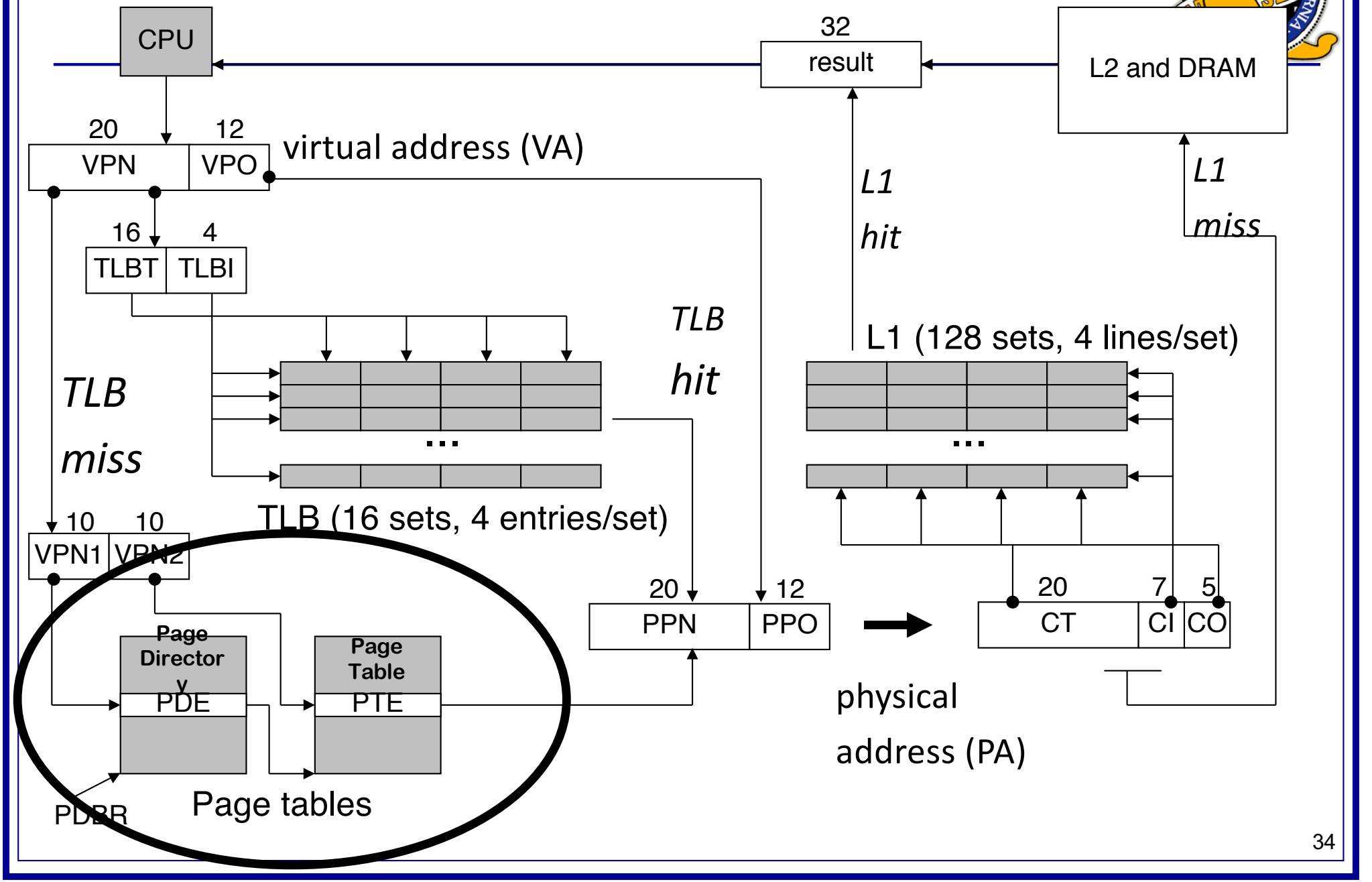
Overview of P6 Address Translation



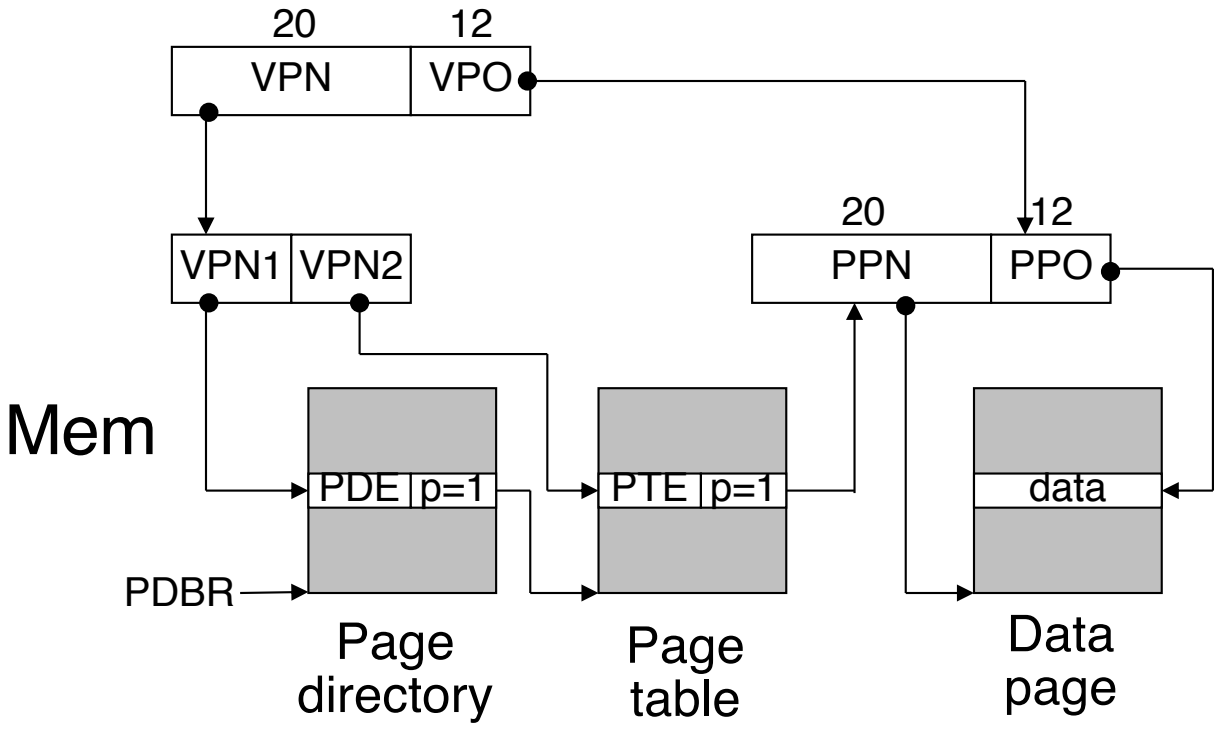
TLB Translation



