Virtual Memory and Caching

CS 1541

Wonsun Ahn

University of Pittsburgh

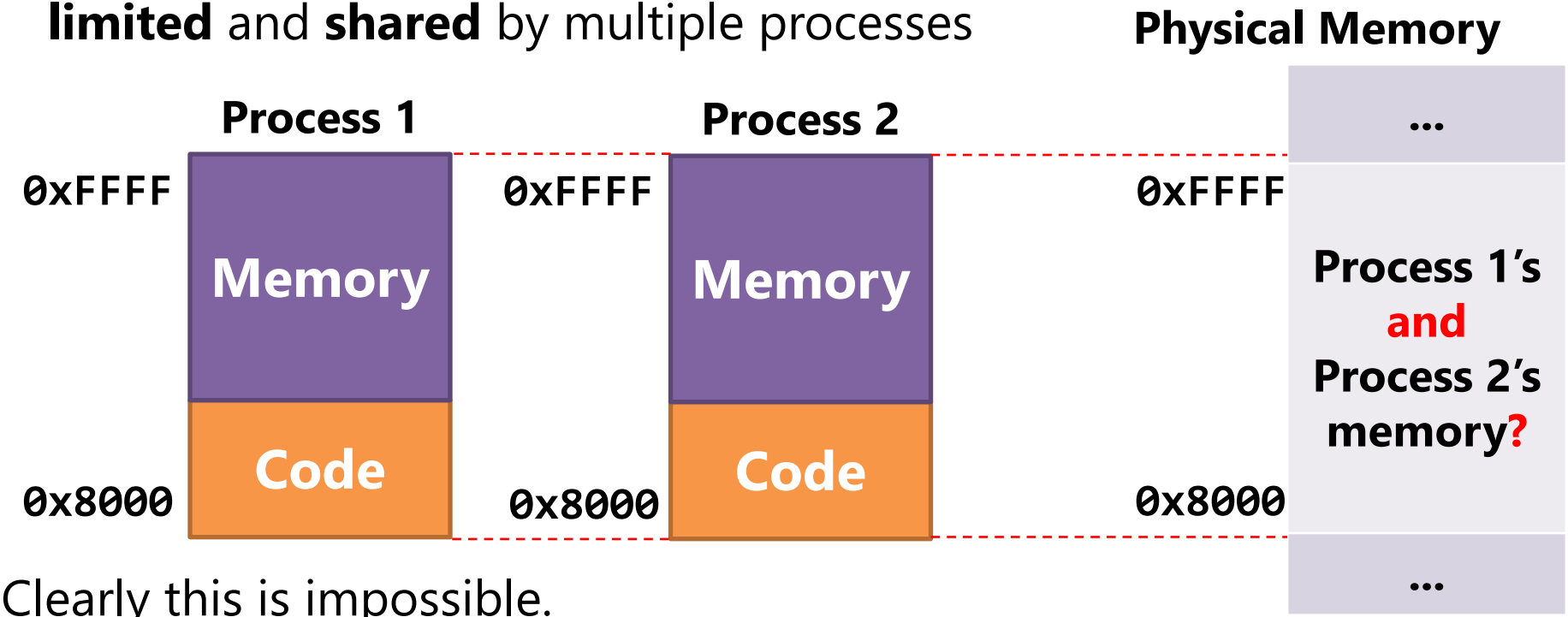
Virtual Memory and Caching

- So what does virtual memory have to do with caching?
- *A lot* actually.
- But first let's do a quick review of virtual memory
  - To warm up your cache with CS 449 info

Virtual Memory Review

Virtual Memory: Type of Virtualization

- **Virtualization**: hiding the complexities of hardware to software
- **Virtual Memory**: hides the fact that physical memory (DRAM) is **limited** and **shared** by multiple processes

