

Lecture 8

Paging

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Outline

- Introduction to paging
- Multi-level page tables
- Other page table structures
- Real-world paging schemes
- Translation lookaside buffer

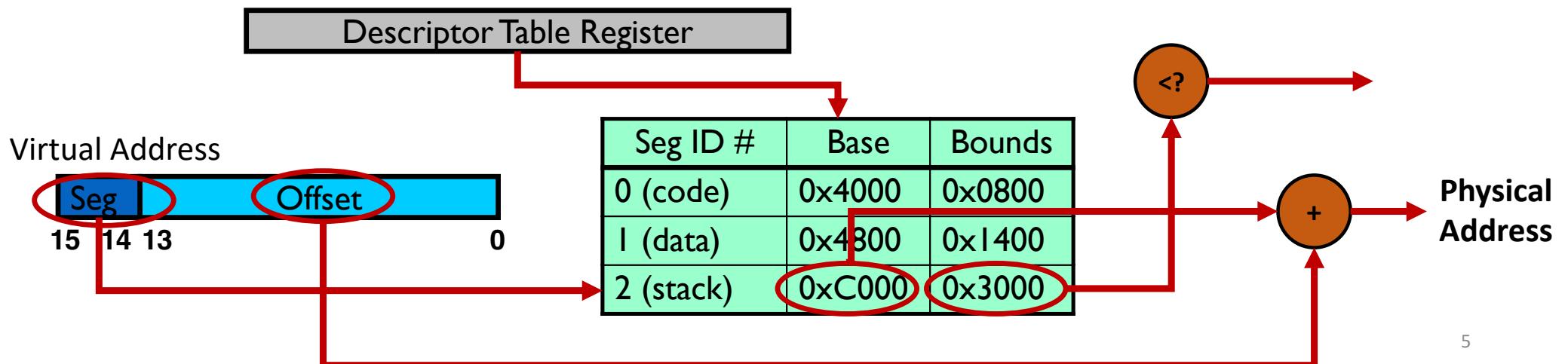
Introduction to Paging

Recall: Problems with Segmentation

- OS context switch must also save and restore all pairs of segment registers
- A segment may grow, which may or may not be possible
- Management of free spaces of physical memory with variable-sized segments
- **External fragmentation:** gaps between allocated segments
 - Segmentation may also have internal fragmentation if more space allocated than needed.

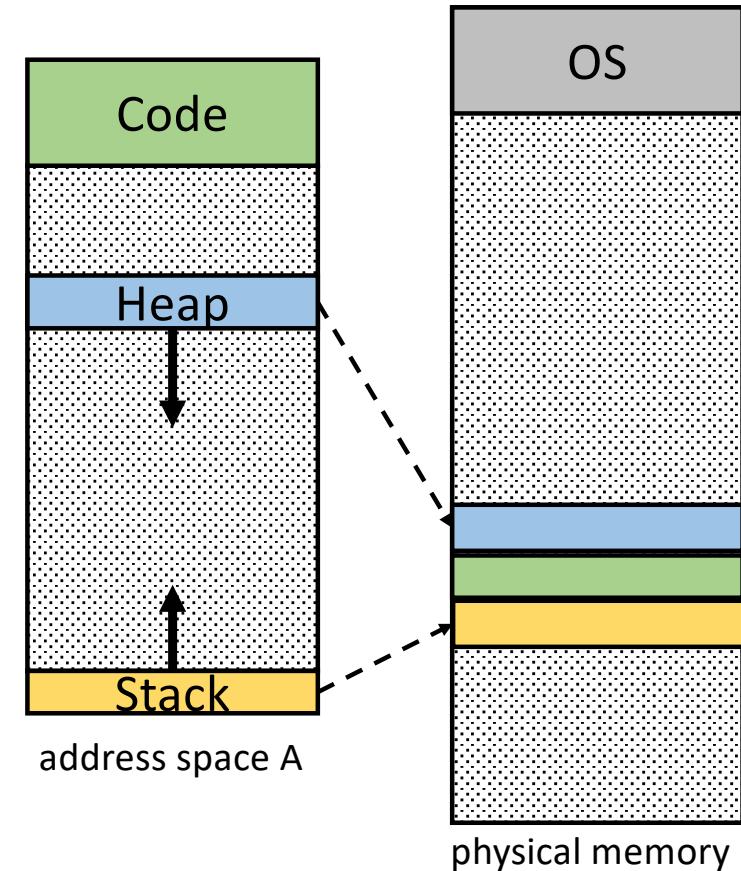
Solutions for Segmentation

- OS context switch must also save and restore all pairs of segment registers
 - Table of base/bounds stored in memory rather than registers
 - Pointer to the table stored in a register
 - Cons: one more memory read per address translation



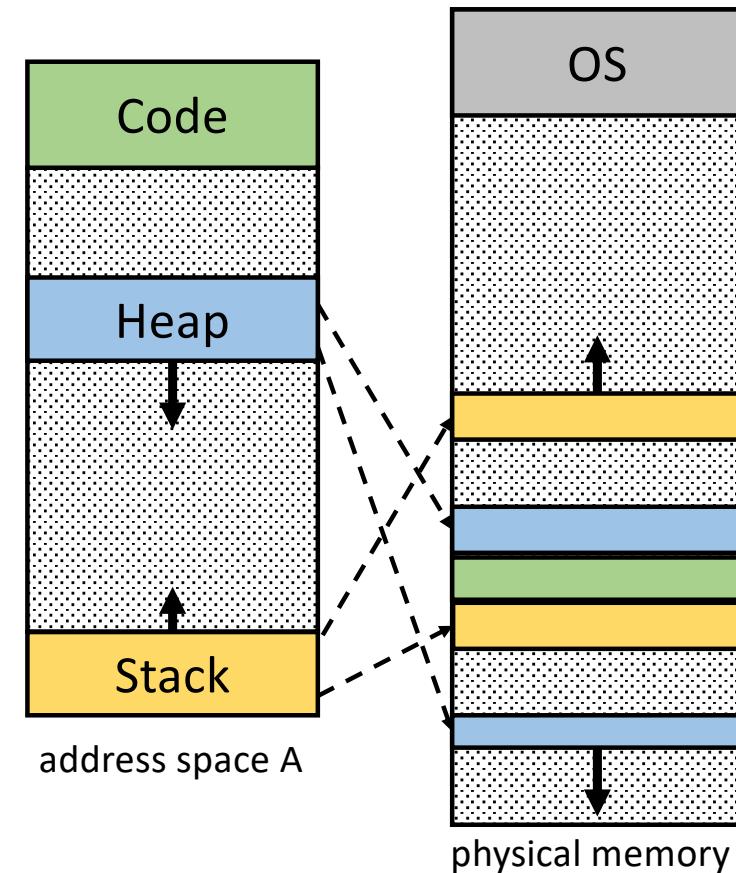
Solutions for Segmentation (Cont'd)

- A segment may grow, which may or may not be possible



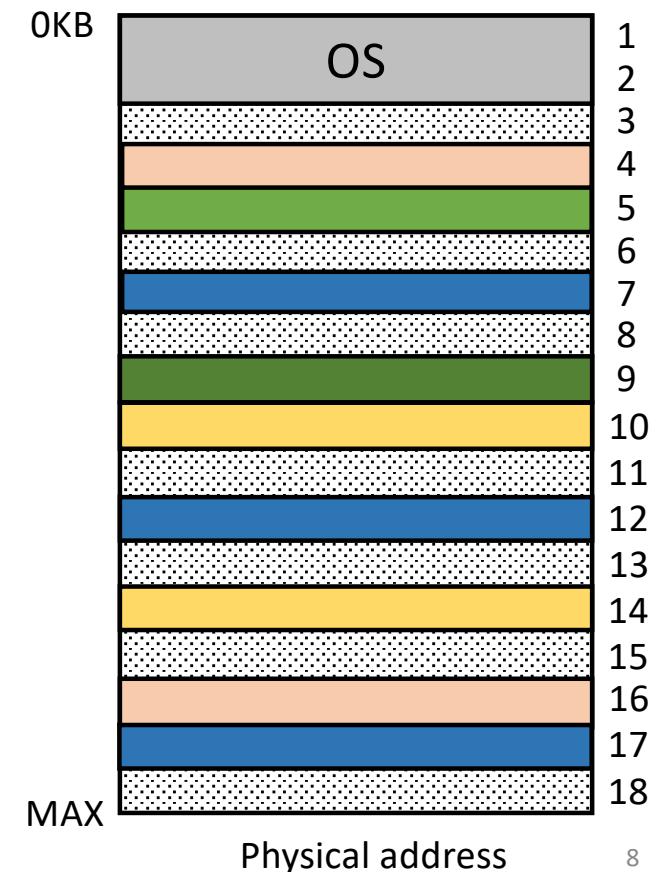
Solutions for Segmentation (Cont'd)

- A segment may grow, which may or may not be possible
 - Virtually continuous memory can be physically discontinuous



Solutions for Segmentation (Cont'd)

- Management of free spaces of physical memory with variable-sized segments
 - **Fixed-sized segments**
 - Physical memory curved into **fixed** sized chunks, **index by an integer**
 - Can use simple vector of bits to handle allocation (1-allocated, 0-free)
11011010110101010110
- External fragmentation
 - **Fixed-sized segments**
 - Each request is of the same fixed size - always fit, no external fragmentation



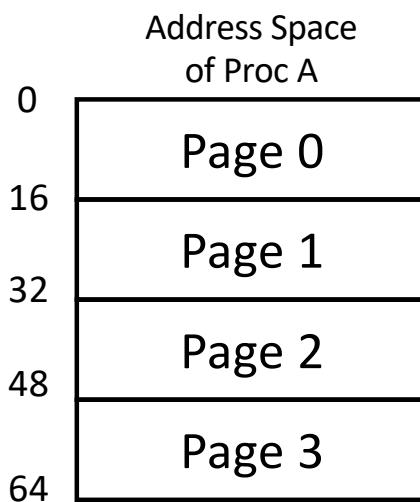
Paging: Put All These Ideas Together

- Physical memory conceptually divided into fixed size
 - Each is called a **page frame**
 - Typical size 1KB to 16KB, most ISA uses 4KB
- Virtual address space conceptually divided into the same size
 - Each is called a **page**
- **Page mapped to page frame**
 - One to one mapping
 - Many to one mapping → memory sharing
- **One page table per process**
 - Resides in physical memory
 - One entry for one virtual->physical translation

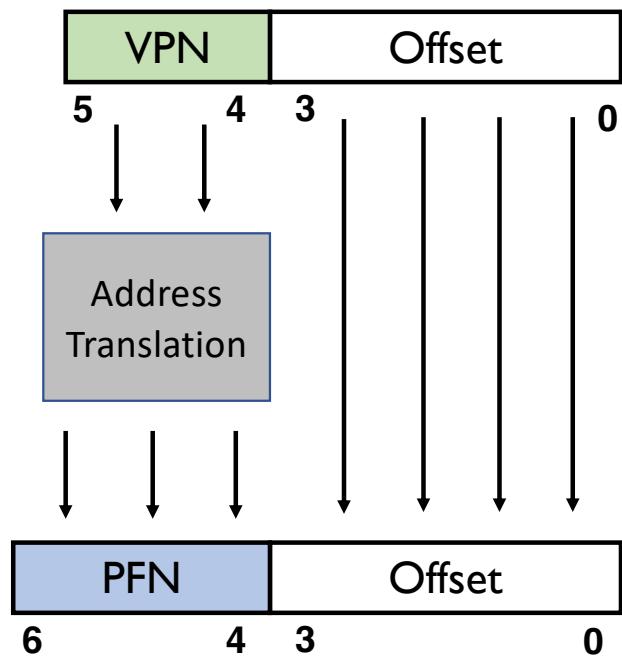
How big is one page (frame)?