Page Table Translation

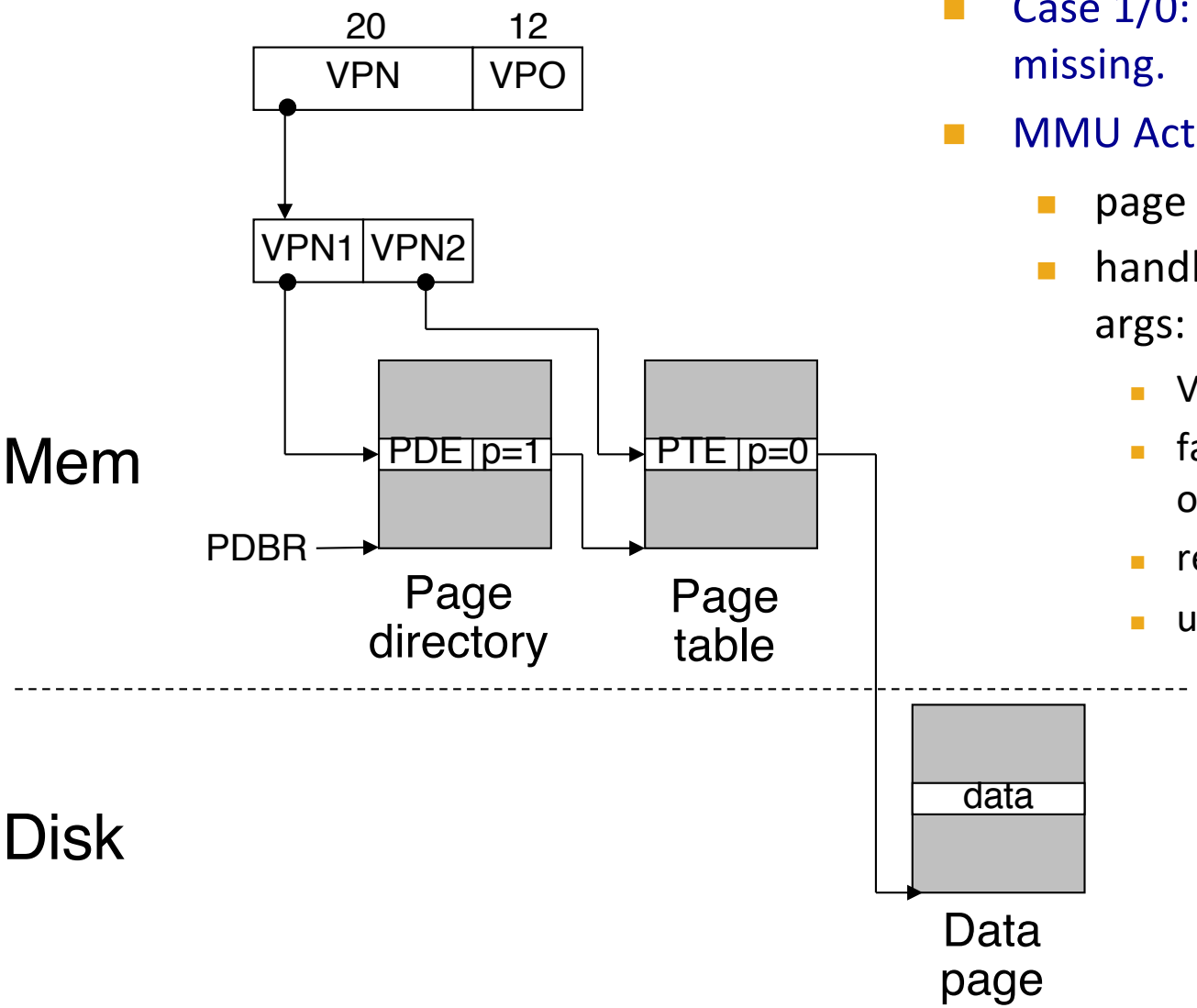


Translating with the P6 page tables (case 1/1)



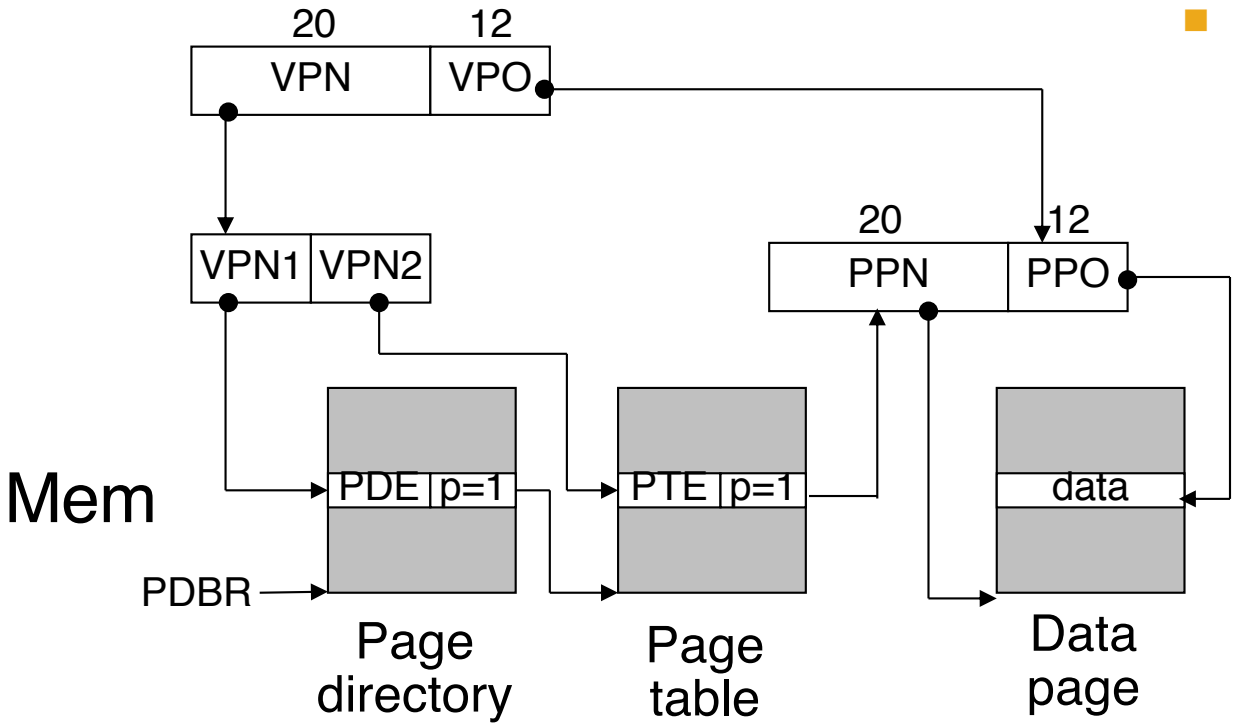
- Case 1/1: page table and page present.
- MMU Action:
  - MMU build physical address and fetch data word.
- OS action
  - none