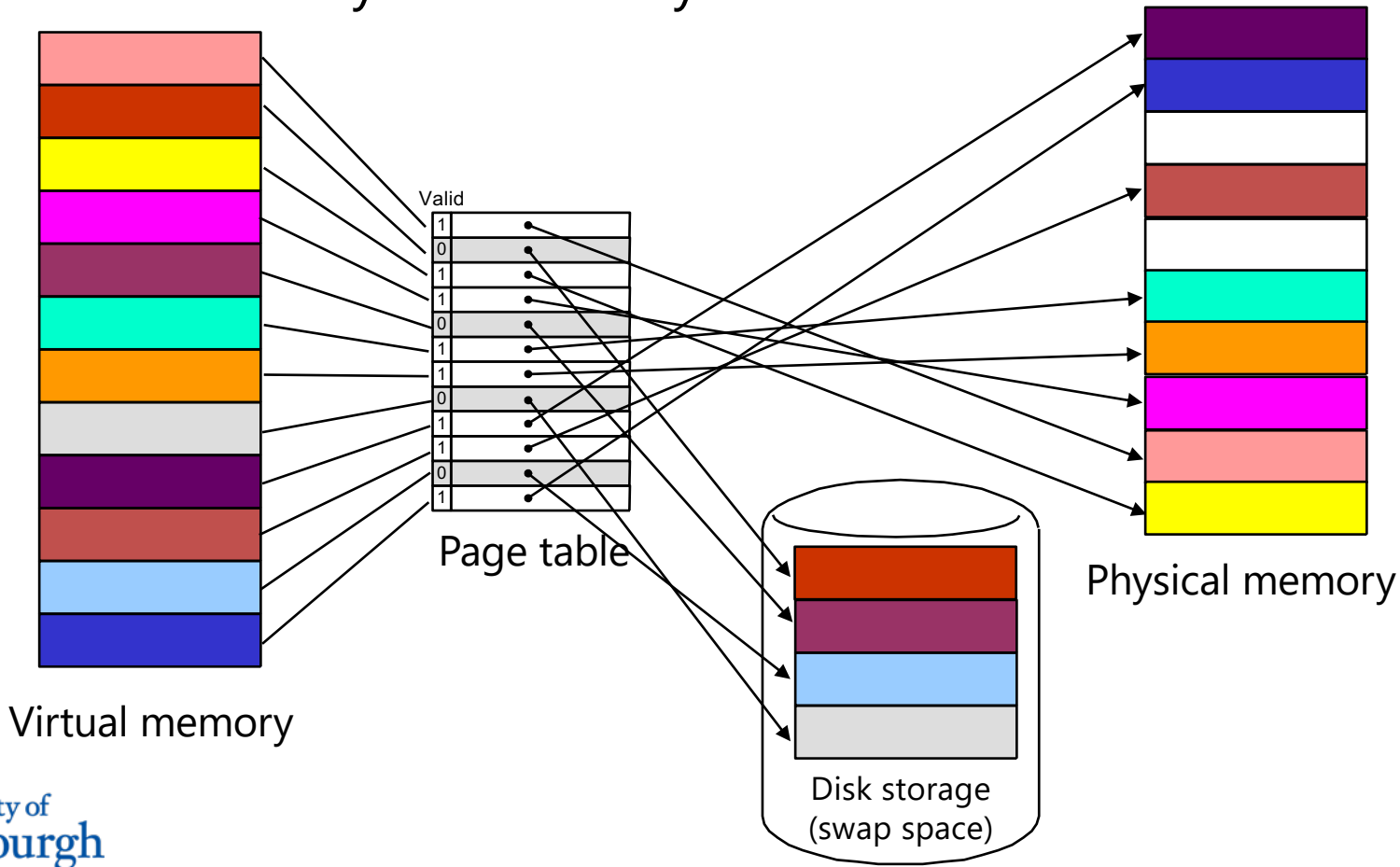


Clearly this is impossible.

But programs see this view of memory.

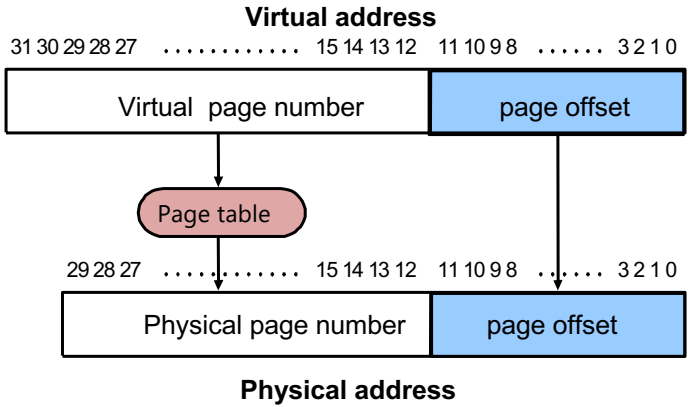
Virtual Memory: Behind the Scenes

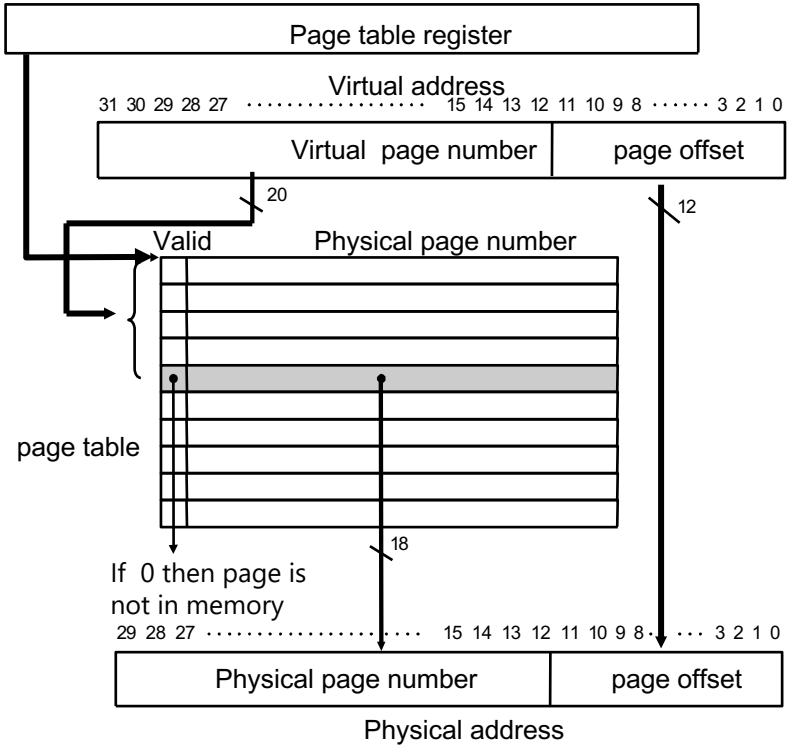
- **Pages** of memory are mapped to either physical memory or disk
  - Look familiar? Physical memory acts as a **cache** for disk storage



How virtual to physical address translation happens

1. CPU extracts virtual page number from virtual address
2. CPU locates page table pointed to by **page table register**
3. Page table is indexed using virtual page number





DRAM as Cache

Physical Memory as a Cache

- Relationship between DRAM ↔ Disk is same as Cache ↔ DRAM
  - DRAM is fast but small and expensive
  - Disk is slow but big and cheap
- If you view DRAM as cache, some design decisions become obvious
  - Size of block: **4 KB pages**. Why?
    - For **spatial locality**. Capacity is less of a problem for DRAM.
  - Associativity: **Fully-associative** (can map page anywhere). Why?
    - A miss (**page fault**) is expensive. You need to read from disk!
    - But now **page hits become expensive** due to **lookup** cost
  - Block replacement scheme: **LRU, or some approximation**. Why?
    - Did I say a page fault is expensive?
  - Write policy: **Write-back** (a.k.a. **page swapping**). Why?
    - Bandwidth for write-through to disk is too much for I/O bus