- Too big → internal fragmentation
- Too small → page table too big

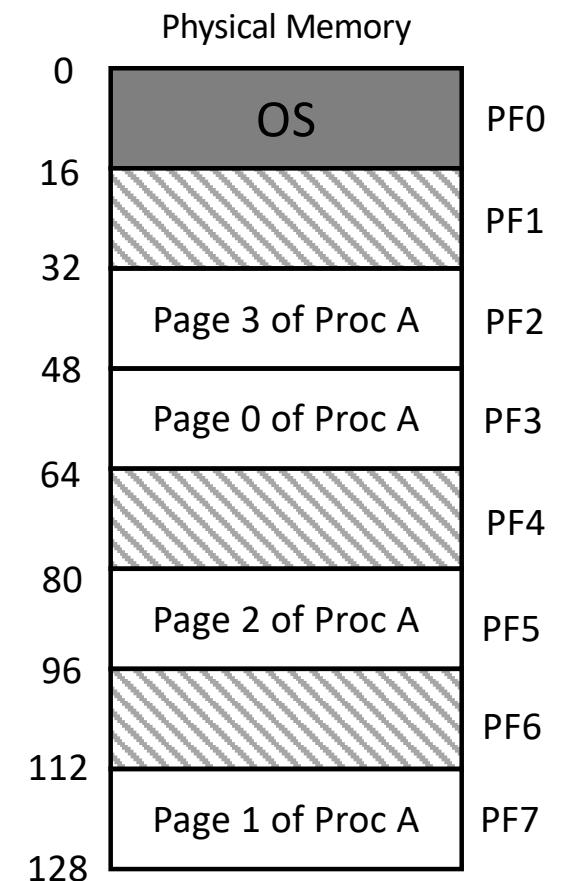
Paging Illustrated



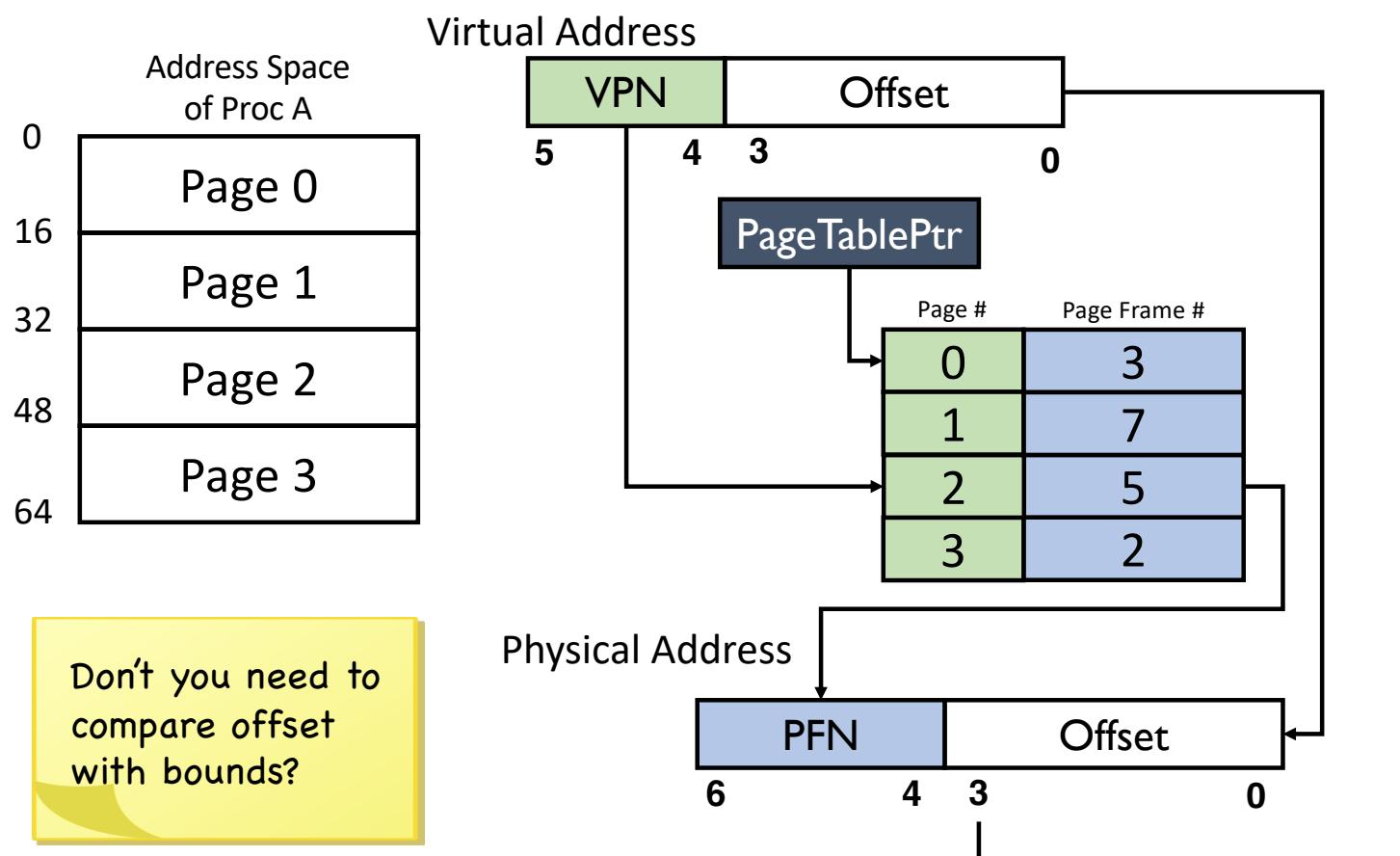
Virtual Address = Virtual Page Number || Offset



Physical Address = Page Frame Number || Offset

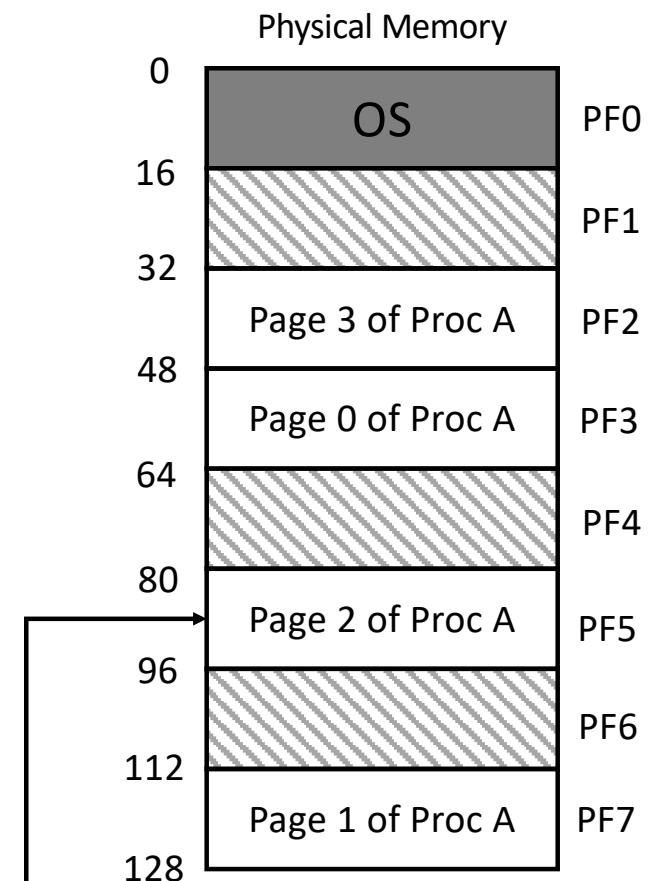


Paging Illustrated (Cont'd)

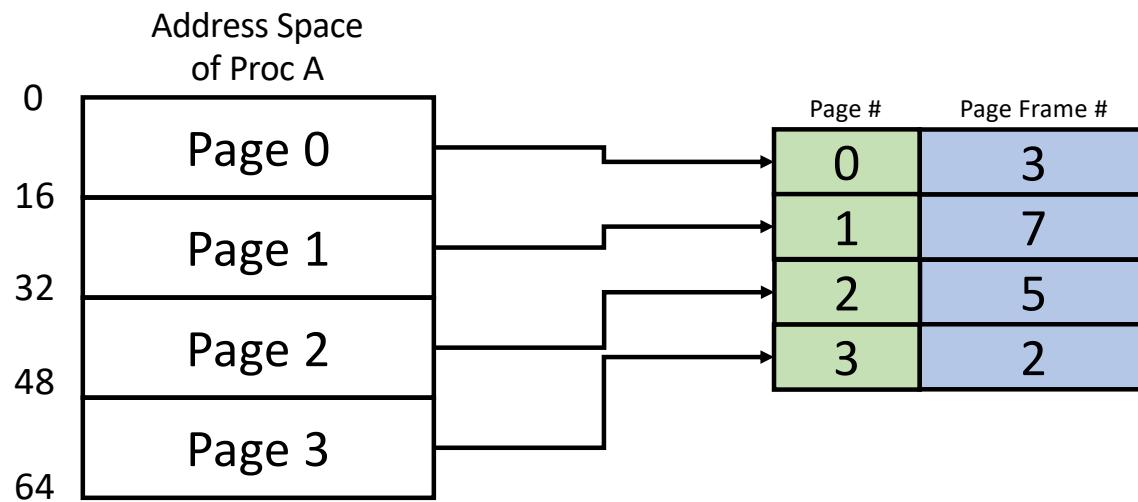


分段: 需要比较偏移量与界限, 确保偏移量在段的有效范围内。

分页: 不需要比较偏移量与界限, 因为分页是按固定页面大小来分配内存的, 偏移量始终在有效范围内。

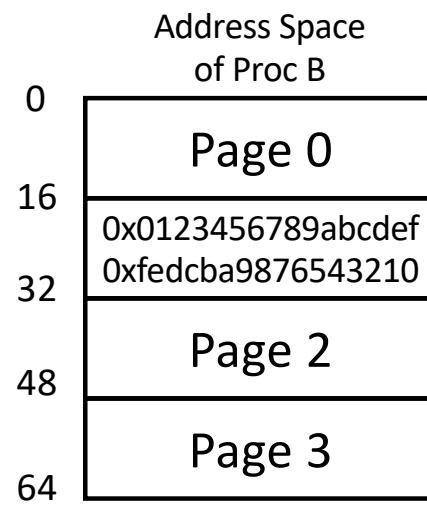
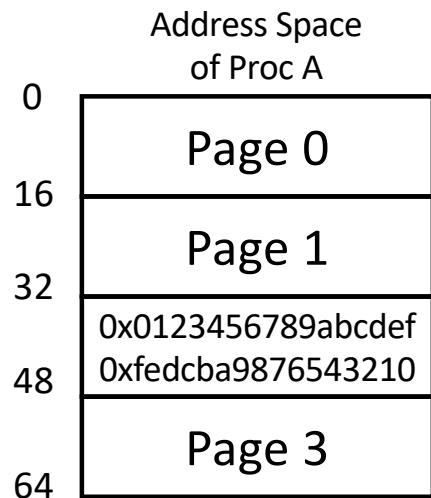


Paging Illustrated (Cont'd)



- Address translation in paging:
 - A mapping from a virtual page to a physical page frame