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



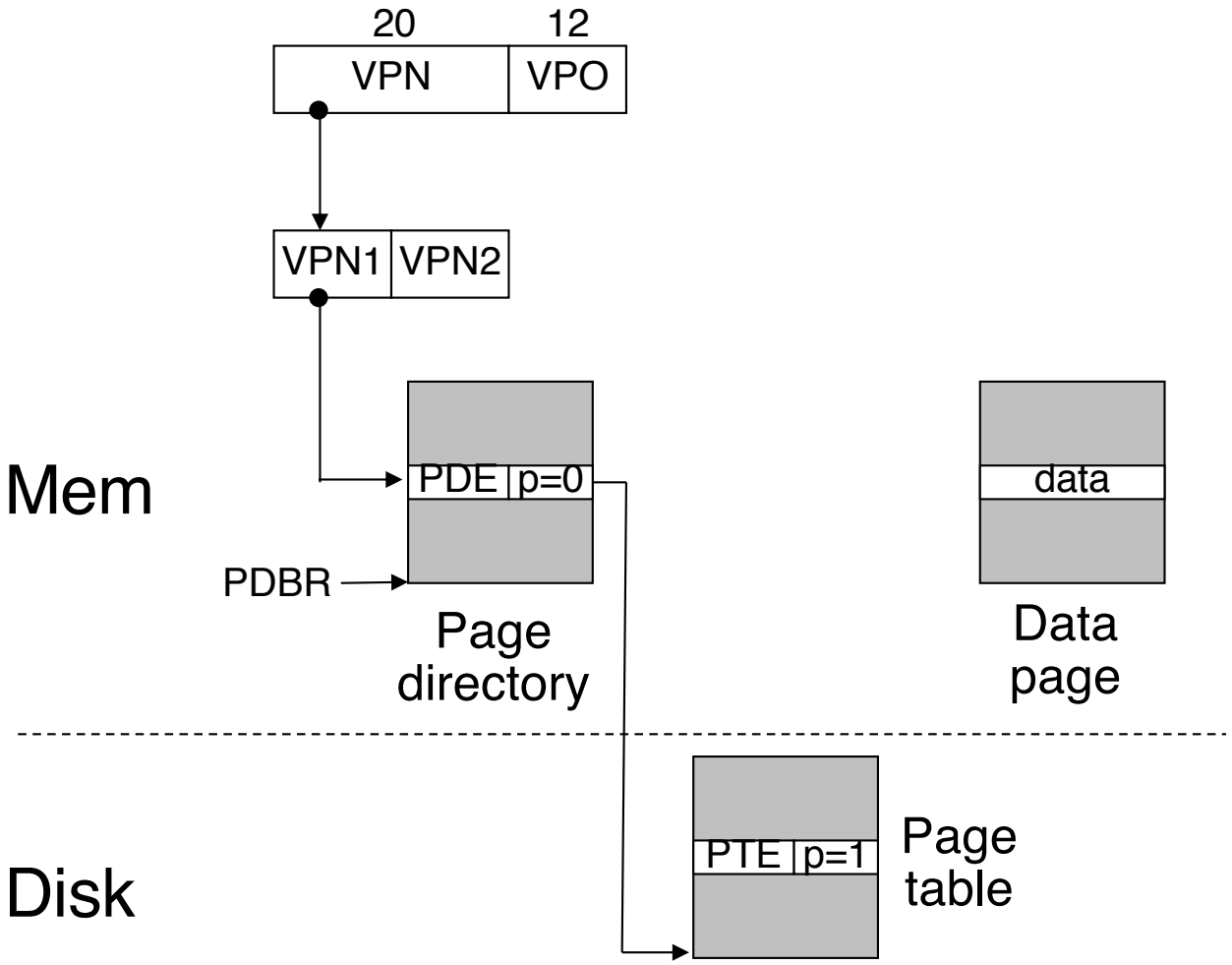
- Case 1/0: page table present but page missing.
- MMU Action:
  - page fault exception
  - handler receives the following args:
    - VA that caused fault
    - fault caused by non-present page or page-level protection violation
    - read/write
    - user/supervisor