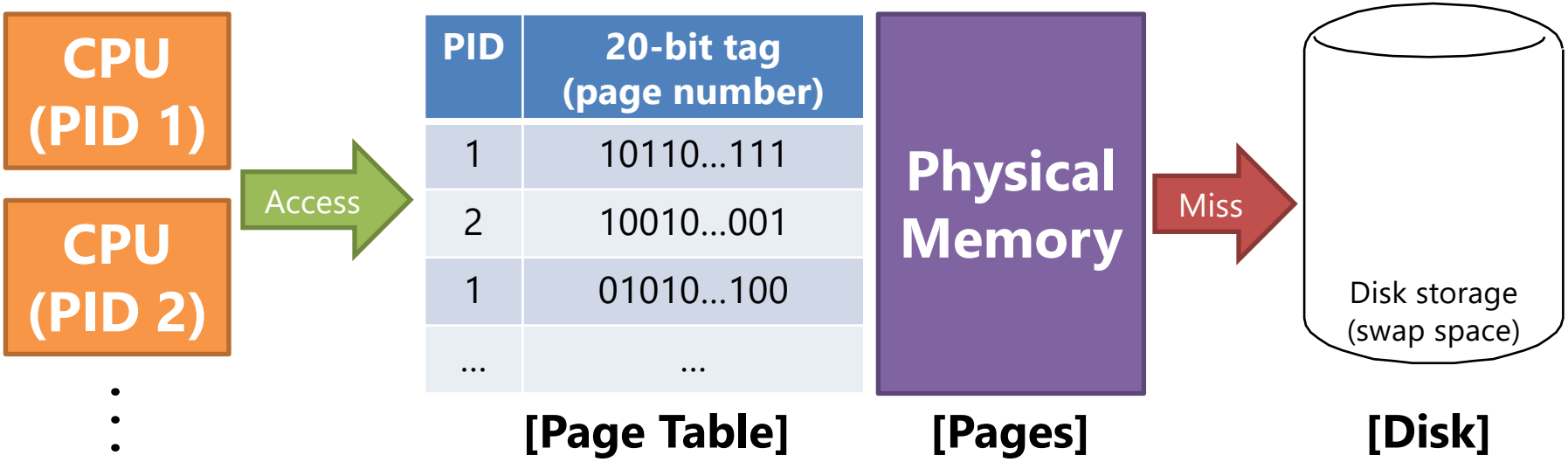
Physical Memory as a Cache

- If you treated each page as a cache block, what would be the tag?
  - 32-bit address:

Tag (20 bits): page number	Page offset (12 bits)

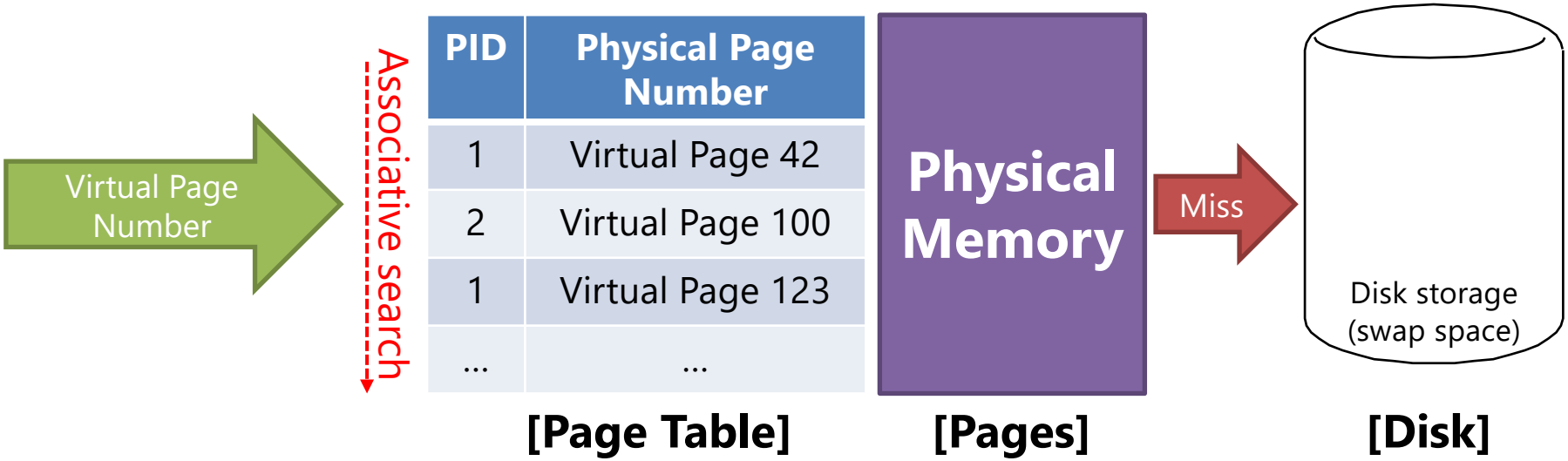
  - Fully-associative, so row bits and 4 KB pages, so 12 bits for offset

- How would the page table for searching physical memory look?



Inverted Page Table: tags for physical pages

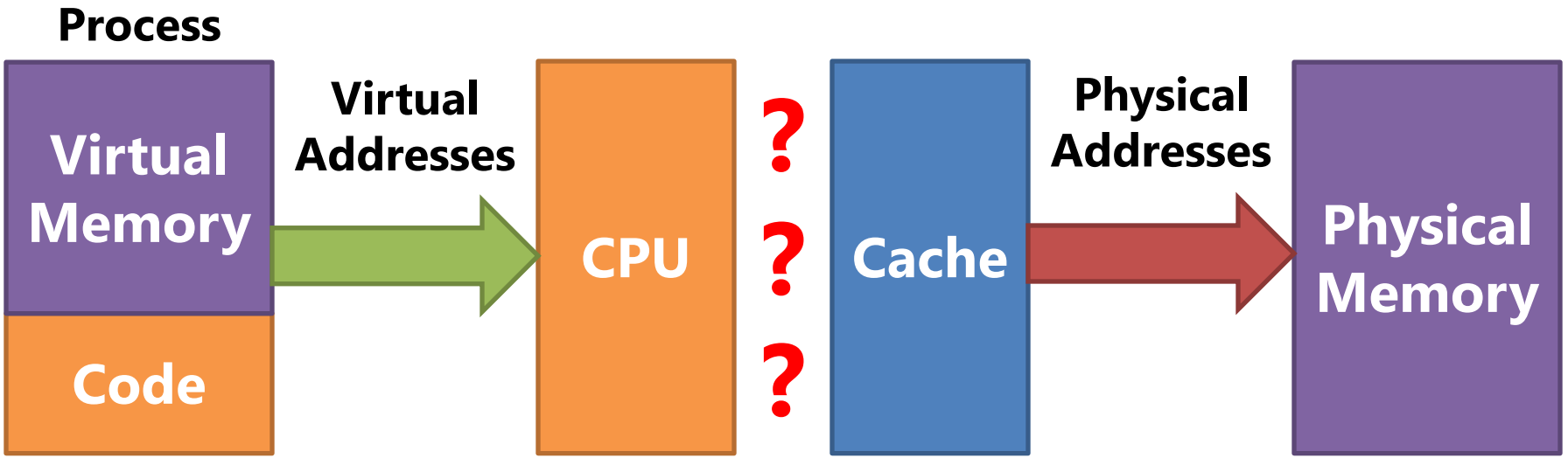
- This type of page table is called an **inverted page table**.