Memory Sharing with Paging

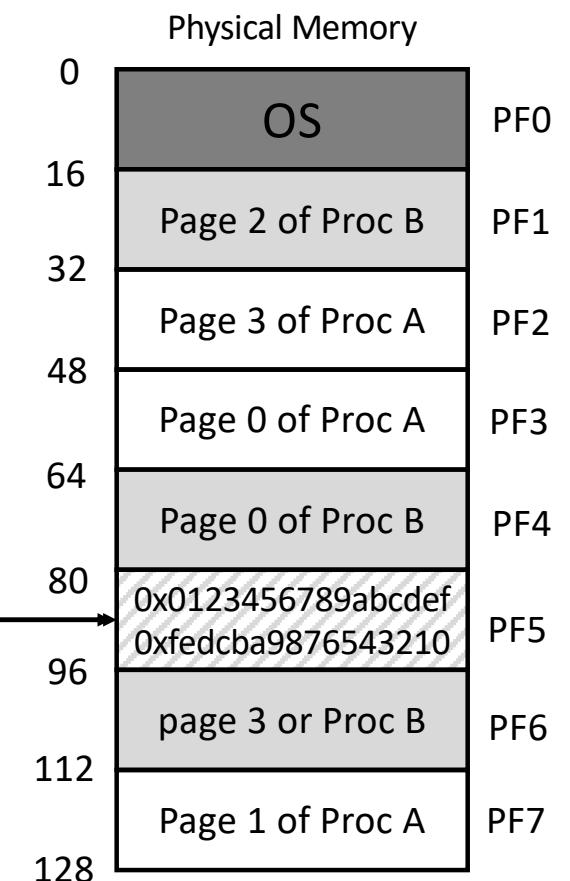


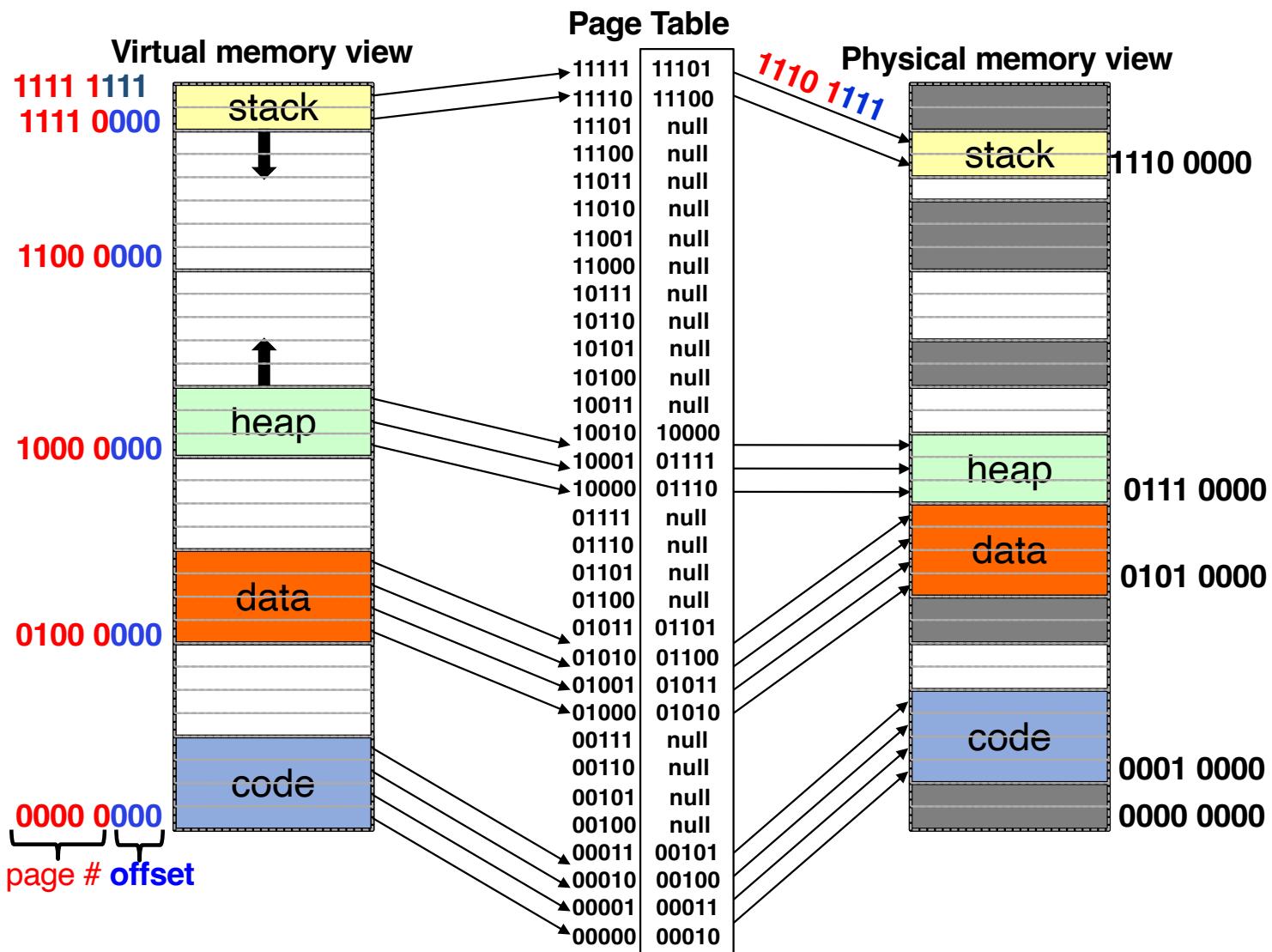
Page #	Page Frame #
0	3
1	7
2	5
3	2

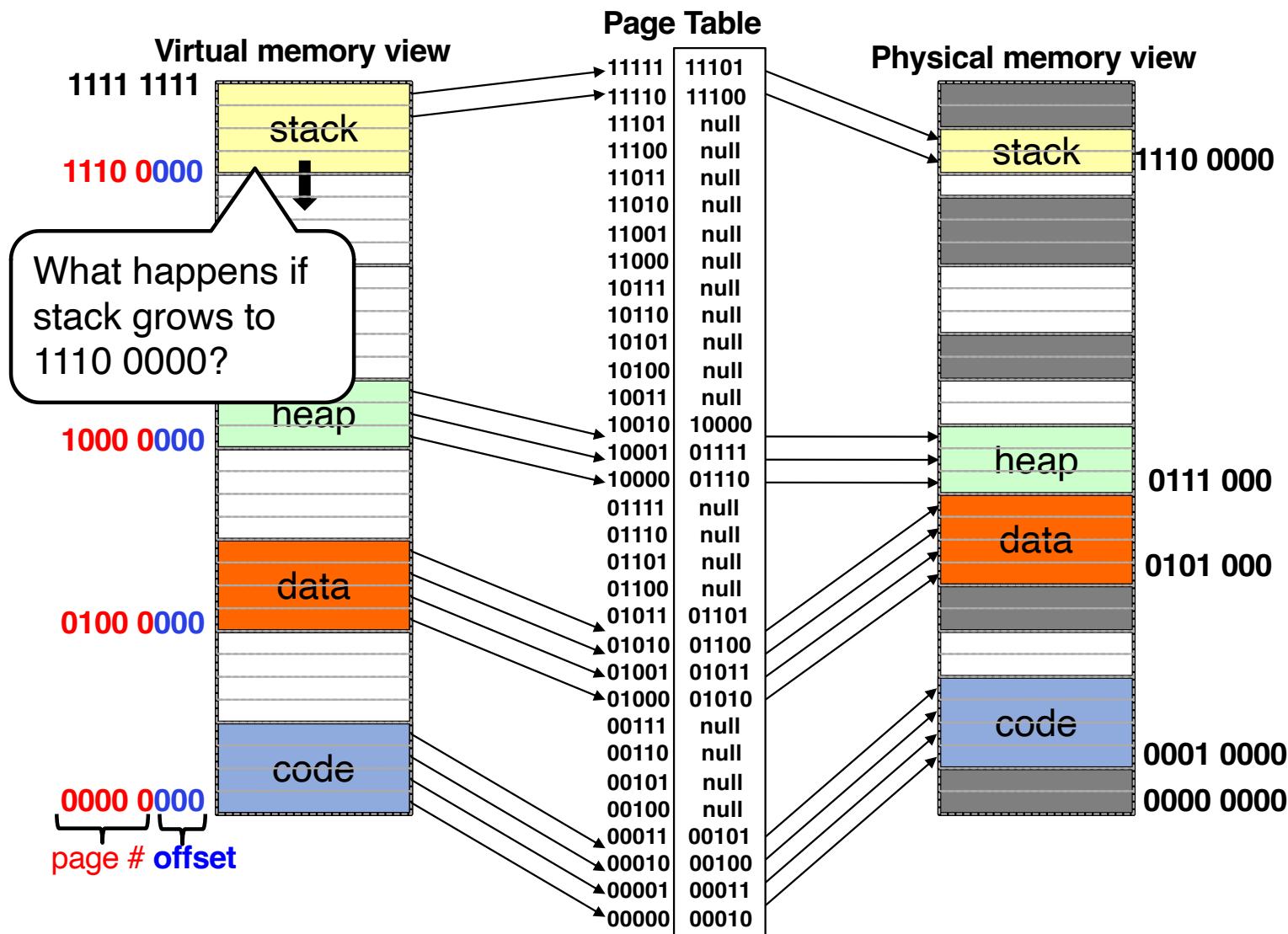
Page table of Proc A

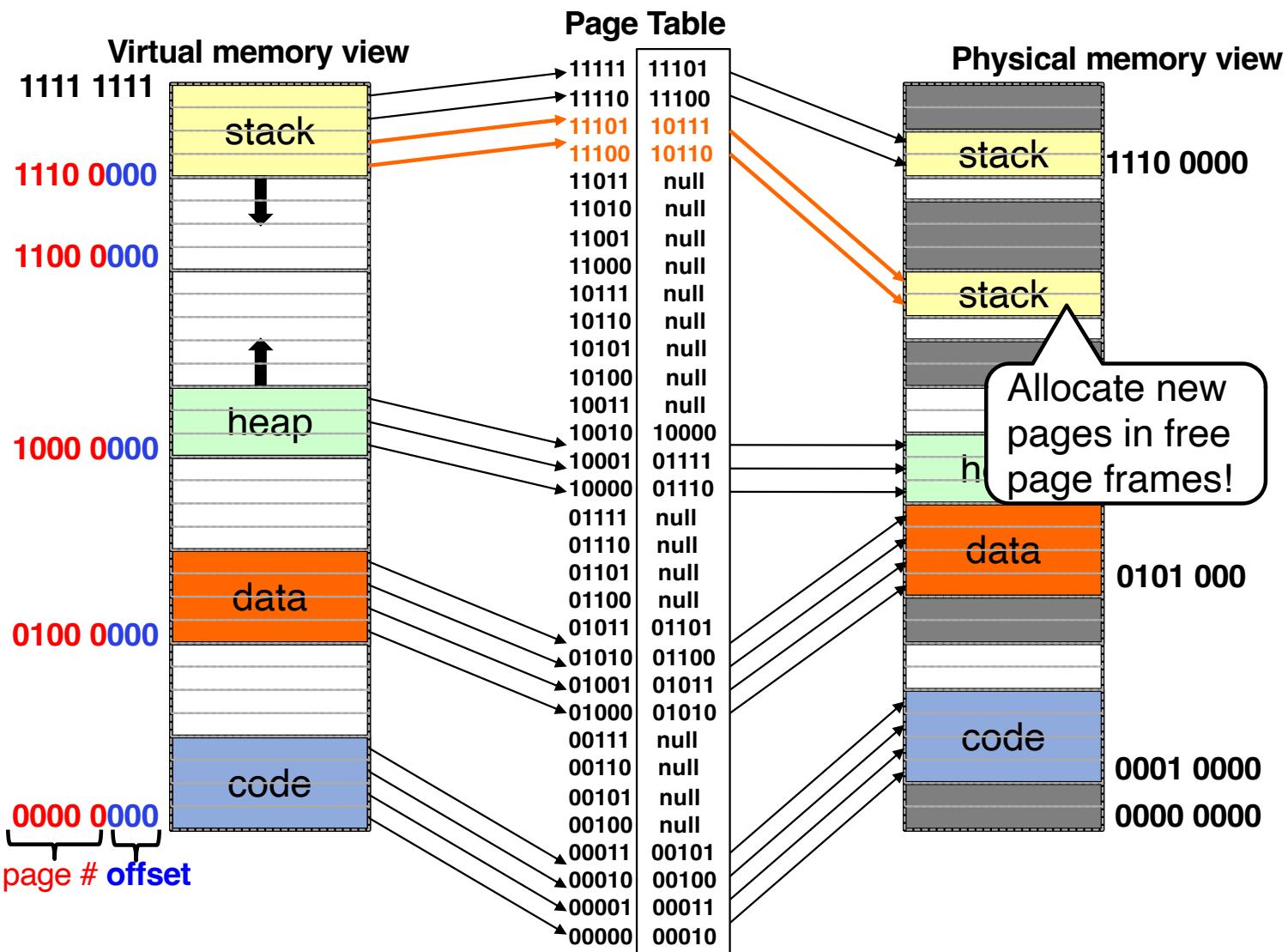
Page #	Page Frame #
0	4
1	5
2	1
3	6

Page table of Proc B





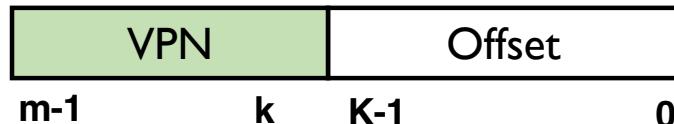




Virtual Address and Paging

- Length of virtual address determines size of address space
- Length of offset determines size of a page/page frame
- In case of m-bit virtual address and k-bit offset
 - Size of address space: 2^m
 - Size of a page: 2^k
 - e.g., 32-bit virtual address, 4KB page: m = **32**, k = **12**

Virtual Address



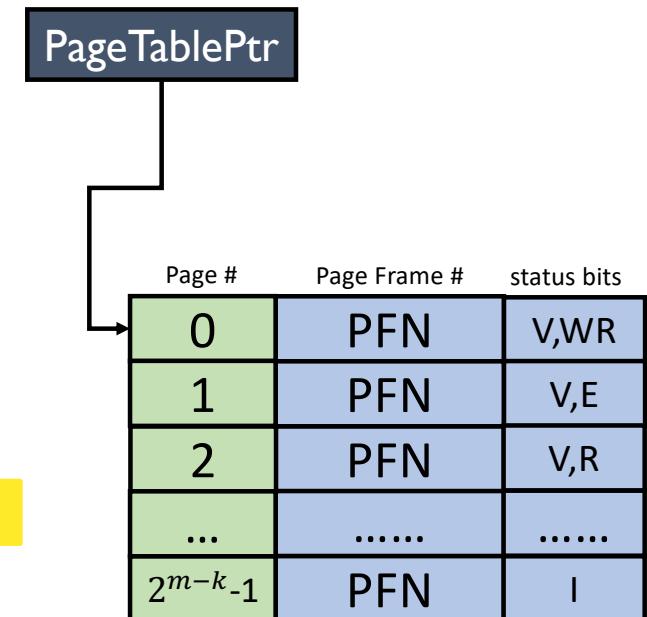
Page #	Page Frame #
0	PFN
1	PFN
2	PFN
...
$2^{m-k}-1$	PFN

Page Table Entry

- An entry in the page table is called a page table entry (PTE).
- Besides PFN, PTE also contains **a valid bit**
 - Virtual pages with no valid mapping: valid bit = 0
 - Important for sparse address space (e.g., 2^{64} bytes)
- PTE also contains **protection bits**
 - Permission to read from or write, or execute code on this page
- PTE also contains **an access bit, a dirty bit, a present bit**
 - Present bit: whether this page is in physical memory or on disk
 - Dirty bit: whether the page has been modified since it was brought into memory
 - Access bit: whether a page has been accessed

How Big are Page Tables

- Assume 32-bit machine and 4KB pages, and each PTE takes 4 bytes (PFN plus status bits)
 - Number of PTEs: $2^{32-12} = 2^{20}$
 - Size of page table: 4MB 每个PTE占4字节
 - What if 100 processes running? 400MB
- Page tables are stored in memory and context switch only changes the pointer to page table (e.g., CR3 register)