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



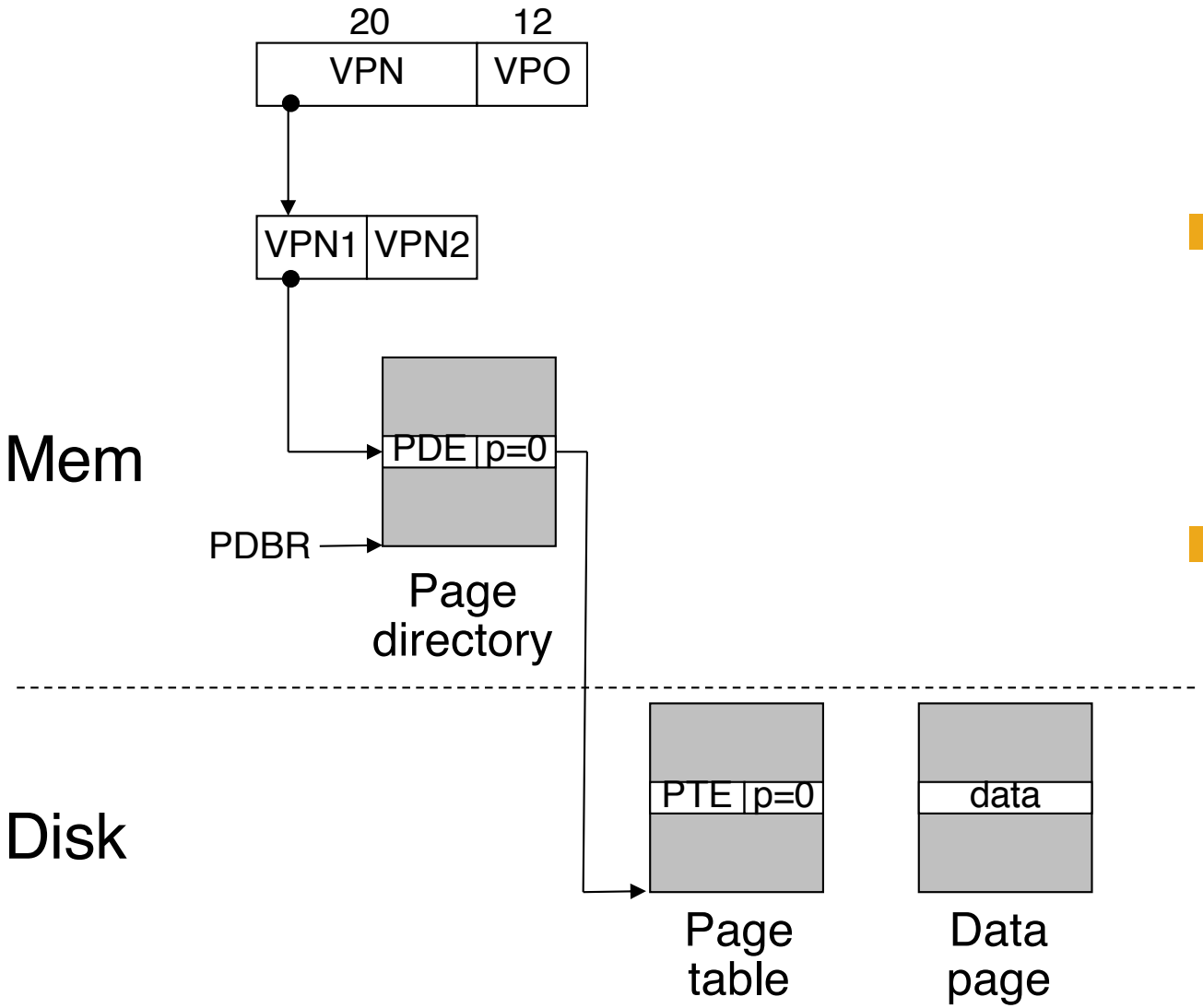
- OS Action:
  - Check for a legal virtual address.
  - Read PTE through PDE.
  - Find free physical page (swapping out current page if necessary)
  - Read virtual page from disk and copy to physical page
  - Restart faulting instruction by returning from exception handler.