- Called inverted because table contains virtual page numbers (Unlike regular page tables which contains physical page numbers)
- **Pro**: Page table only as big as physical mem (**low space complexity**)
- **Con**: Associative search of page table (**high time complexity**)
  → Often hashing used to direct map pages. Causes conflict misses.

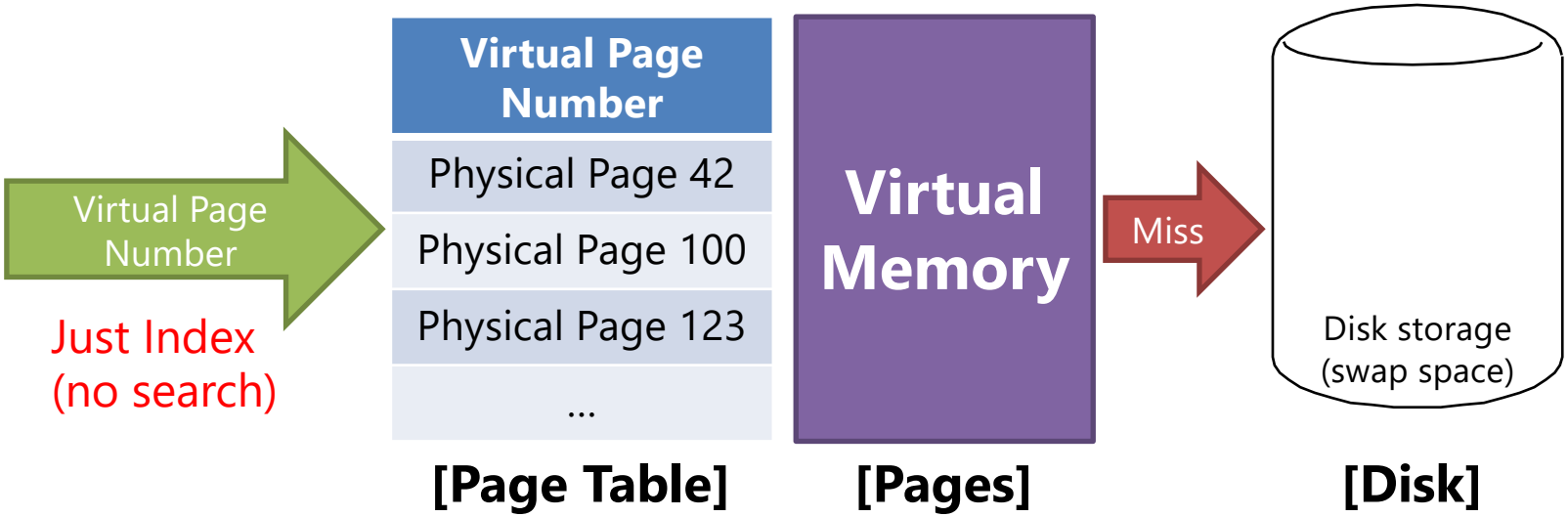
How Often do Lookups Happen?

- Programs use **virtual addresses** to refer to code and data
- DRAM and Caches use **physical addresses**
- How often does the conversion need to happen?
  - At MEM stage of every `lw` or `sw` instruction to convert data addr
  - At FETCH stage of every instruction to convert PC



Address Lookup Using (Regular) Page Table

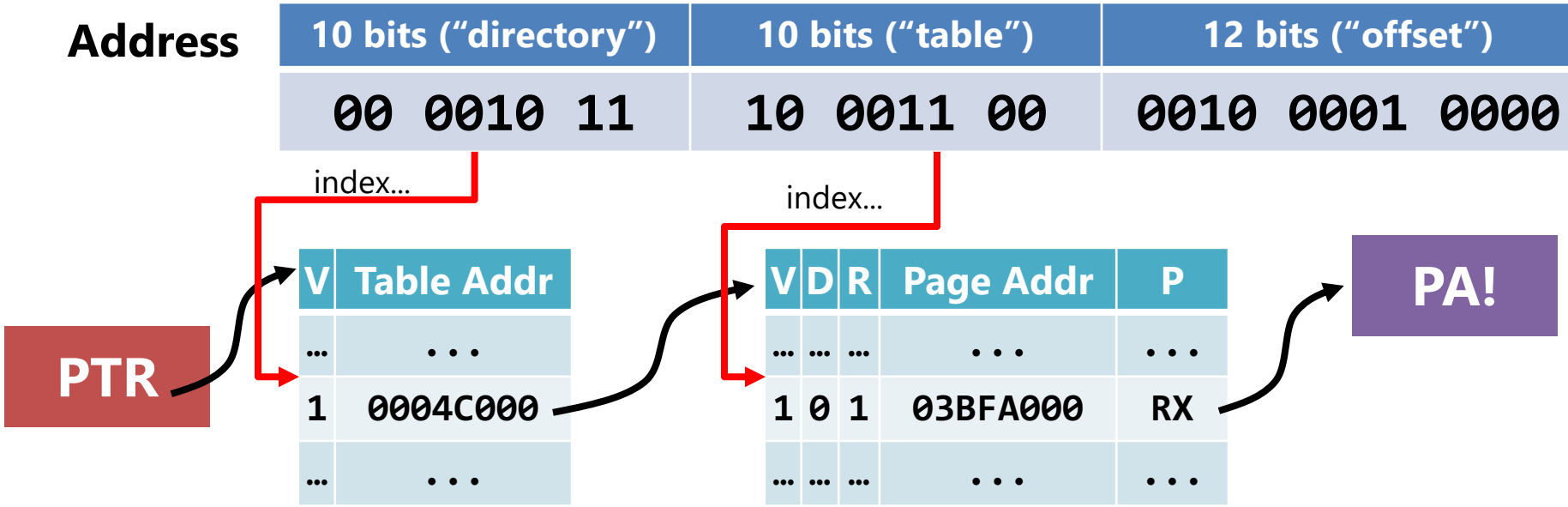
- Lookup is done by **indexing** page table using virtual page number.