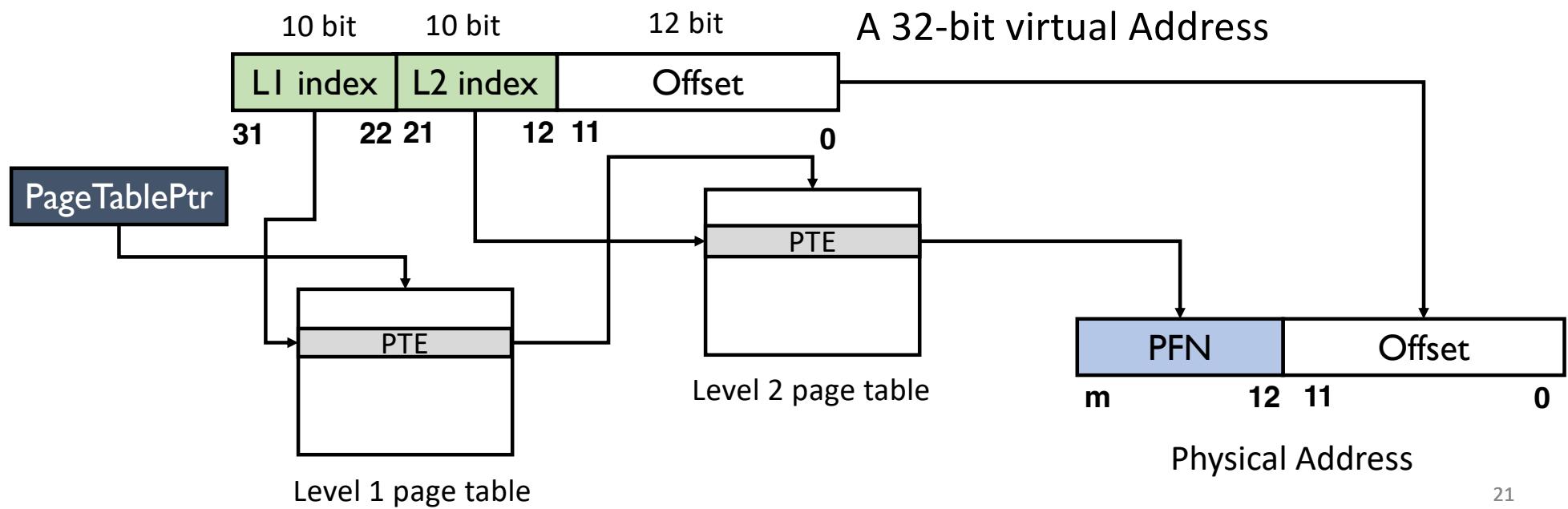


每次上下文切换时，操作系统仅需要更改指向当前进程页表的指针（如CR3寄存器指向的页表指针）。因此，操作系统不需要每次都加载完整的页表。

Multi-level Page Tables

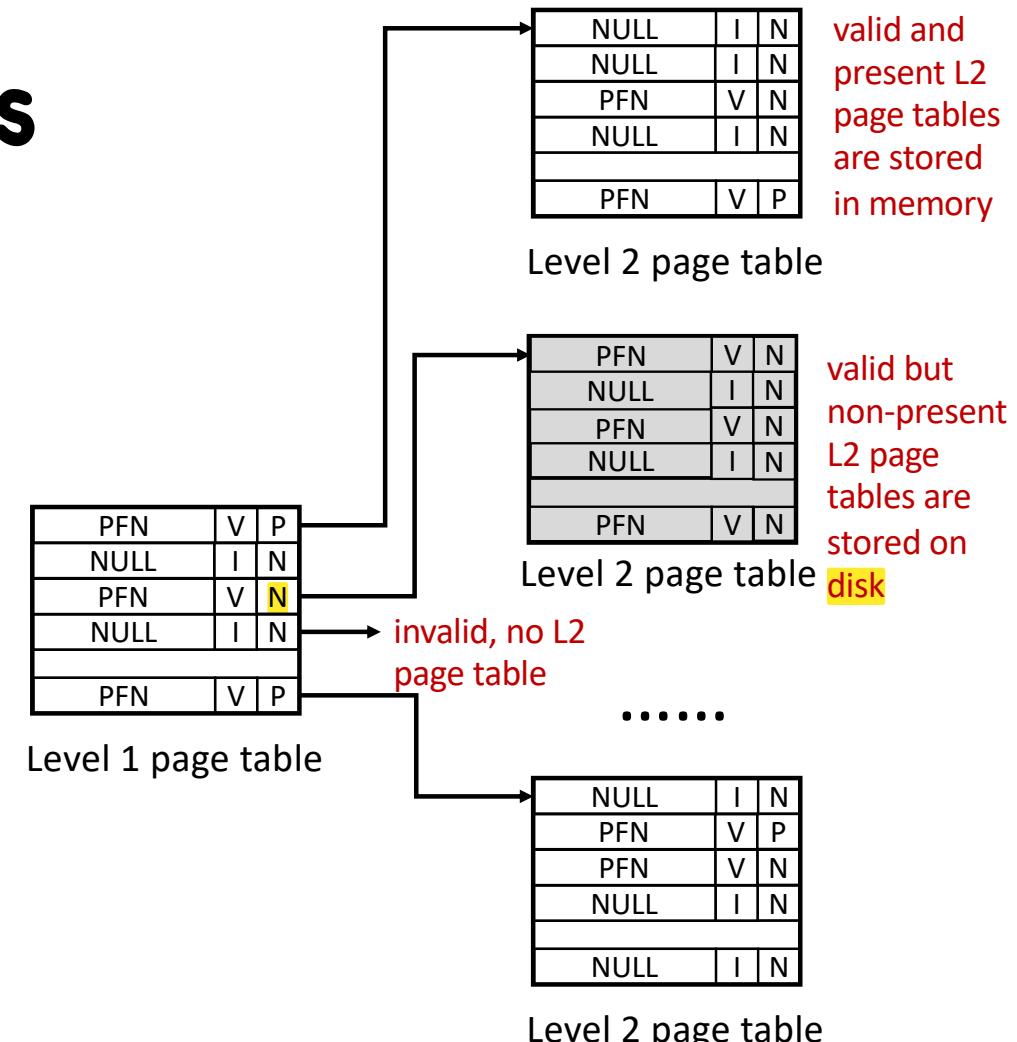
Two-level Page Tables

- Use two levels of page tables to save space

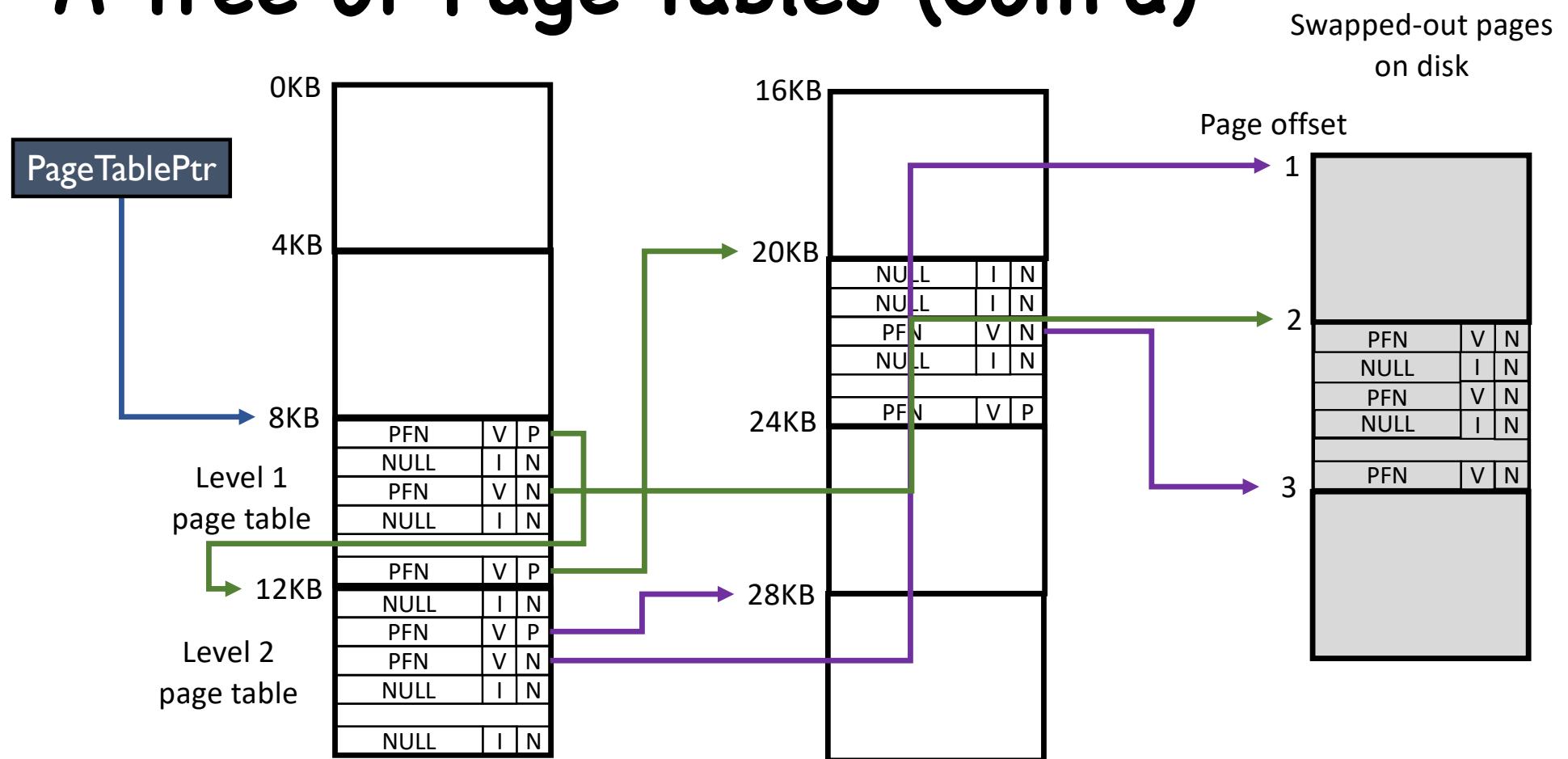


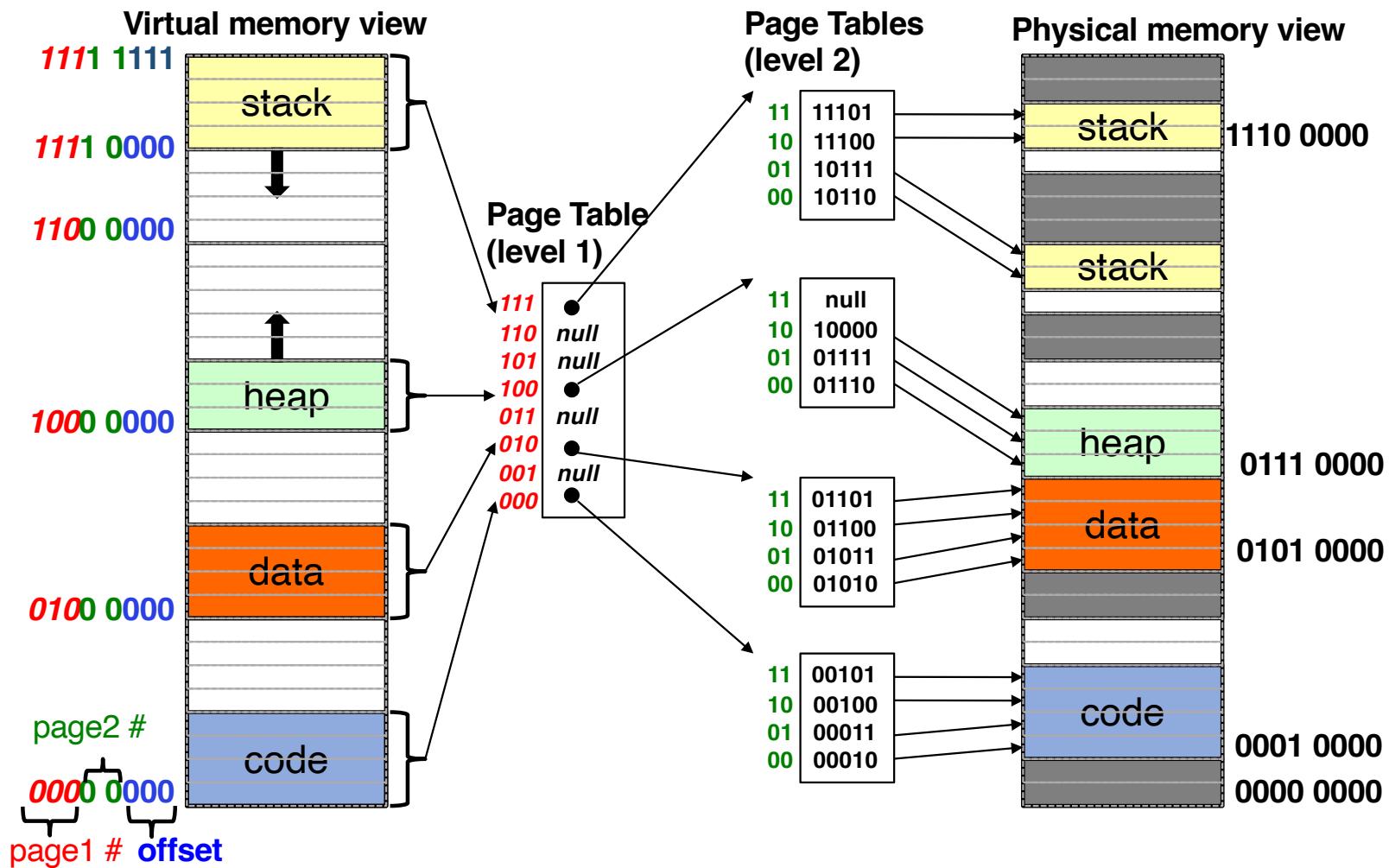
A Tree of Page Tables