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



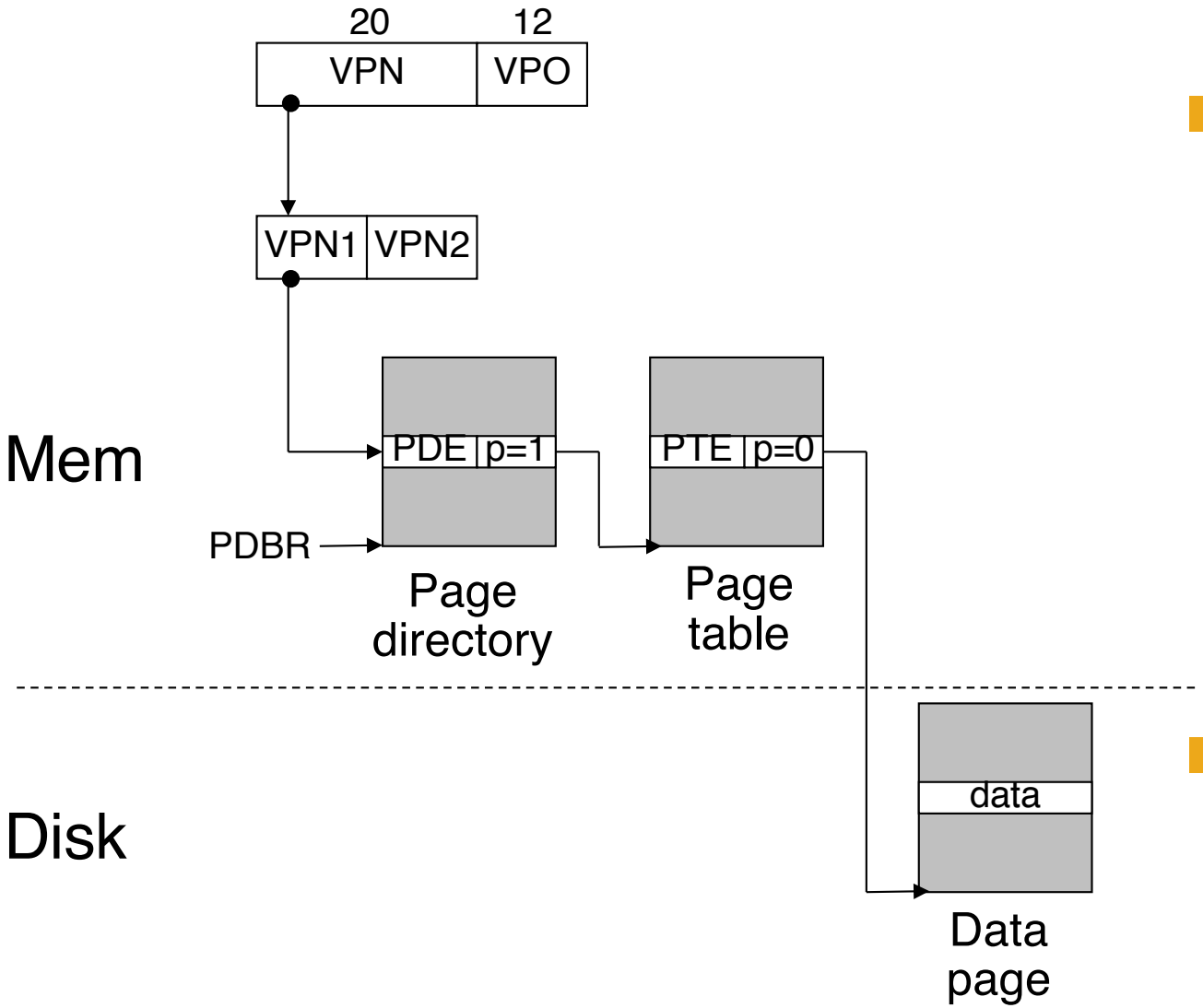
- Case 0/1: page table missing but page present.
- Introduces consistency issue.
  - potentially every page out requires update of disk page table.
- Linux disallows this
  - if a page table is swapped out, then swap out its data pages too.

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



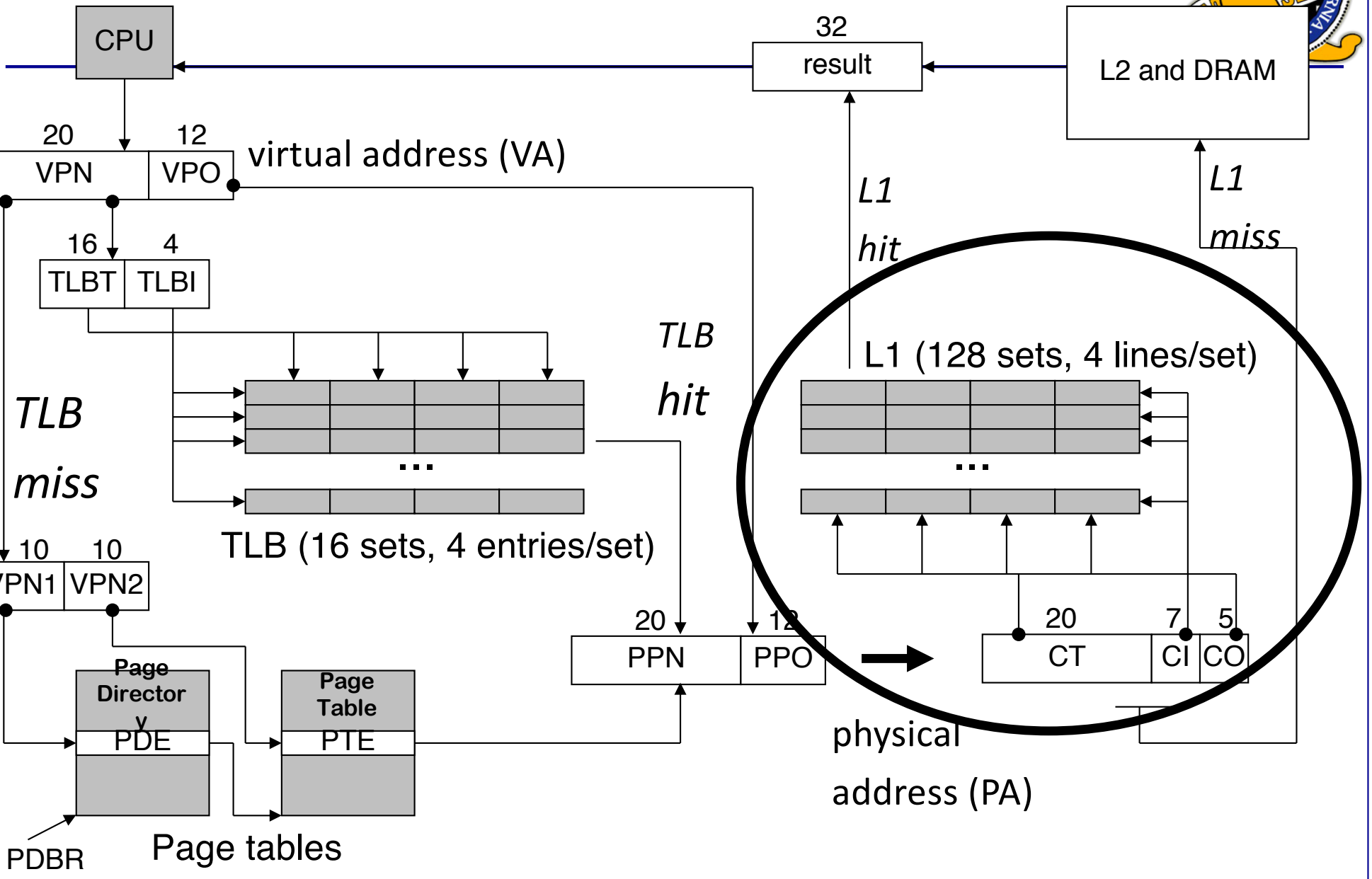
- Case 0/0: page table and page missing.
- MMU Action:
  - page fault exception