- Note: no PID needed since all virtual pages belong to one process
- **Pro**: Indexing can be done in constant time (**low time complexity**)
- **Con**: Page table as big as virtual mem (**high space complexity**)

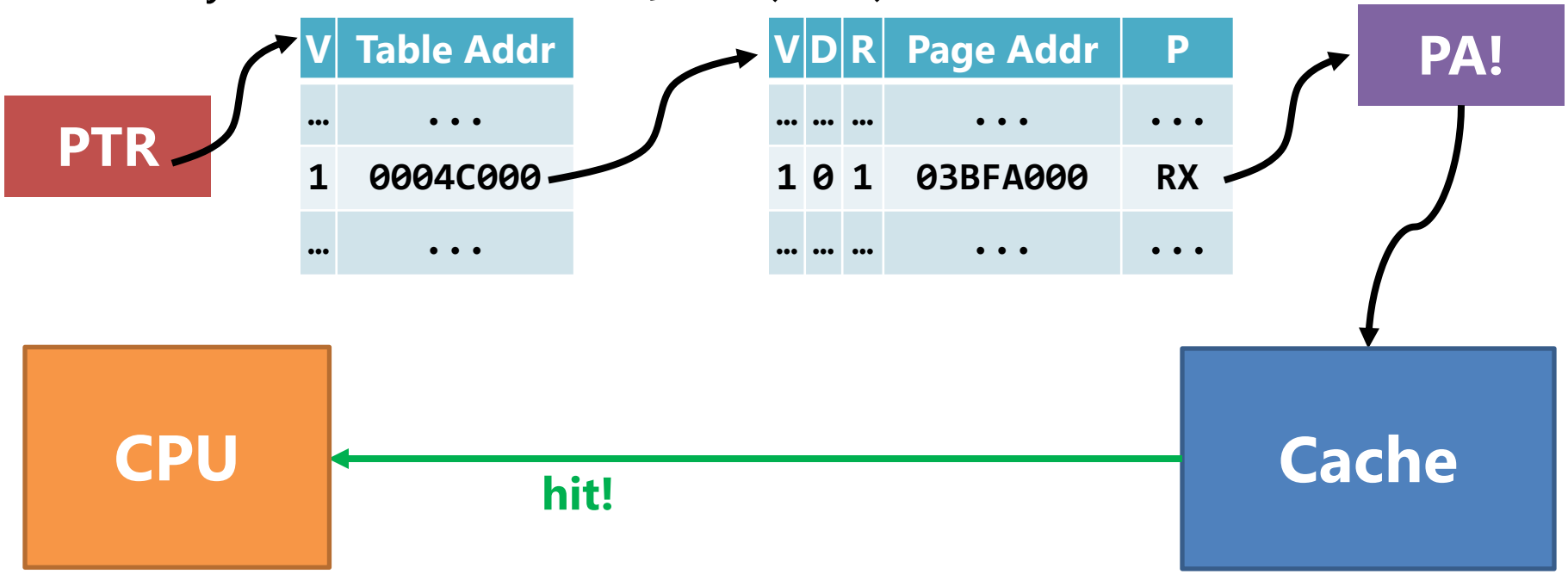
How big is the Page Table?

- 32-bit addresses with 4KiB (2^{12} B) pages means **2^{20}** (**1M**) PTEs.
- 64-bit addresses with 4KiB pages means **2^{52}** (**4 quadrillion**) PTEs.
- We can use **hierarchical page tables** as a **sparse data structure.**