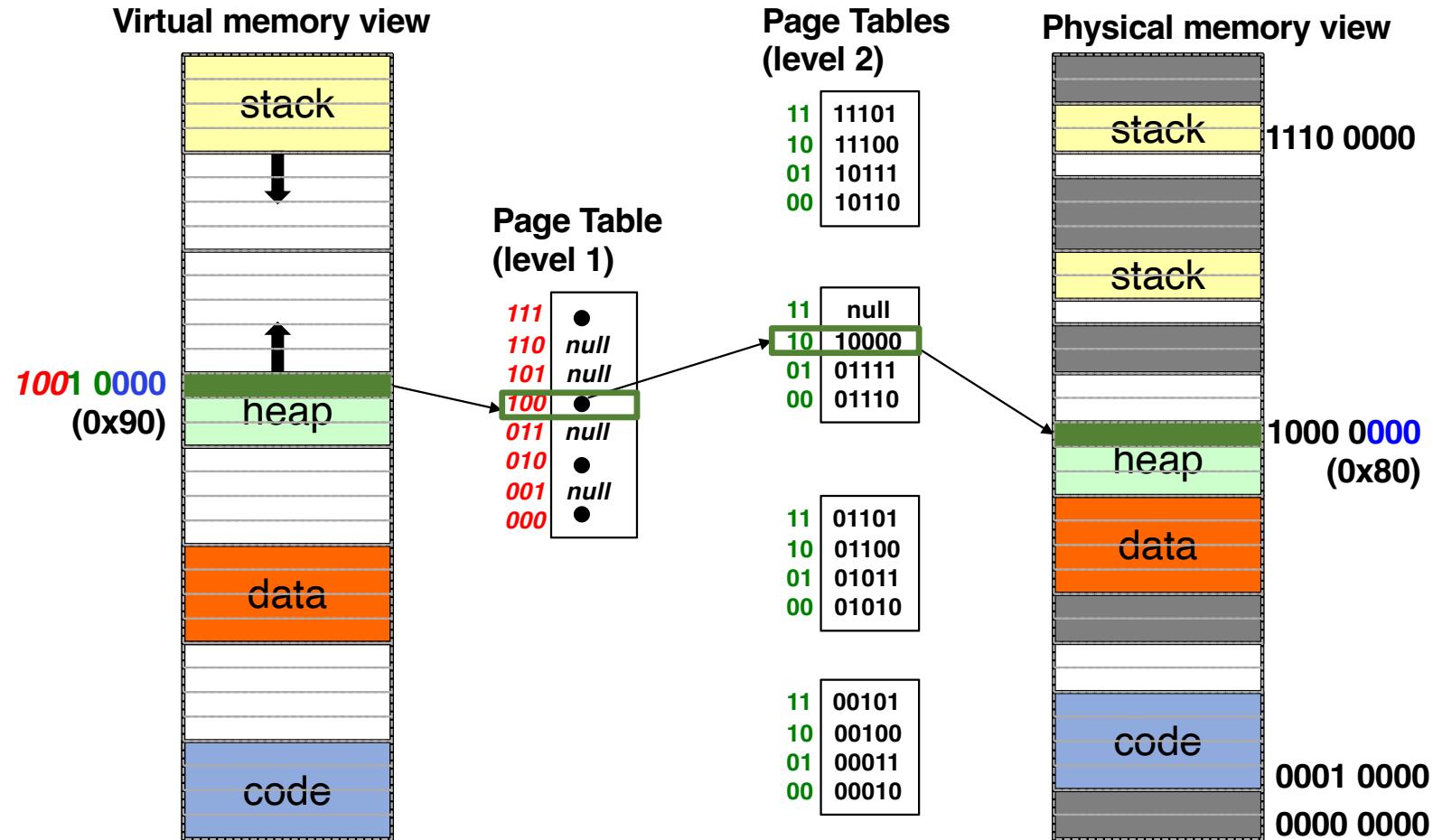
- A page table page also occupies a page frame
 - e.g., 4KB page and 4-byte PTE: 1024 entries per table
- Two-level page table forms a tree of page tables
 - In theory 1024 level-2 page tables, but only a subset are valid
 - A subset of valid page tables are stored in memory (others on disk)



A Tree of Page Tables (Cont'd)