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

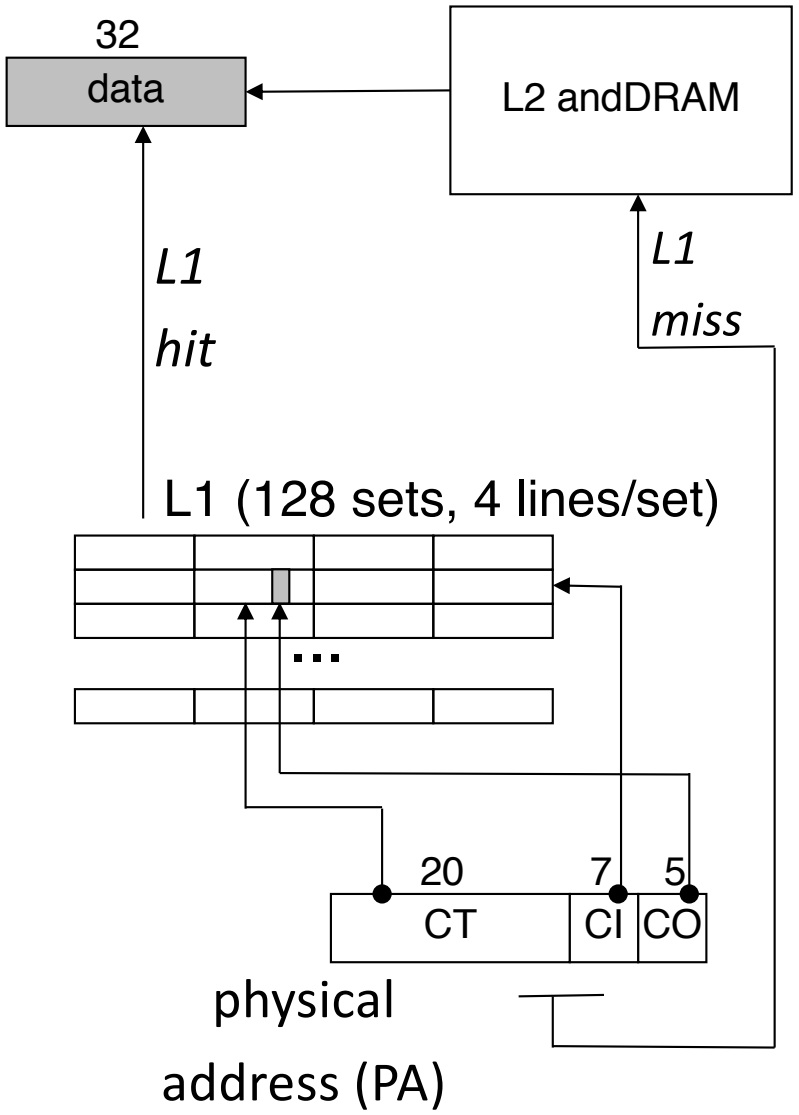


- OS action:
  - swap in page table.
  - restart faulting instruction by returning from handler.
- Like case 0/1 from here on.