Page Table Lookup Cost

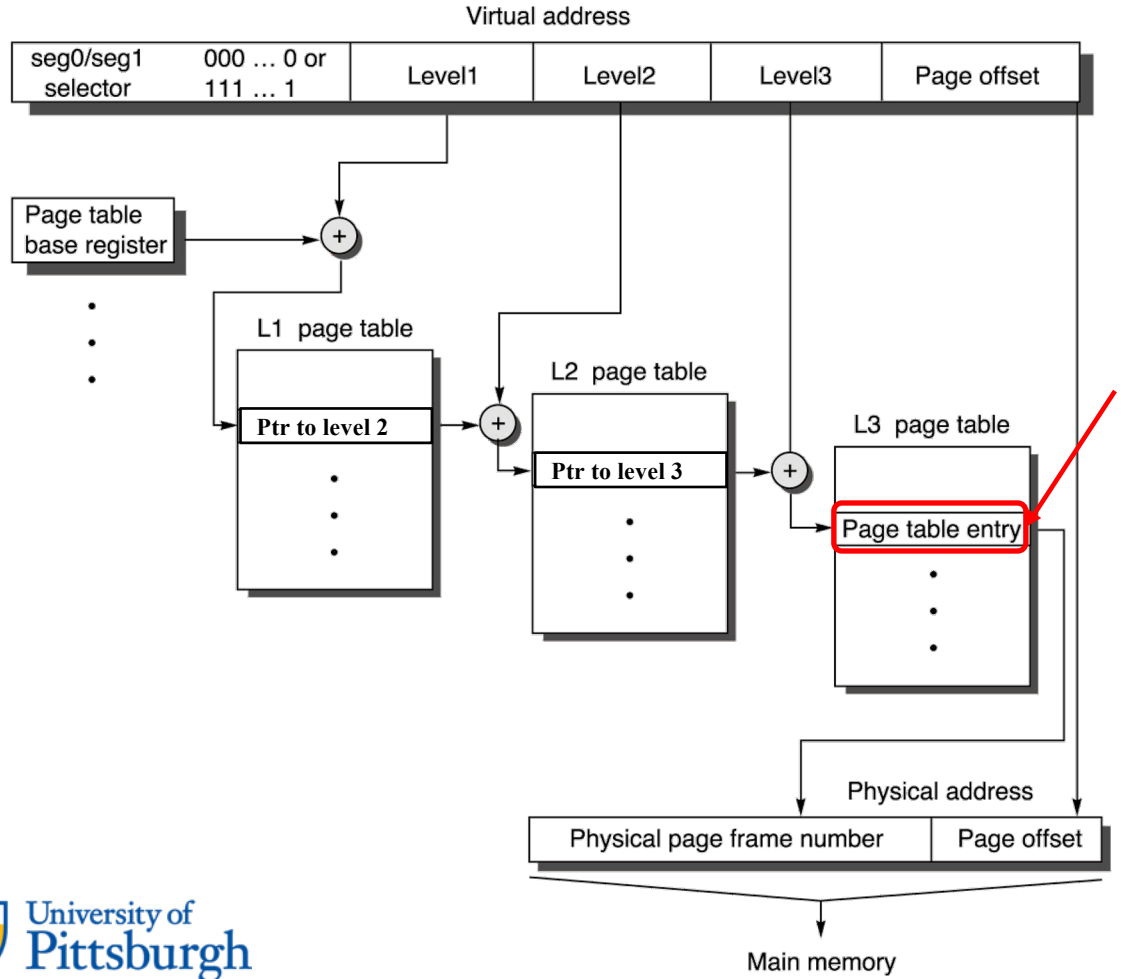
- Let's say we have a `lw $t0, 16($s0)`



- Must perform two memory accesses to hierarchical page table
  - Page table accesses may miss in cache and cause further delay!

The real picture looks more like this

- Alpha 21264 CPU with 3-level page table:



In the end, the PTE (Page Table Entry) is all you need for a translation.

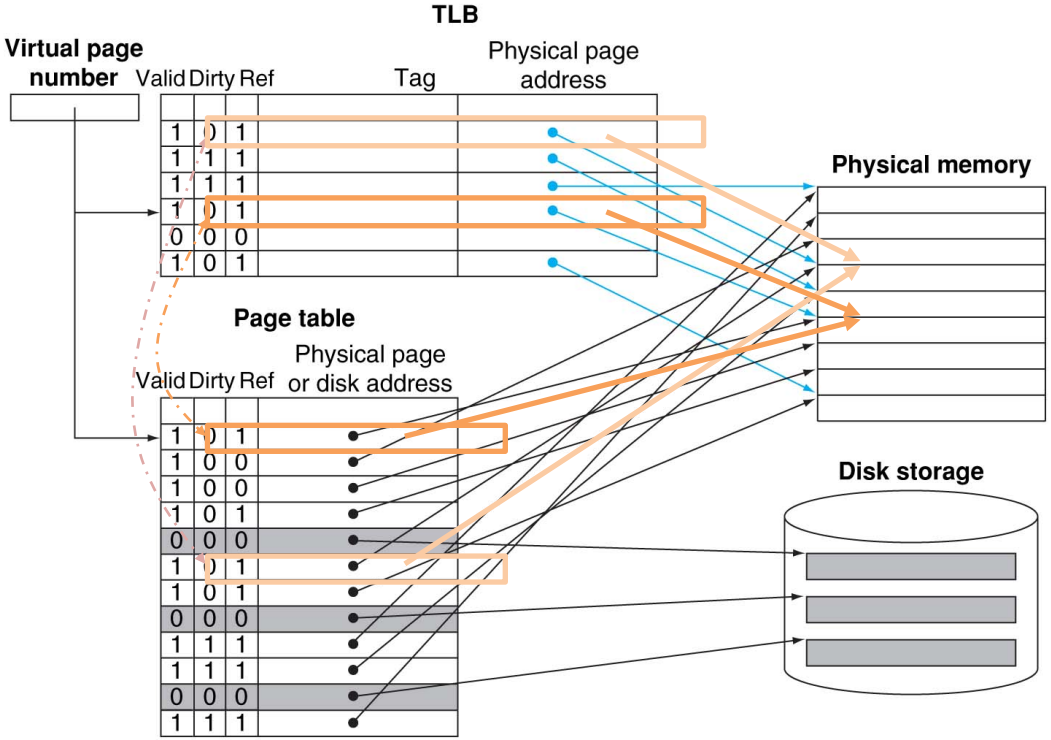
How can I make access to it faster?

Where have I heard that before... making accesses faster... I wonder...