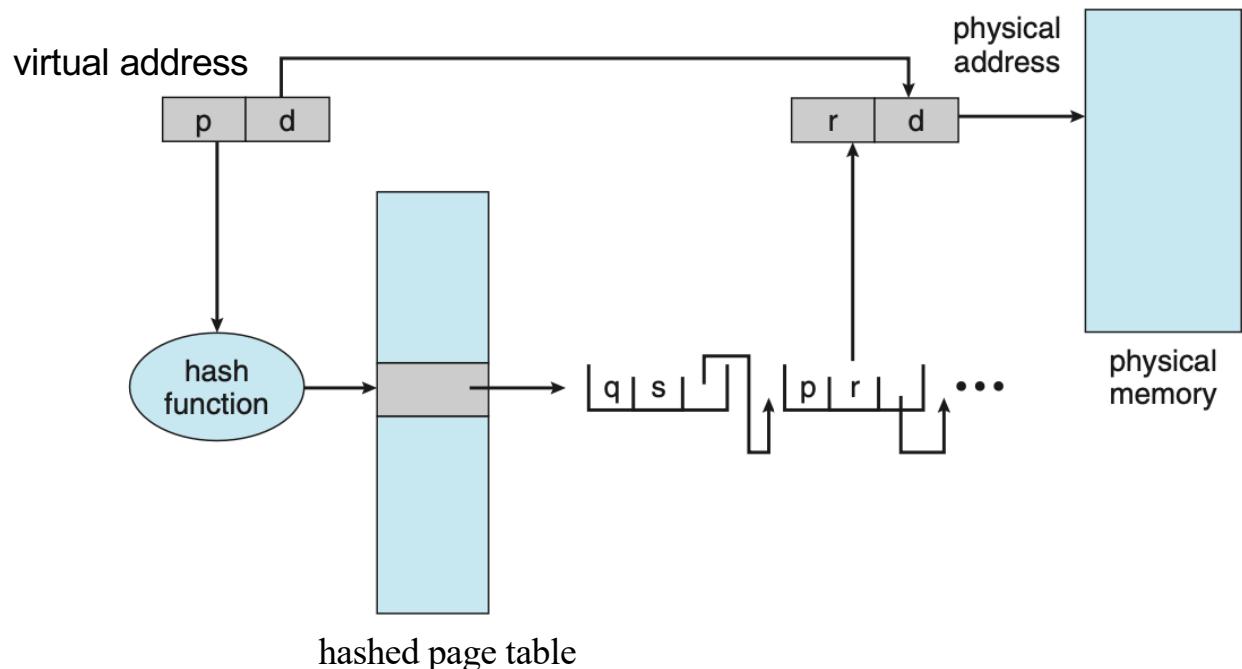
Other Page Table Structures

Page Table Structures

- Hierarchical page tables
 - 2-level page tables
 - 3-level page tables
 - 4-level page tables
- Hashed Page Tables
- Inverted Page Tables

Hashed Page Tables

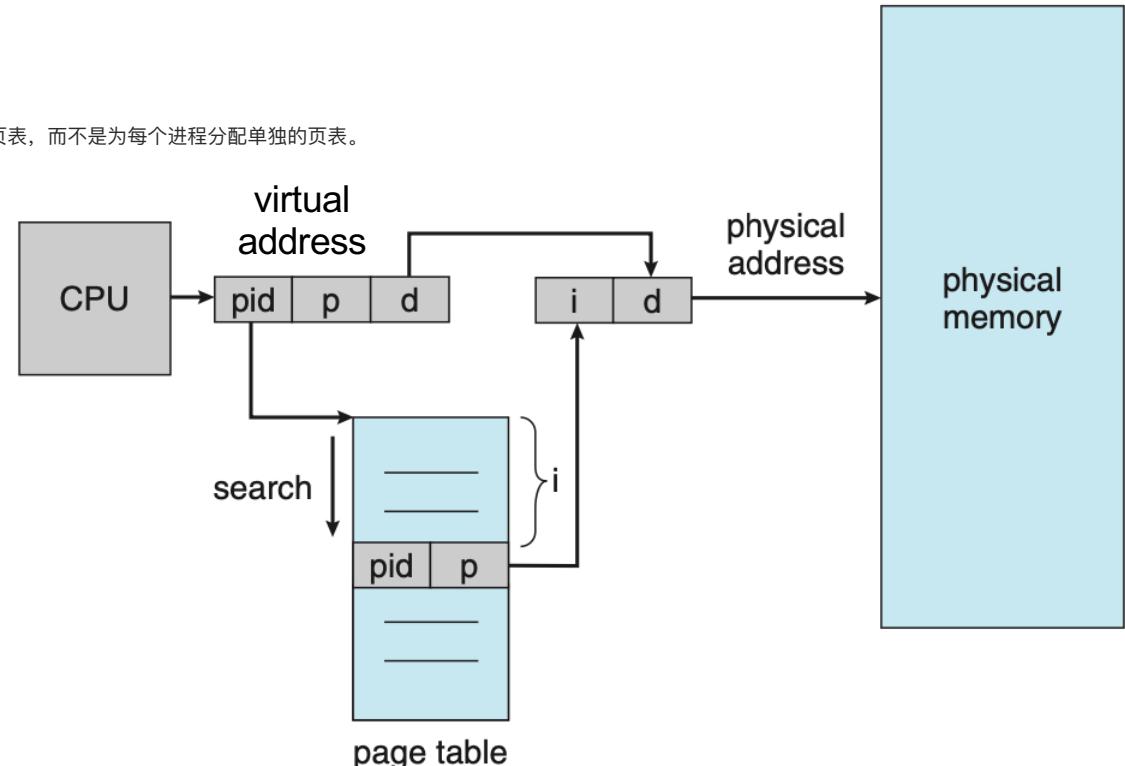
- Hash function
 - input: VPN
 - output: index in the hashed page table
- Collision handling
 - A linked list
 - Each element consists of three fields: (1) VPN, (2) PFN, and (3) pointer to the next element



Inverted Page Tables

- One page table for the whole system
 - Used in 64-bit UltraSPARC and PowerPC
- Each entry corresponds to one physical page frame
 - Process ID and VPN
- Page table lookup requires linear search of the entire table
- Memory sharing is hard

使用一个全局的页表，而不是为每个进程分配单独的页表。

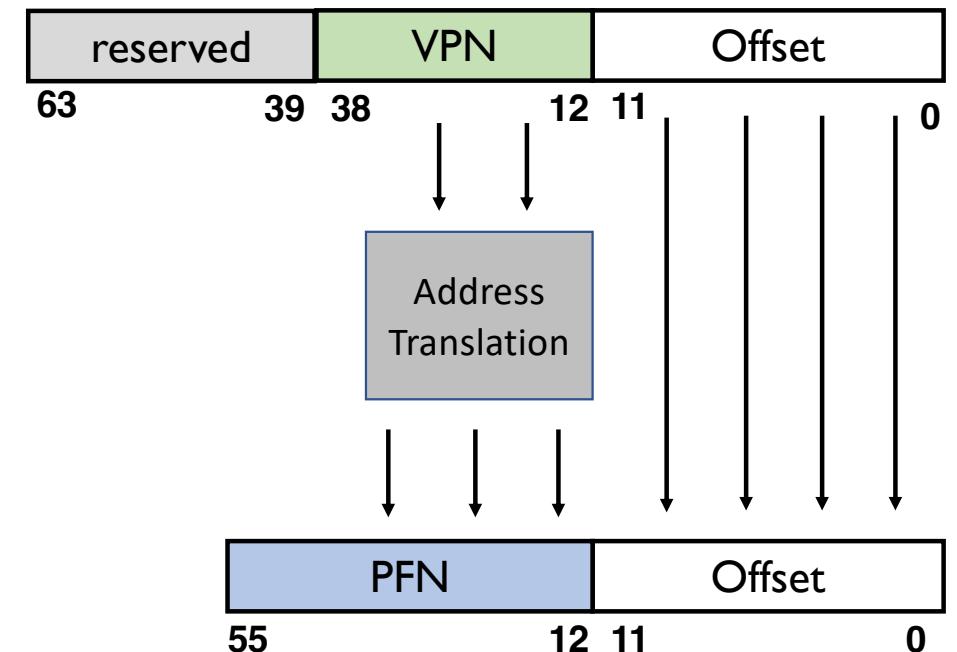


每个条目不仅包含物理页框号（PFN），还存储与该物理页框关联的进程ID（pid）和虚拟页号（VPN）。

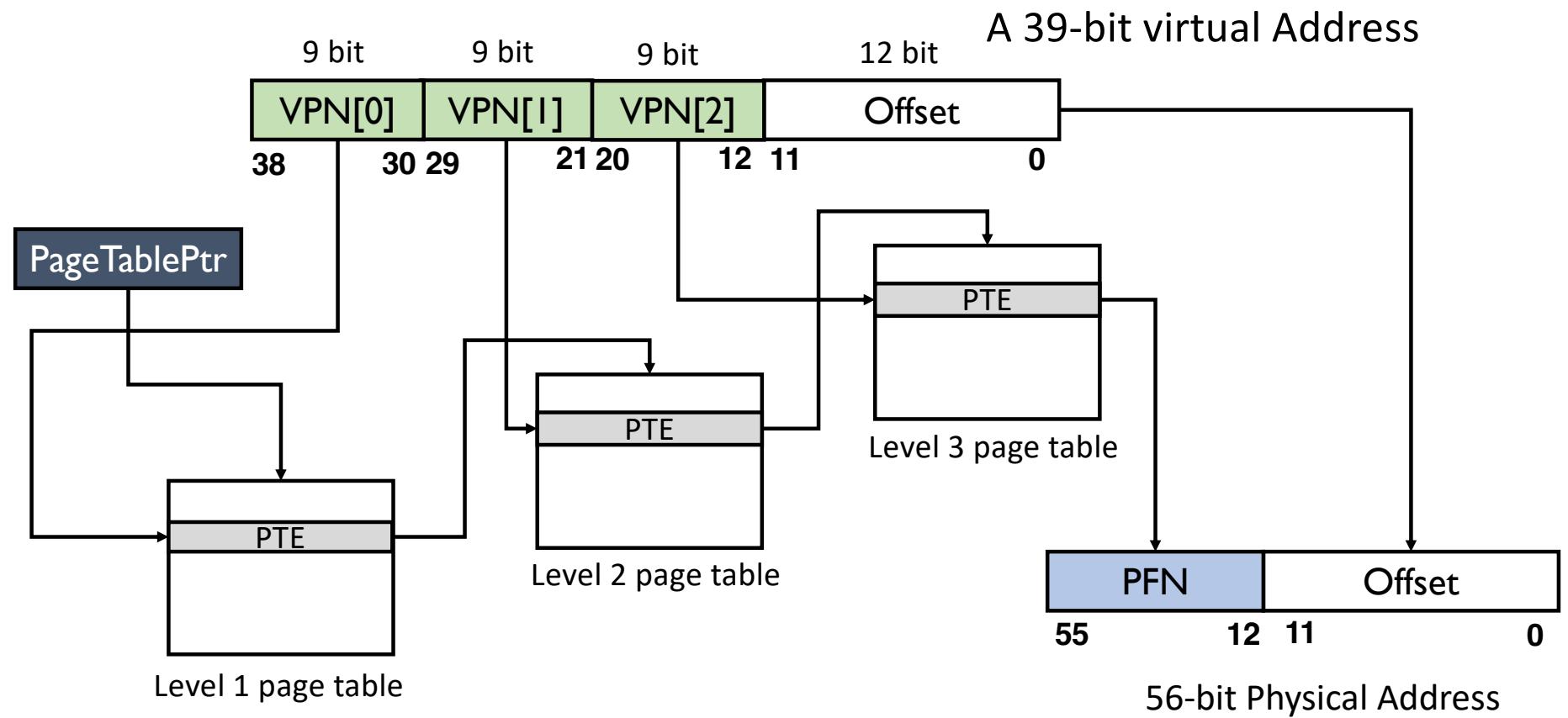
Real-world Paging Schemes

Virtual Memory on RISC-V

- RISC-V supports multiple MMU
 - For RV32: SV32
 - For RV64: SV39 and SV48
- Here we introduce **SV39**
 - Page size: 4KB
 - Virtual address: 39 bits
 - remaining bits of total 64 bits reserved
 - Physical address: 56 bits