L1 Cache Access

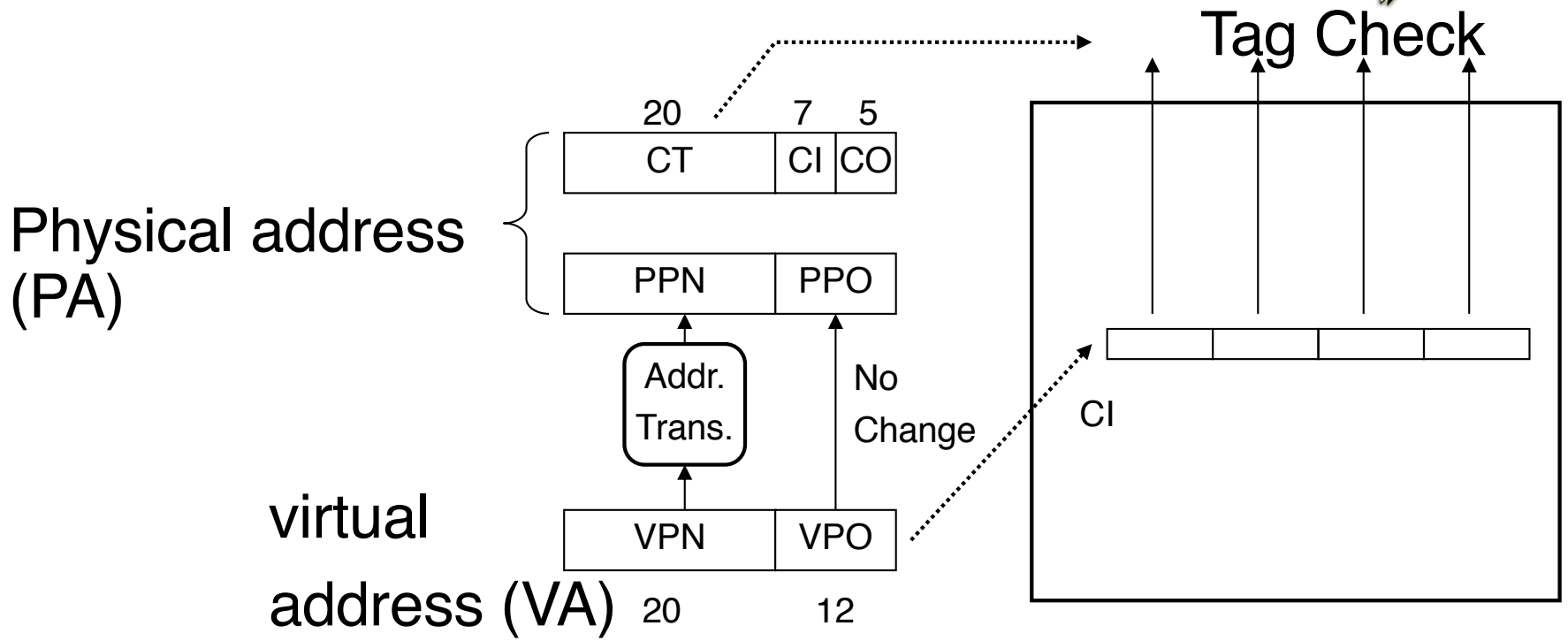


L1 Cache Access



- Partition PA into CO, CI, and CT
- Use CT to if line at set CI is hit or miss
  - If miss, check L2
  - If hit, 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”

Virtual Memory Summary

Use hard disk (or Flash) as a large storage for data of all programs

- Main memory (DRAM) is a cache for the disk
- Managed jointly by hardware and the operating system (OS)

Each running program has its own virtual address space

- Address space as shown in previous figure (0 – 2^{32}-1 bytes)
- Protected from other programs

Frequently-used portions of virtual address space copied to DRAM

- DRAM = physical address space
- Hardware + OS translate virtual addresses (VA) used by program to physical addresses (PA) used by the hardware
- Translation enables relocation (DRAM<->disk) & protection

HW Support for the OS

- Mechanisms to protect OS from user programs
  - Modes + virtual memory
- Mechanisms to switch control flow between OS and user programs
  - System calls + exceptions/interrupts
- Mechanisms to protect user programs from each other
  - Virtual memory
- Mechanisms to interact with I/O devices
  - Primarily memory-mapped I/O

Hardware Modes
(Protecting OS from User Programs)

2 modes are needed, but some architectures have more

User mode: Used to run user processes

- Accessible instructions: user portion of the ISA
  - The instructions we have seen so far
- Accessible state: user registers and memory
  - But virtual memory translation is always on
  - Cannot access EPC, Cause, … registers
- Exceptions and interrupts are always on

Kernel mode: used to run (most of) the kernel

- Accessible instructions: the whole ISA
  - User + privileged instructions
- Accessible state: everything
- Virtual memory, exceptions, and interrupts may be turned off