The TLB:
A Cache for Page Tables

TLB (Translation Lookaside Buffer) is a cache for PTEs

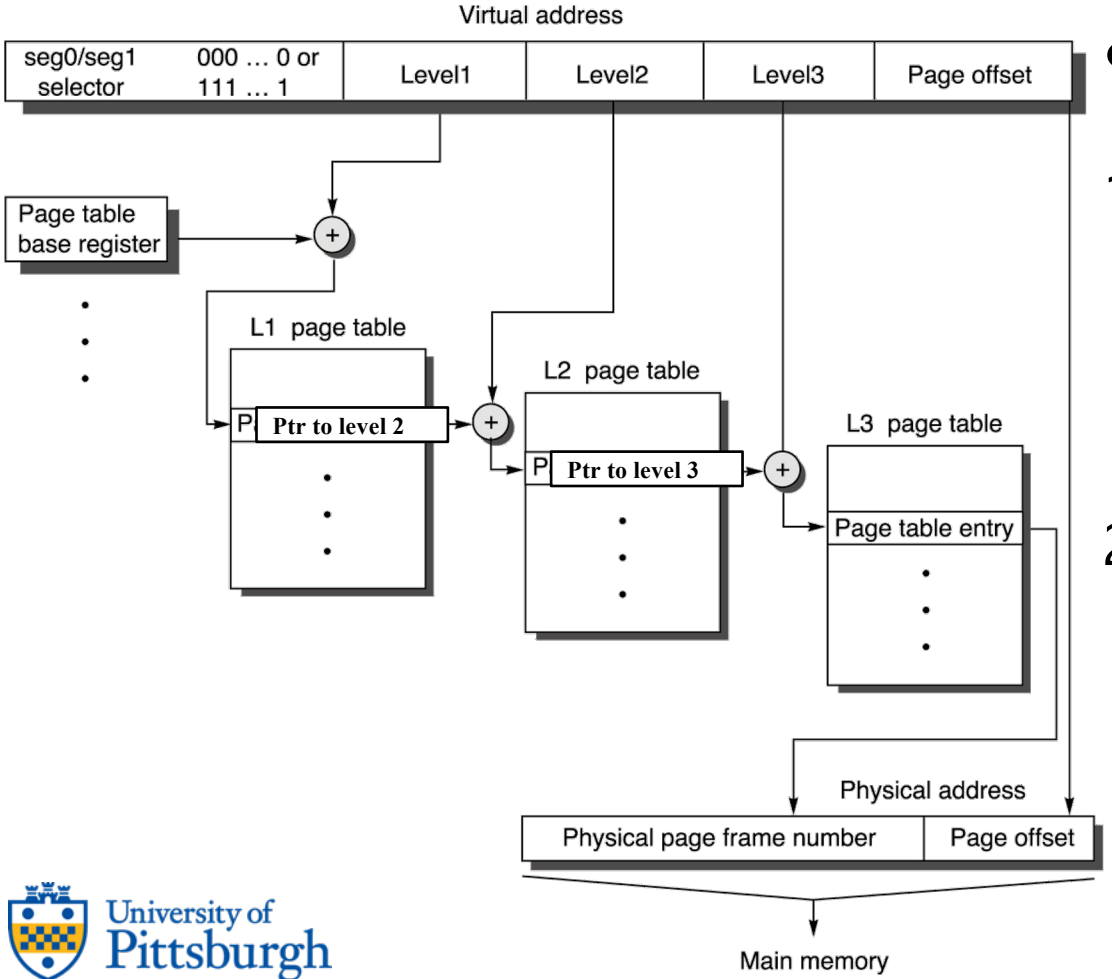
- **TLB**: A **cache** that contains frequently accessed **page table entries**



- TLB just like other caches resides within the CPU
- On a TLB **hit**:
  - No need to access page table in memory
- On a TBL **miss**:
  - Load PTE from page table
  - That means “walking” the hierarchical page table

On TLB miss, Page Table Walking needs to happen

- On a TLB miss, the CPU must "walk" the page table:



- Two options:

1. Software option
   - Miss raises OS exception
   - OS exception handler fills the TLB with PTE

2. Hardware option
   - CPU has special circuitry to walk page table (the **page table walker**)

→ Faster than SW option

TLB is organized as a cache

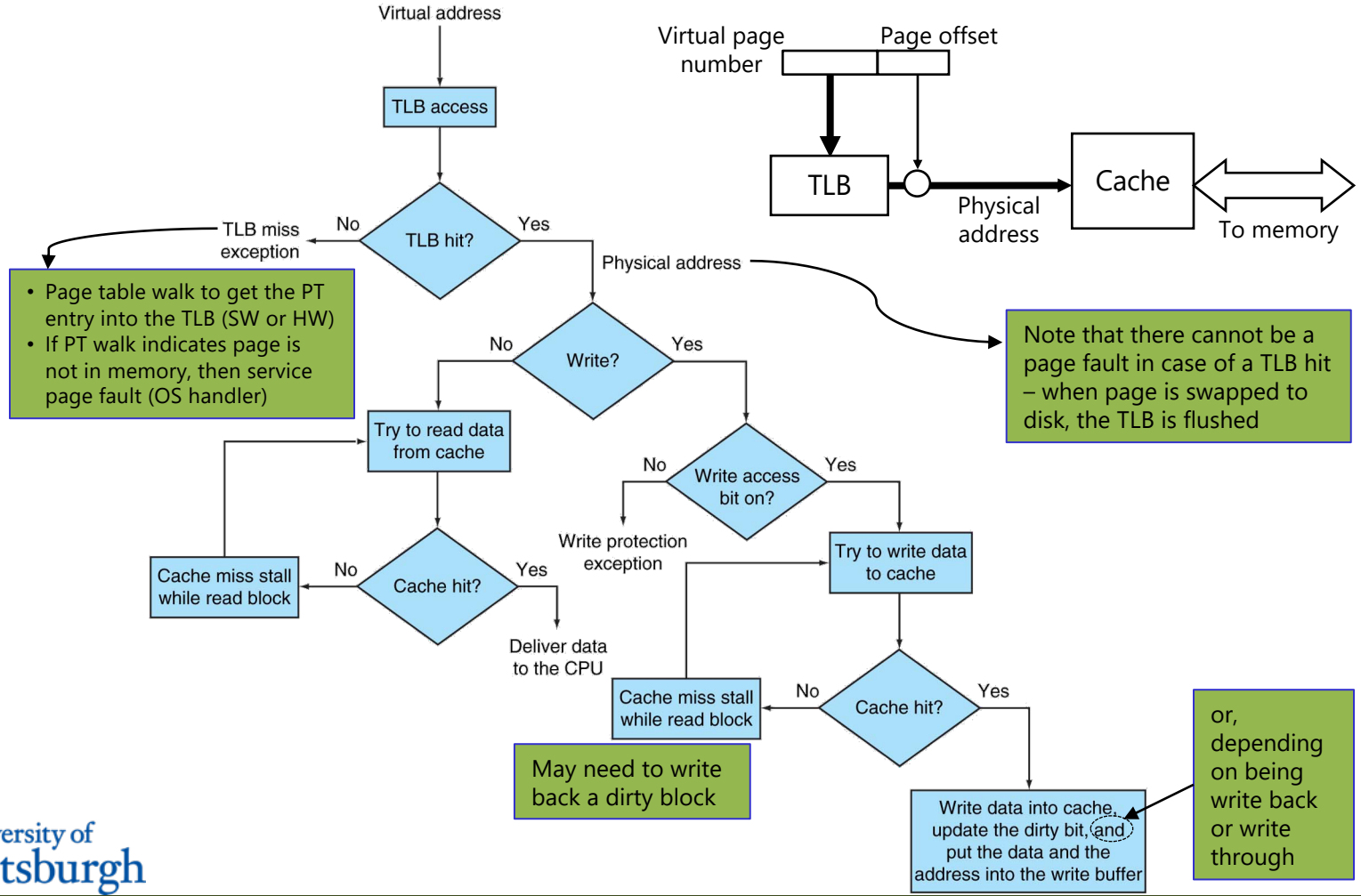
- The TLB holds PTEs – mappings from VAs to Pas