SV39: Three Levels of Page Tables



SV39: Page Table Entries

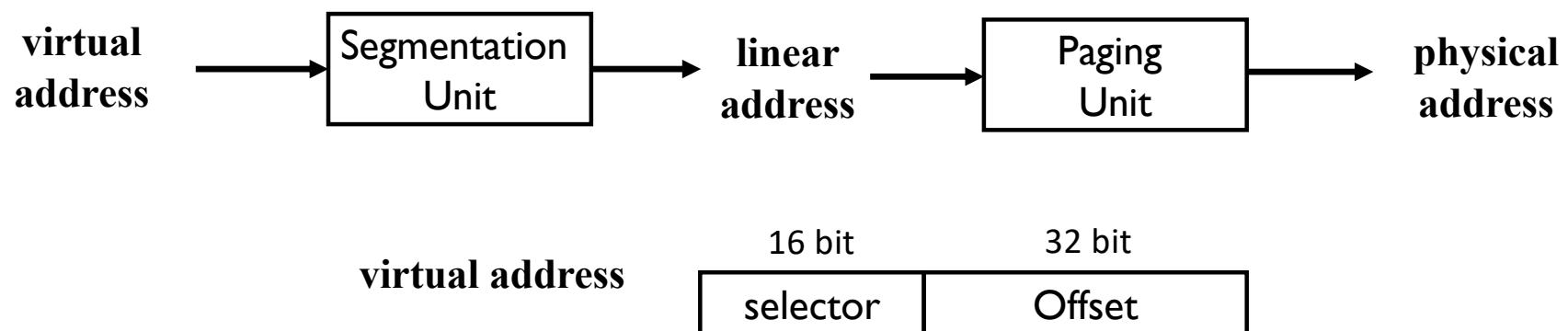
- A PTE in SV39 takes 8 bytes (64 bits)
 - Bit 8-0 status bits
 - Bit 53-10 is PFN (or physical page number, PPN)
 - Bits 63-54 reserved
- The 9 status bits
 - D (dirty), A (accessed), V (valid)
 - G (Global): G=1 the page is mapped in all address spaces
 - U (User): U-mode code may access this page
 - RSW: reserved for s-mode

63	54 53	28 27	19 18	10 9	8	7	6	5	4	3	2	1	0
Reserved	PPN[2]	PPN[1]	PPN[0]	RSW	D	A	G	U	X	W	R	V	

Bit widths: 10, 26, 9, 9, 2, 1, 1, 1, 1, 1, 1, 1, 1.

Virtual Memory on IA-32

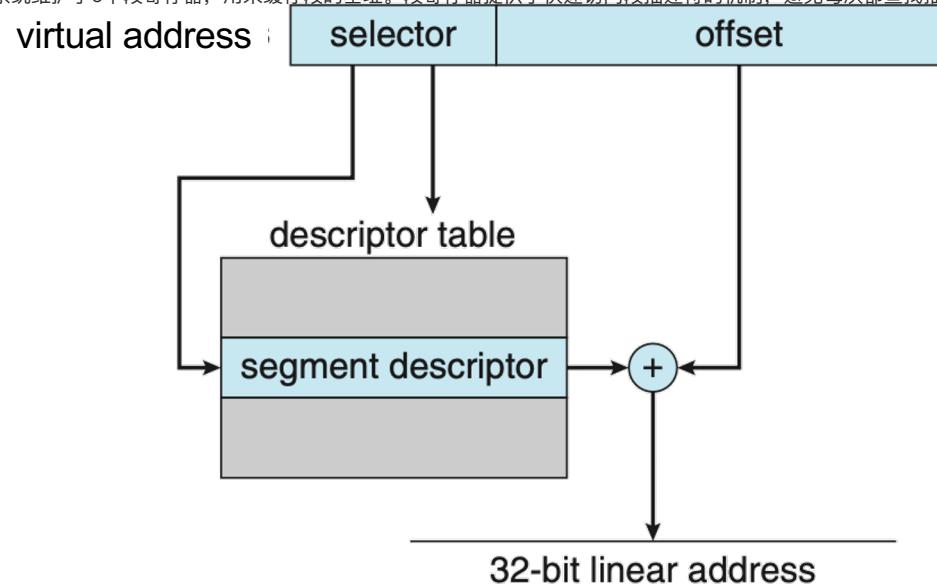
- Intel's 32-bit CPU (IA-32) uses two stage address translation:
segmentation + paging
- A virtual address contains a 16-bit segment selector and 32-bit offset



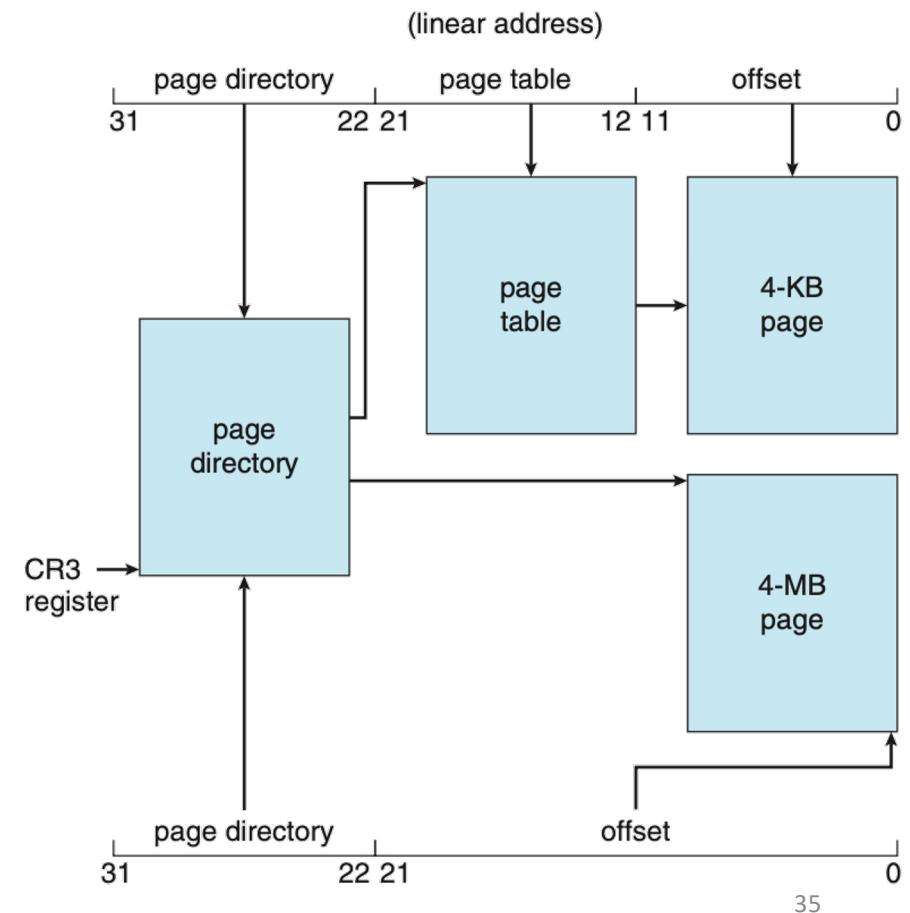
Virtual Memory on IA-32

- Two descriptor tables: GDT & LDT
- Six segment register to cache segment base addresses

操作系统维护了6个段寄存器，用来缓存段的基址。段寄存器提供了快速访问段描述符的机制，避免每次都查找描述符表。



虚拟地址通过段选择符（selector）和偏移量（offset）被转换为线性地址。在转换过程中，段选择符会索引到描述符表，然后通过段描述符得到段的基址，再加上偏移量得到线性地址。



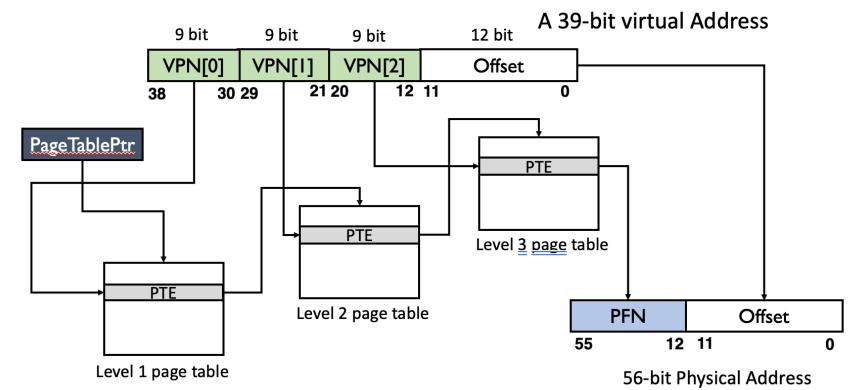
Translation Lookaside Buffer

Issues of Paging

- Time complexity
 - Extra memory references during address translation
 - Three-level page tables **requires 3 additional memory reads**
 - If every memory reference needs 4 memory reads

Question:

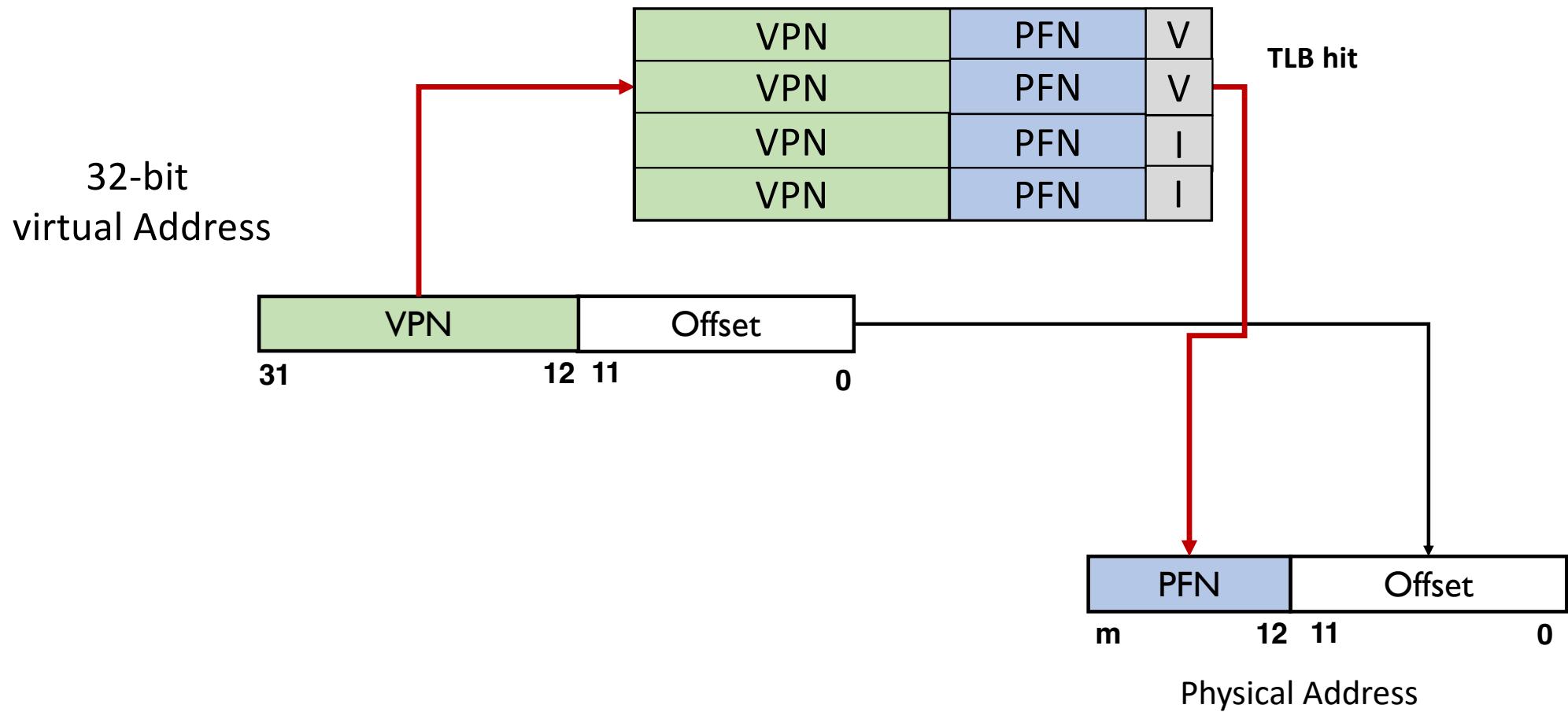
- How to speed up address translation and avoid extra memory reads?



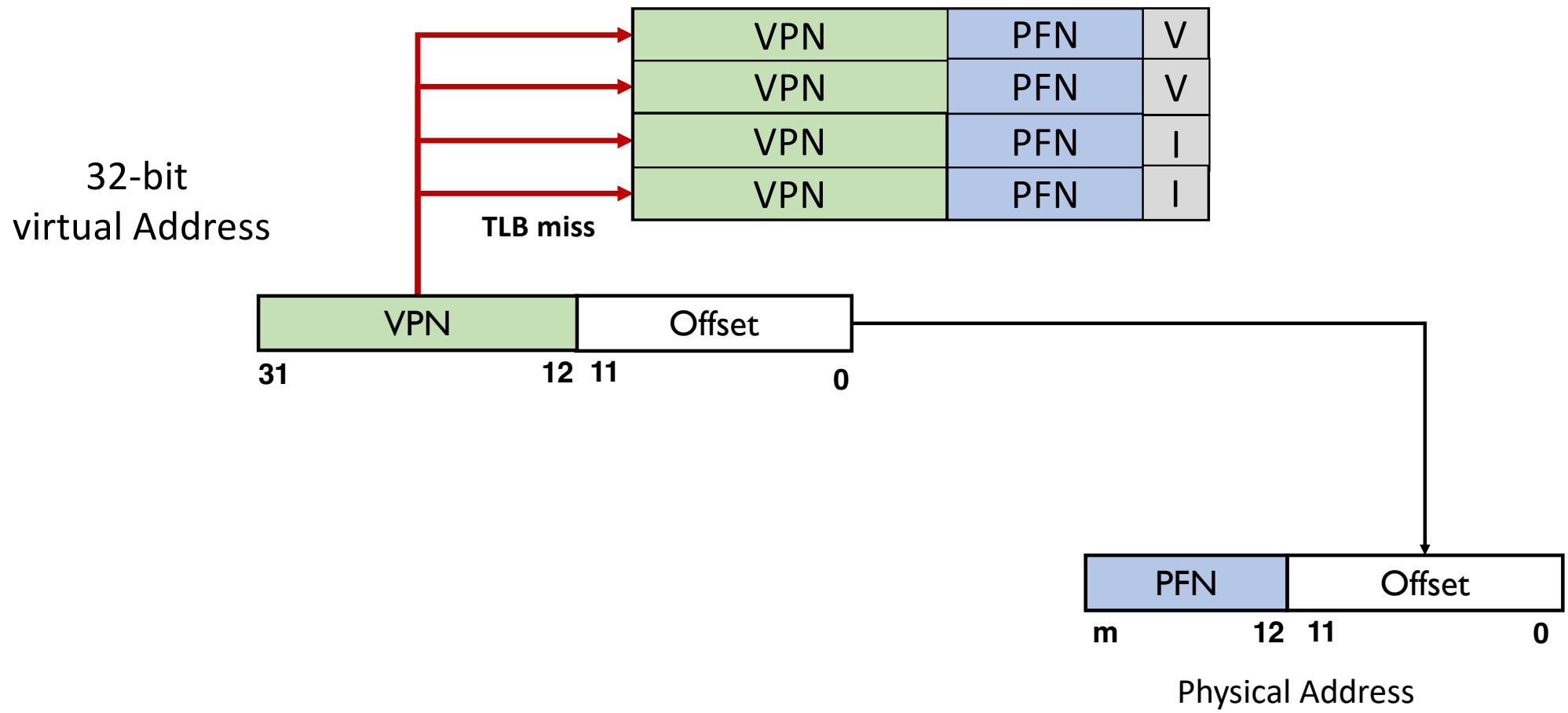
Translation Lookaside Buffer

- A translation lookaside buffer (TLB) is a hardware cache that is part of the MMU
 - A cache for the PTEs: holding **a translation likely to be re-used**
 - Replacement policy: LRU, FIFO, random
 - Each entry holds mapping of a virtual address to a physical address
- Before a virtual-to-physical address translation is to be performed, TLB is looked up using VPN
 - TLB hit: VPN is found, and the PFN of the same entry used
 - TLB miss: VPN not found, page table walk

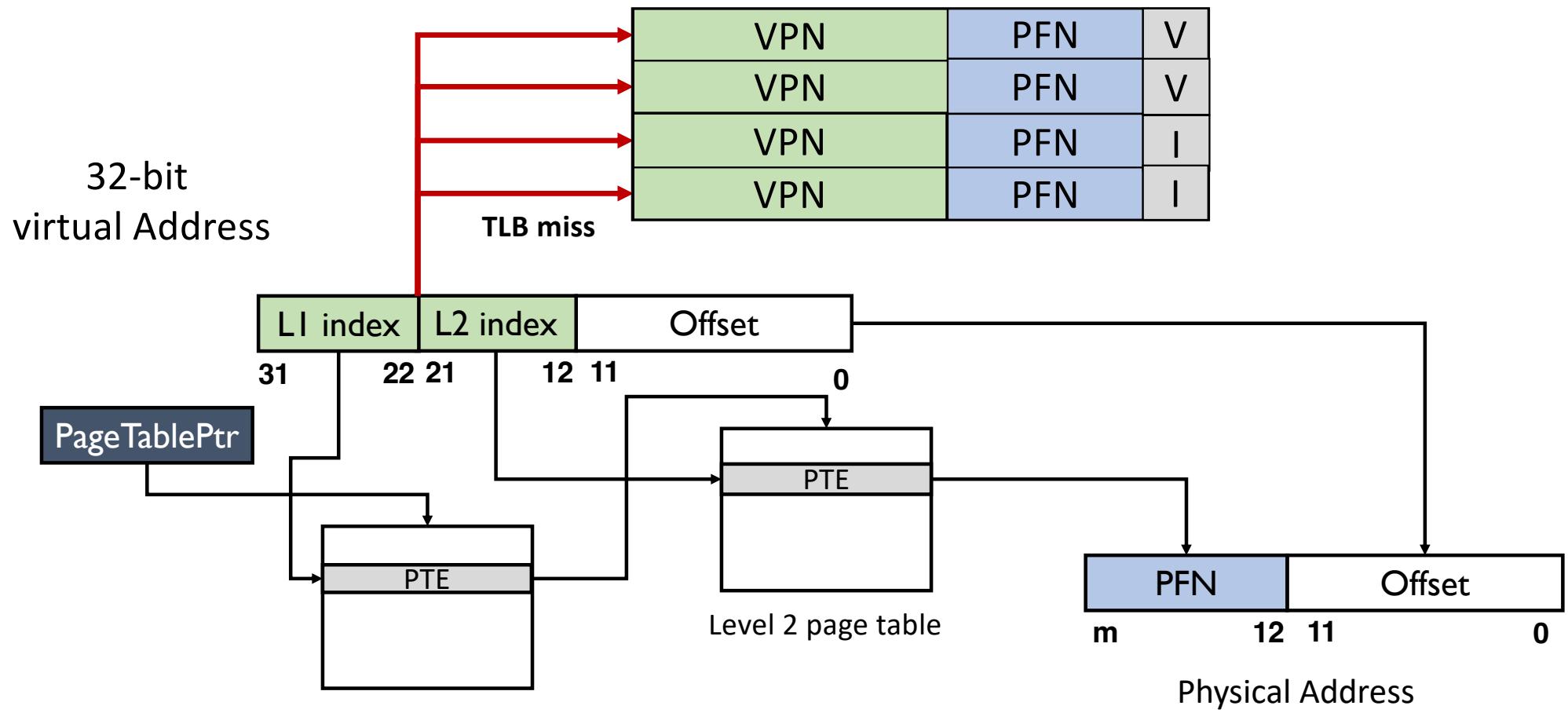
Translation Lookaside Buffer (Cont'd)



Translation Lookaside Buffer (Cont'd)

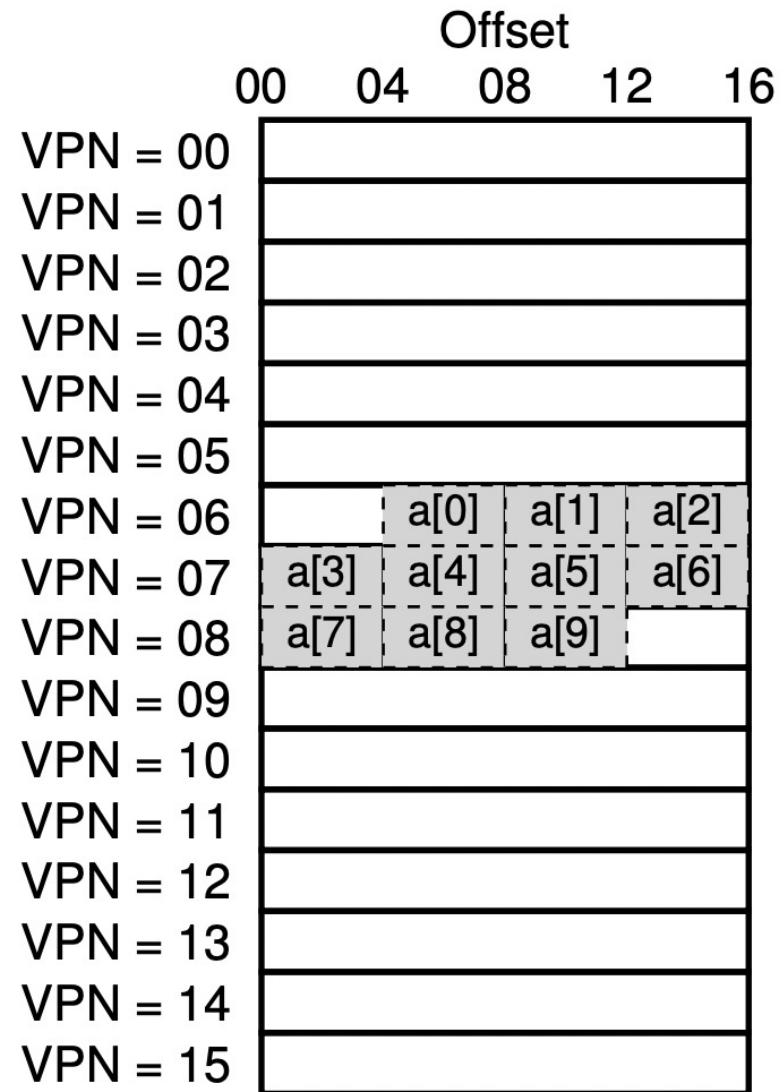


Translation Lookaside Buffer (Cont'd)



Why Does TLB Work?

- Ideally one page table walk for the entire page
 - TLB is smaller than page table, but
- Spatial locality
 - Sequentially executed instructions, local variables (on stack), arrays (on heap) likely on the same page
 - E.g., accessing $a[0]$ to $a[9]$
 - m,h,h,m,h,h,h,m,h,h \rightarrow 70% hit rate
 - Large page size increases hit rate
- Temporal locality
 - Accesses to the same page tend to be close in time



Issues with Context Switch

- Two process **may use the same virtual address**
 - P1: 100 → 110
 - P2: 100 → 170
- Solutions
 - Flush TLB upon context switch
 - Invalidate all entries: V→I
 - Extending TLB with address space ID
 - No need to flush tlb

VPN	PFN	valid
-	-	I
100	110	V
-	-	I
100	170	V

VPN	PFN	valid	ASID
-	-	I	-
100	110	V	1
-	-	I	-
100	170	V	2

Thank you!