V	Tag (VA Page)	Permission bits	PA Page
1	00008	RX (read/exec)	03BFA
1	FFFF3	RW (read/write)	19400
…	…	…	…

- Typically, a fully associate or set-associative cache
  - Since a TLB miss requires a page walk and is expensive!

- V == 1 && Tag (VA Page) Match → TLB hit
  - Permission bits are checked, if no permission, exception is raised
  - Otherwise, physical address translation is returned

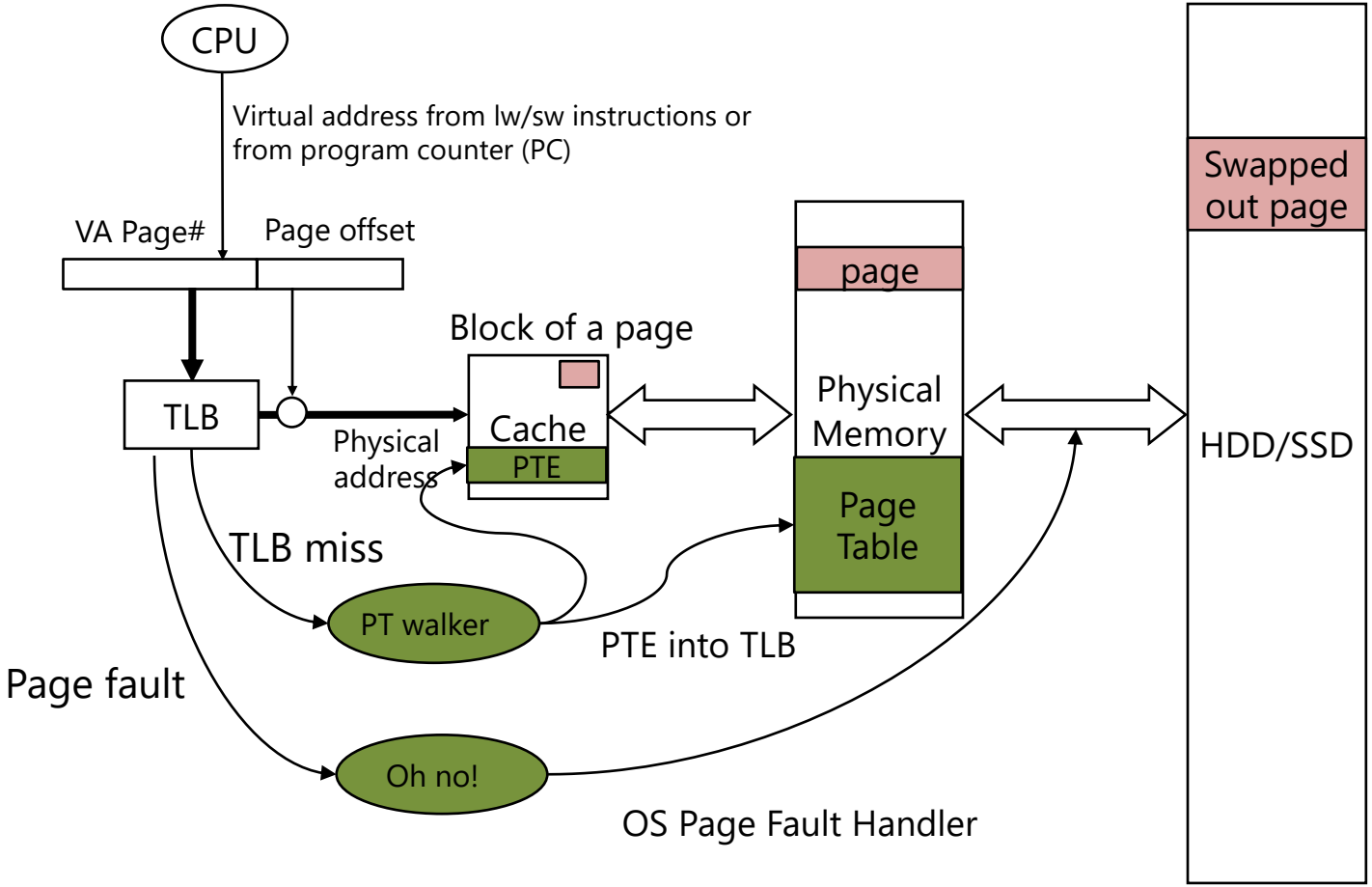
Memory Access Flowchart



TLBs in Real Processors

Characteristic	ARM Cortex-A8	Intel Core i7
Virtual address	32 bits	48 bits
Physical address	32 bits	44 bits
Page size	Variable: 4, 16, 64 KiB, 1, 16 MiB	Variable: 4 KiB, 2/4 MiB
TLB organization	1 TLB for instructions and 1 TLB for data Both TLBs are fully associative, with 32 entries, round robin replacement TLB misses handled in hardware	1 TLB for instructions and 1 TLB for data per core Both L1 TLBs are four-way set associative, LRU replacement L1 I-TLB has 128 entries for small pages, 7 per thread for large pages L1 D-TLB has 64 entries for small pages, 32 for large pages The L2 TLB is four-way set associative, LRU replacement The L2 TLB has 512 entries TLB misses handled in hardware

Caching Makes Everything Faster



Overall Memory System Design

- Fast memory access is possible through SW / HW collaboration: