Lecture 13:
Virtual Memory

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Outline

- Virtual Memory
  - Basics
  - Address Translation
  - Cache vs VM
  - Paging
  - Replacement
  - TLBs
  - Segmentation
  - Page Tables

Memory Hierarchy

Capacity
Access Time
Cost

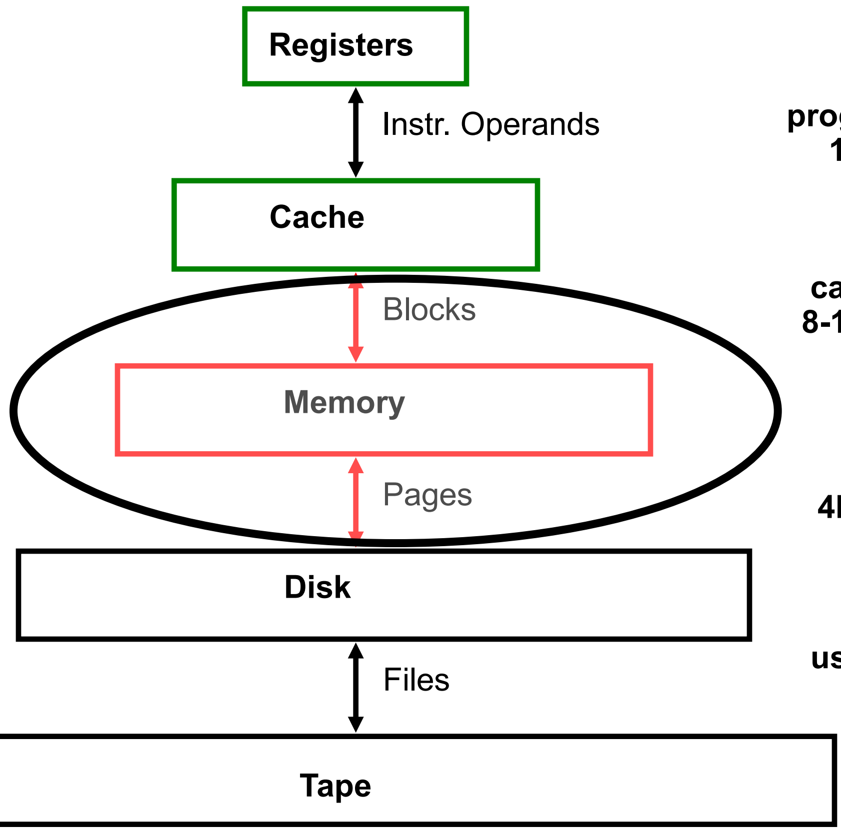
CPU Registers
100s Bytes
<10s ns

Cache
K Bytes
10-100 ns
1-0.1 cents/bit

Main Memory
M Bytes
200ns- 500ns
$.0001-.00001 cents /bit

Disk
G Bytes, 10 ms
(10,000,000 ns)
10^{-5} - 10^{-6} cents/bit

Tape
infinite
sec-min
10^{-8}



Staging
Xfer Unit

prog./compiler
1-8 bytes

cache cntl
8-128 bytes

OS
4K-16K bytes

user/operator
Mbytes

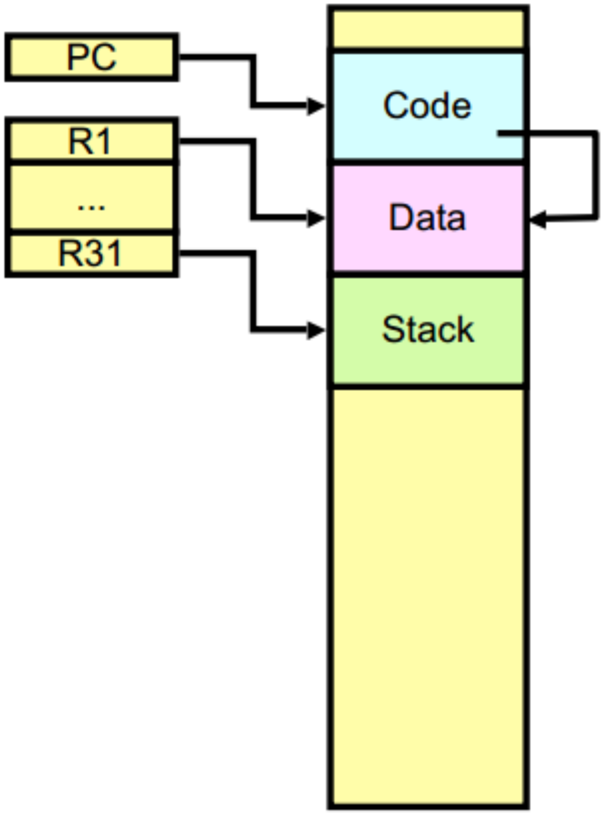
Upper Level

faster

Larger

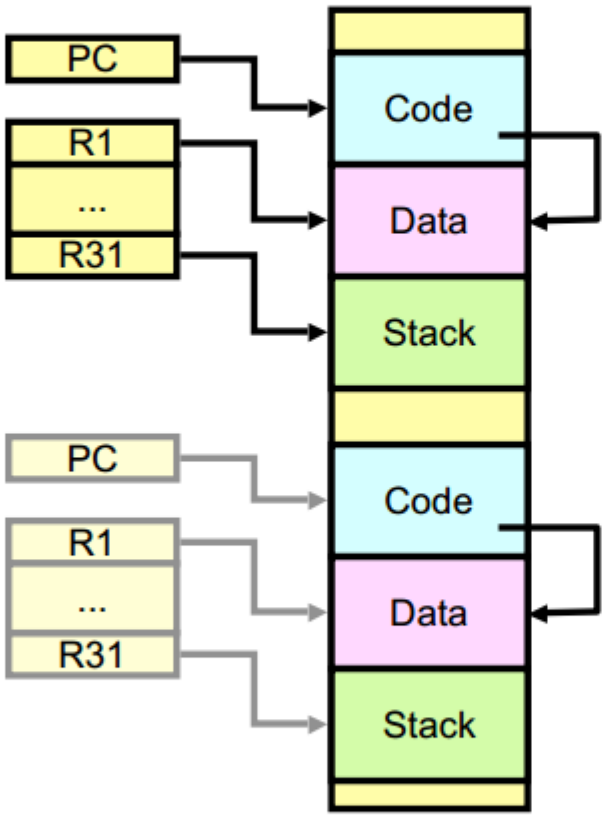
Lower Level

Simple View of Memory



- Single *program* runs at a time
- Code and static data are at fixed locations
  - code starts at fixed location, e.g., 0x100
  - subroutines may be at fixed locations (absolute jumps)
- data locations may be *wired* into code
- Stack accesses relative to stack pointer.

Running Two Programs (Relocation) No Protection



- Need to relocate *logical* addresses to *physical* locations
- Stack is already relocatable
  - all accesses relative to SP
- Code can be made relocatable
  - allow only relative jumps
  - all accesses relative to PC
- Data segment
  - can calculate all addresses relative to a DP
    - expensive
  - faster with hardware support
    - base register

Virtual Memory

- Some facts of computer life…
  - Computers run lots of processes simultaneously
  - No full address space of memory for each process
  - Must share smaller amounts of physical memory among many processes
- Virtual memory is the answer!
  - Divides physical memory into blocks (physical pages), assigns them to different processes
  - Virtual memory (VM) allows main memory (DRAM) to act like a cache for secondary storage (magnetic disk).
  - VM address translation provides a mapping from the virtual address of the processor to the physical address in main memory or on disk.

Three Advantages of Virtual Memory

- **Translation:**
  - Program can be given consistent view of memory, even though physical memory is scrambled
  - Makes multithreading reasonable (now used a lot!)
  - Only the most important part of program ("Working Set") must be in physical memory.
  - Contiguous structures (like stacks) use only as much physical memory as necessary yet still grow later.
- **Protection:**
  - Different threads (or processes) protected from each other.
  - Different pages can be given special behavior
    - » (Read Only, Invisible to user programs, etc).
  - Kernel data protected from User programs
  - Very important for protection from malicious programs
- **Sharing:**
  - Can map same physical page to multiple users ("Shared memory")

Protection with Virtual Memory

- Virtual memory allows protection without the requirement that pages be pre-allocated in contiguous chunks

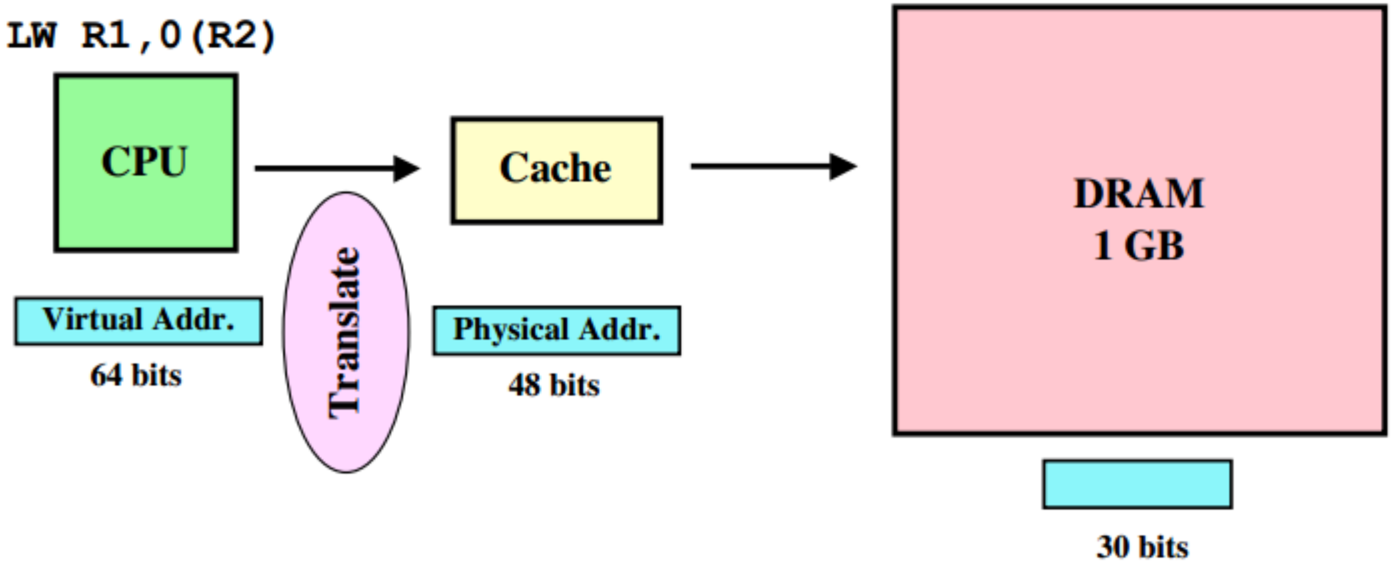
- Physical pages are allocated based on program needs and physical pages belonging to different processes may be adjacent – efficient use of memory

- Each page has certain read/write properties for user/kernel that is checked on every access
  - a program's executable can not be modified
  - part of kernel data cannot be modified/read by user
  - page tables can be modified by kernel and read by user

Basics

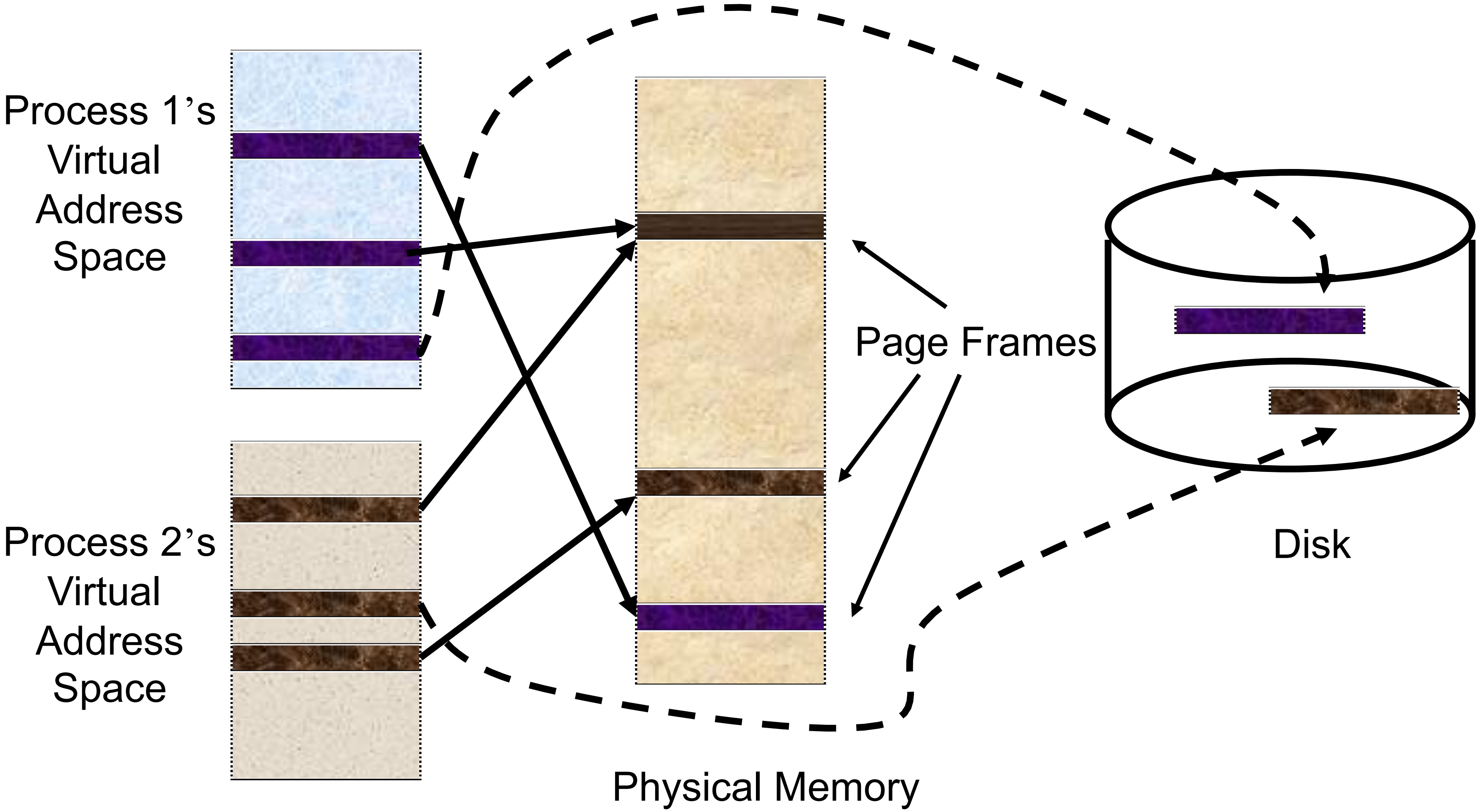
- Programs reference “virtual” addresses in a non-existent memory
  – These are then translated into real “physical” addresses
  – Virtual address space may be bigger than physical address space
- Divide physical memory into blocks, called pages
  – Anywhere from 512B to 16MB (4k typical)
- Virtual-to-physical translation by indexed table lookup
  – Add another cache for recent translations (the TLB)
- Invisible to the programmer
  – Looks to your application like you have a lot of memory!

A Load to Virtual Memory

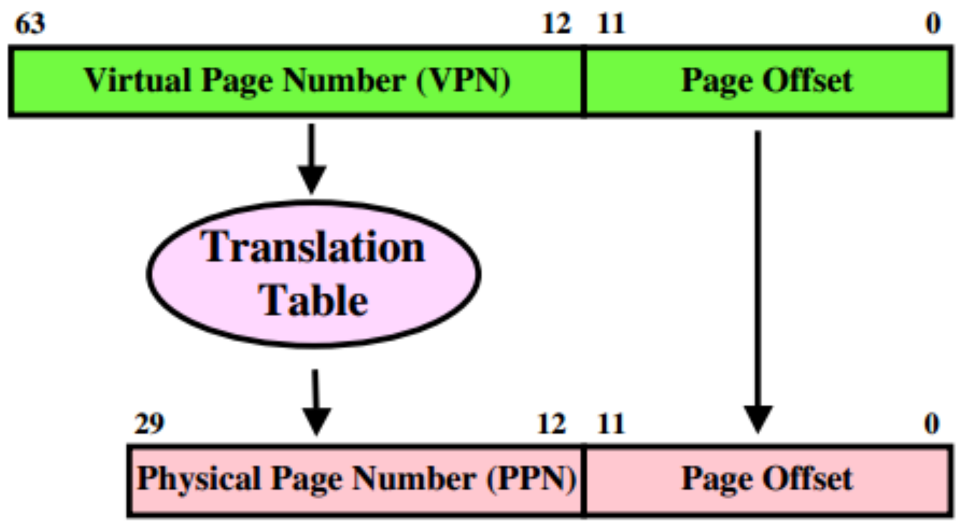


- Translate from virtual space to physical space
  - VA ⇒ PA
  - May need to go to disk

VM: Page Mapping



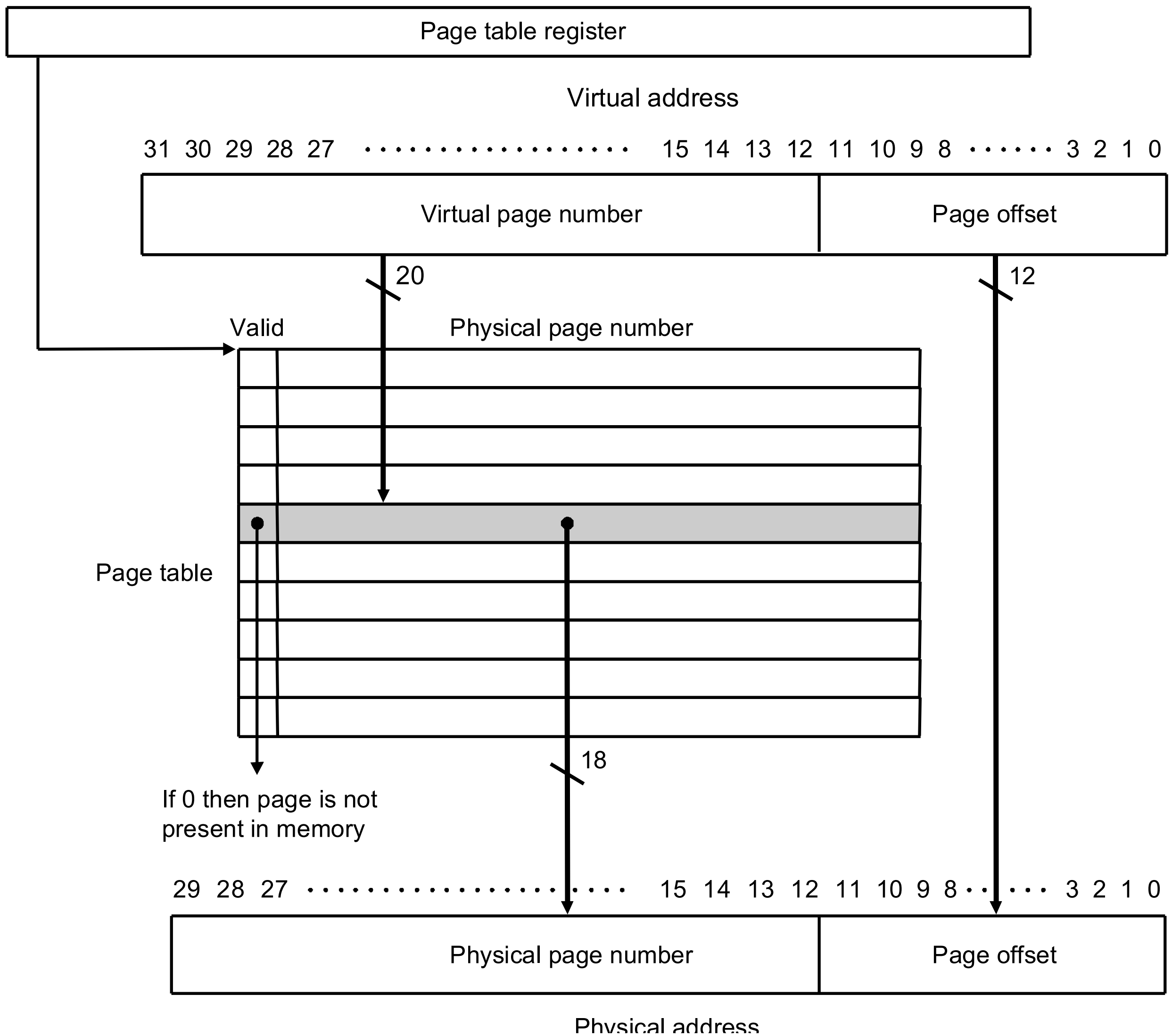
Virtual Address Translation



- Main Memory = 1 GB
- Page Size = 4KB
- VPN = 52 bits
- PPN = 18 bits

- Translation table
  - aka "Page Table"

Virtual Address Translation



Cache terms vs. VM terms

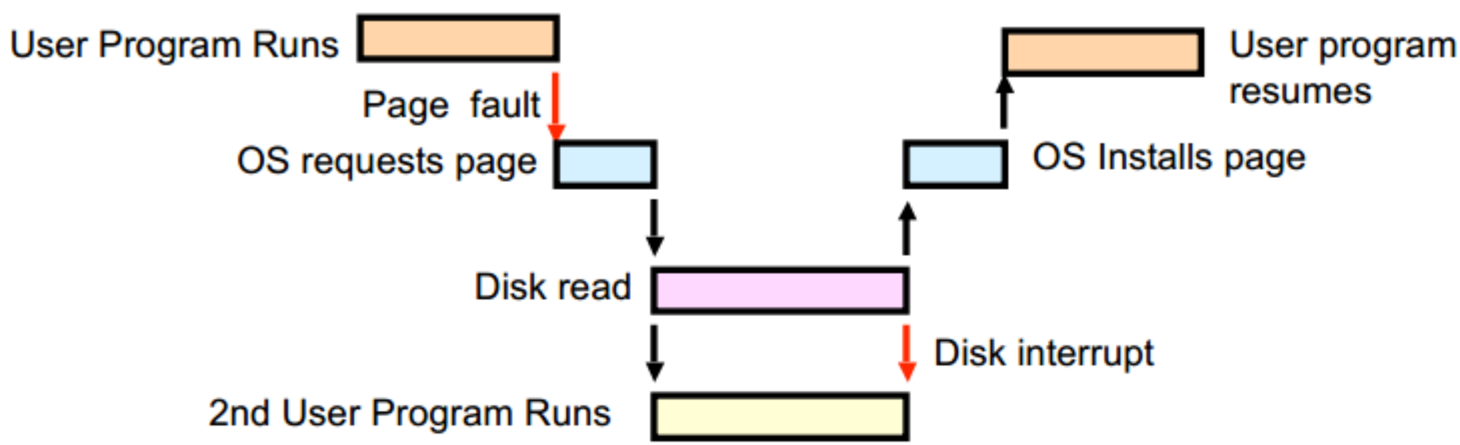
"real"/physical memory

So, some definitions/"analogies"

– A "*page*" or "*segment*" of memory is analogous to a "block" in a cache

– A "*page fault*" or "*address fault*" is analogous to a cache miss

so, if we go to main memory and our data isn't there, we need to get it from disk…



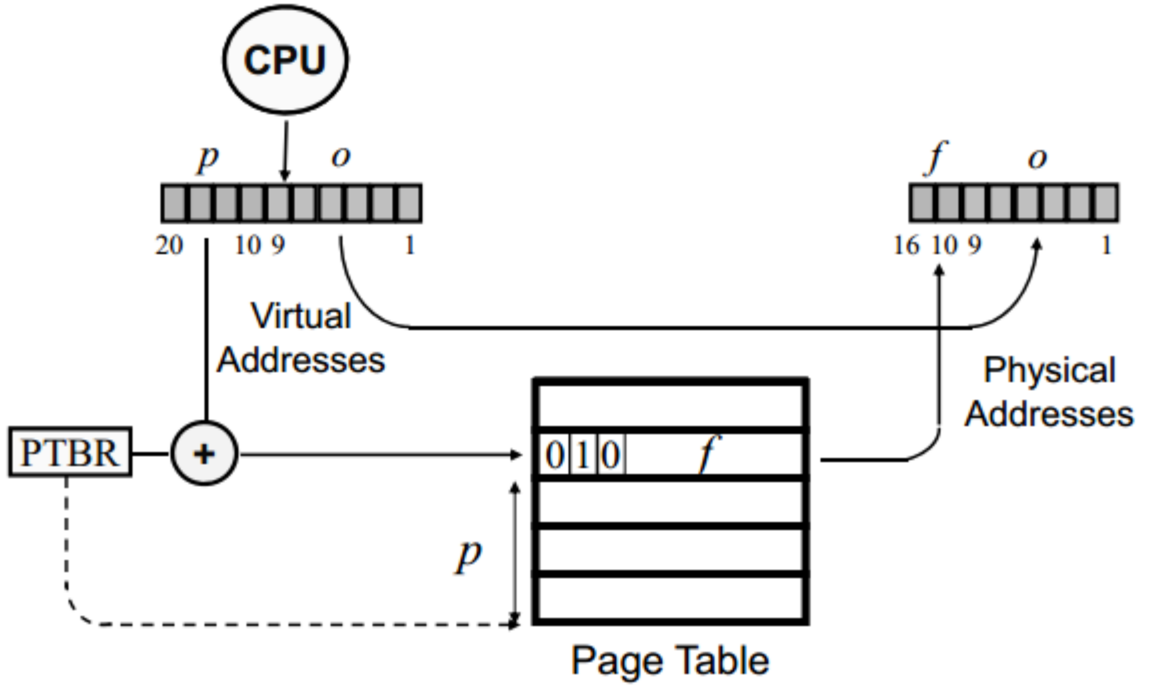
Page Fault

- What happens when a process references a virtual address in a page that has been evicted (or never loaded)?
  - when the page was evicted, the OS set the PTE as invalid and noted the disk location of the page in a data structure (that looks like a page table but holds disk addresses)
  - when a process tries to access the page, the invalid PTE will cause an exception (page fault) to be thrown
    - OK, it's actually an interrupt!
  - the OS will run the page fault handler in response
    - handler uses the "like a page table" data structure to locate the page on disk (disk map)
    - handler reads page into a physical frame, updates PTE to point to it and to be valid
    - OS restarts the faulting process
    - **there are a million and one details …**
      for example: *demand paging* loads pages into memory only as they are needed by the process

Virtual Address Translation Details

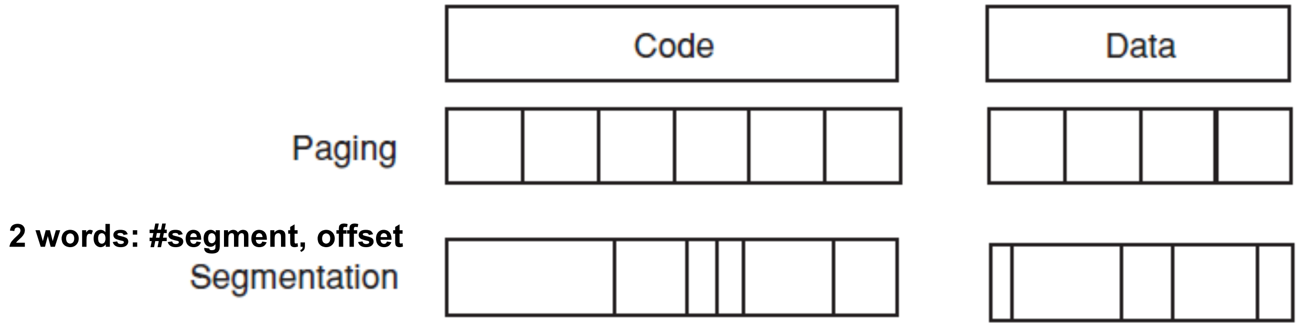
1 table per process
Part of process's state

- Contents:
  - Flags — dirty bit, resident bit, clock/reference bit
  - Frame number



PTBR: Page Table Base Register

Segmentaion VS Paging



	Page	Segment
Words per address	One	Two (segment and offset)
Programmer visible?	Invisible to application programmer	May be visible to application programmer
Replacing a block	Trivial (all blocks are the same size)	Hard (must find contiguous, variable-size, unused portion of main memory)
Memory use inefficiency	Internal fragmentation (unused portion of page)	External fragmentation (unused pieces of main memory)
Efficient disk traffic	Yes (adjust page size to balance access time and transfer time)	Not always (small segments may transfer just a few bytes)

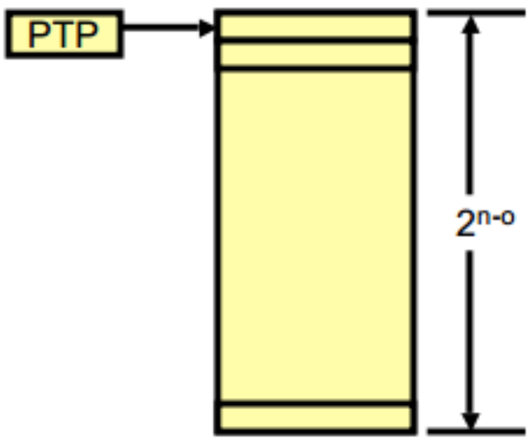
*Hybrid solution: 1) **Paged segments**, segment is an integral number of pages*
*2) **Multiple page sizes**, with larger sizes being powers of 2 times*

Cache VS VM

Parameter	First-level cache	Virtual memory
Block (page) size	12-128 bytes	4096-65,536 bytes
Hit time	1-2 clock cycles	40-100 clock cycles
Miss penalty (Access time) (Transfer time)	8-100 clock cycles (6-60 clock cycles) (2-40 clock cycles)	700,000 – 6,000,000 clock cycles (500,000 – 4,000,000 clock cycles) (200,000 – 2,000,000 clock cycles)
Miss rate	0.5 – 10%	0.00001 – 0.001%
Data memory size	0.016 – 1 MB	4MB – 4GB

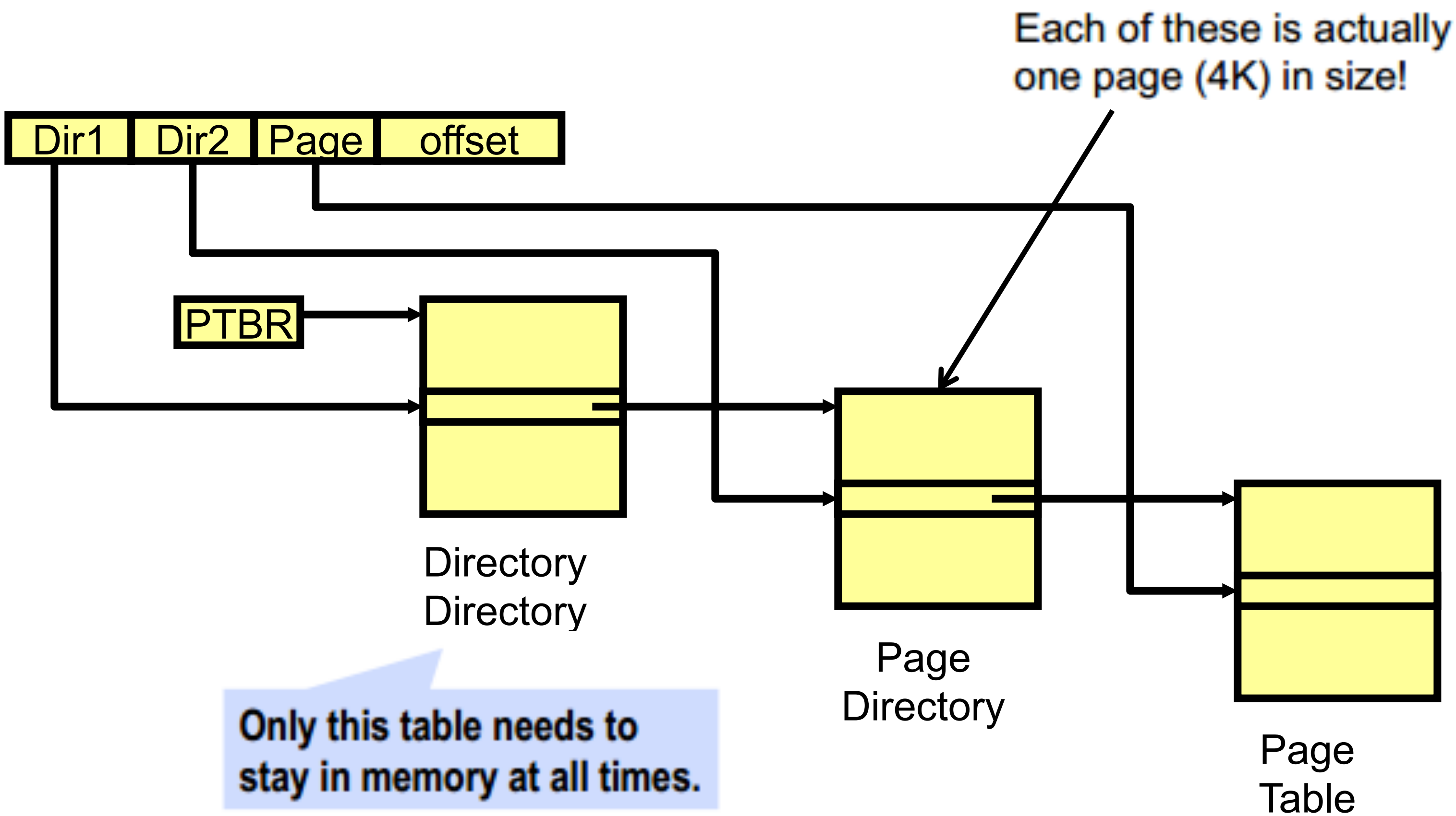
- Replacement on cache misses is primarily controlled by hardware
- The size of the processor address determines the size of virtual memory
- Secondary storage is also used for the file system

Page Table Organization



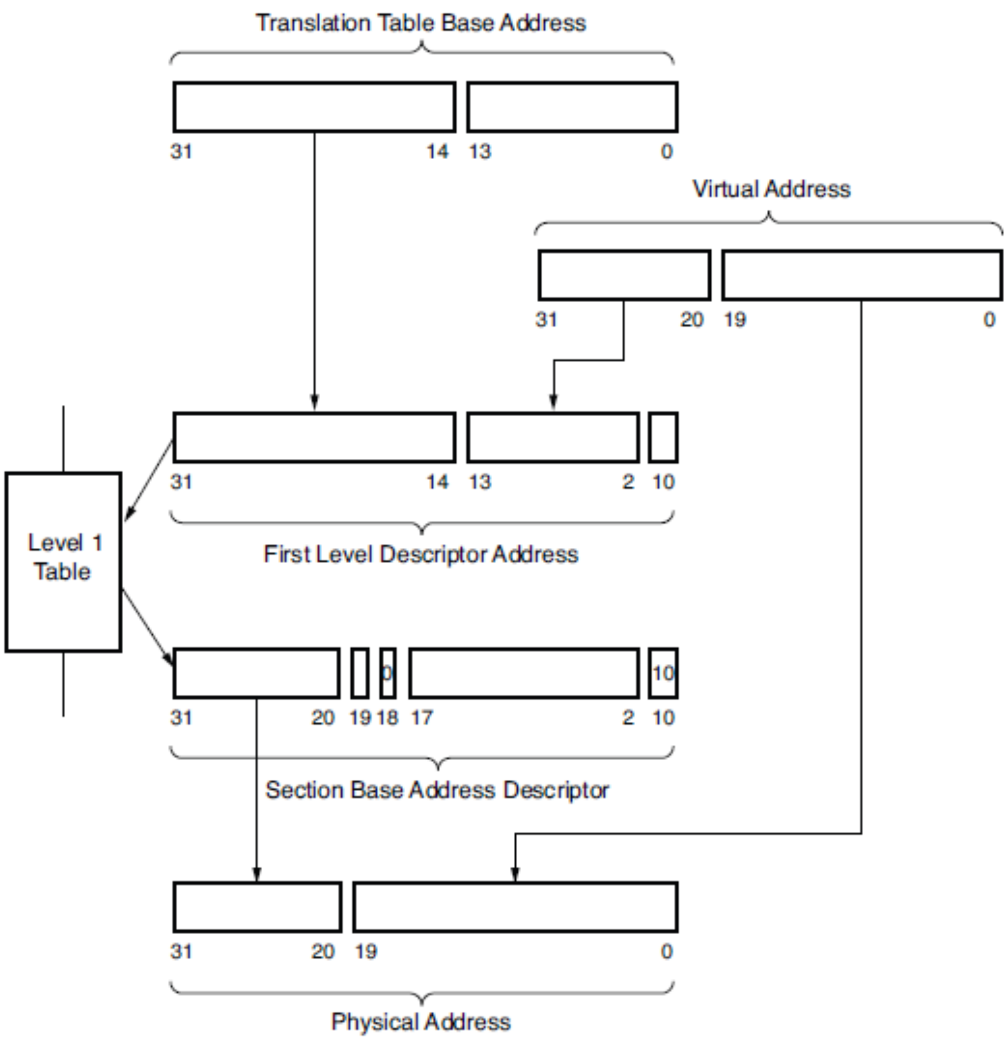
- Flat page table has size proportional to size of *virtual* address space
  - can be very large for a machine with 64-bit addresses and several processes
- Three solutions
  - page the page table (fixed mapping)
    - what really needs to be *locked down?*
  - multi-level page table (lower levels paged - Tree)
  - inverted page table (hash table)

Multi-Level Page Table



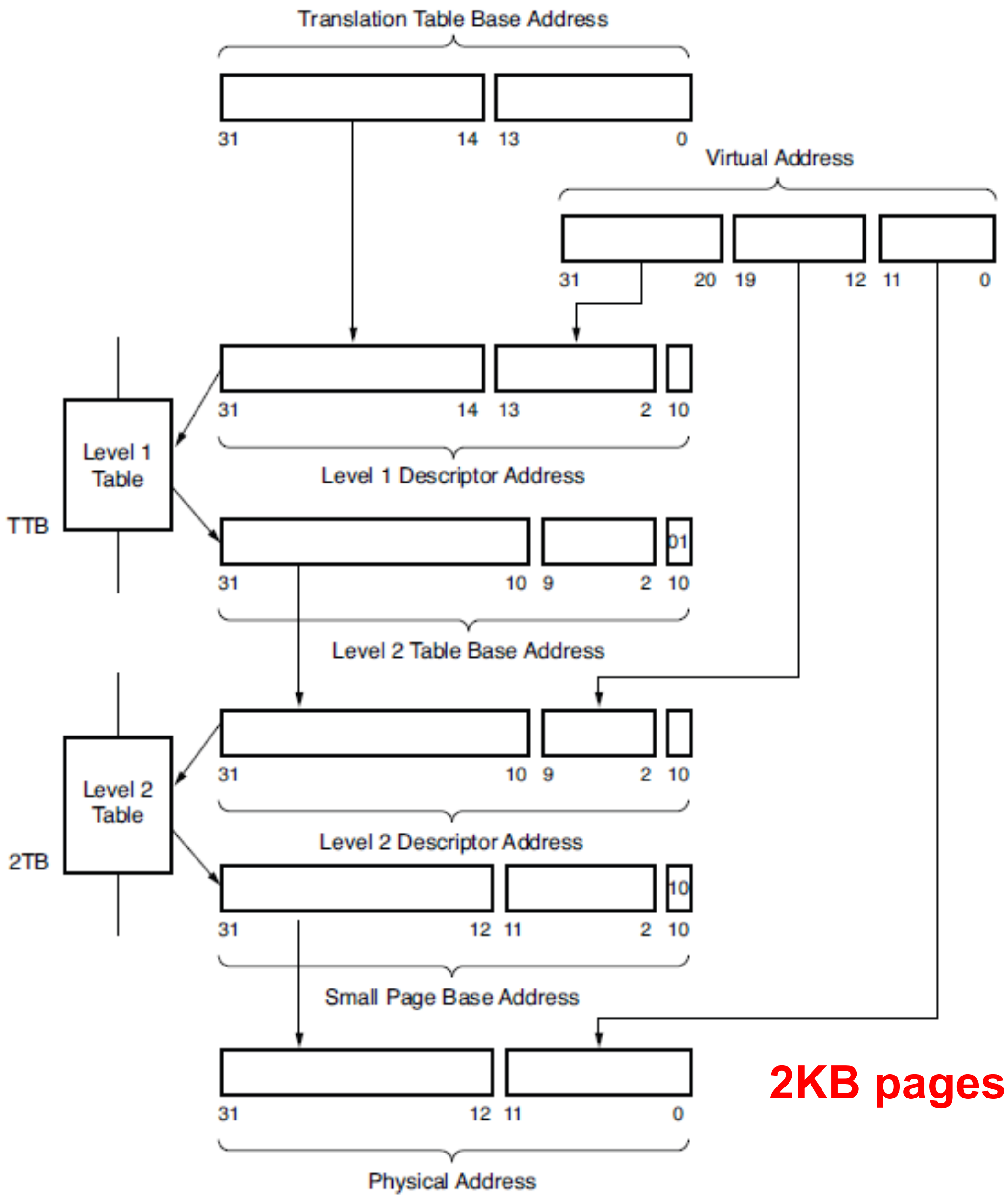
e.g., 42-bit VA with 12-bit offset
10-bits for each of three fields
1024 4-byte entries in each table (one page)

Translation Table Base Address/Register



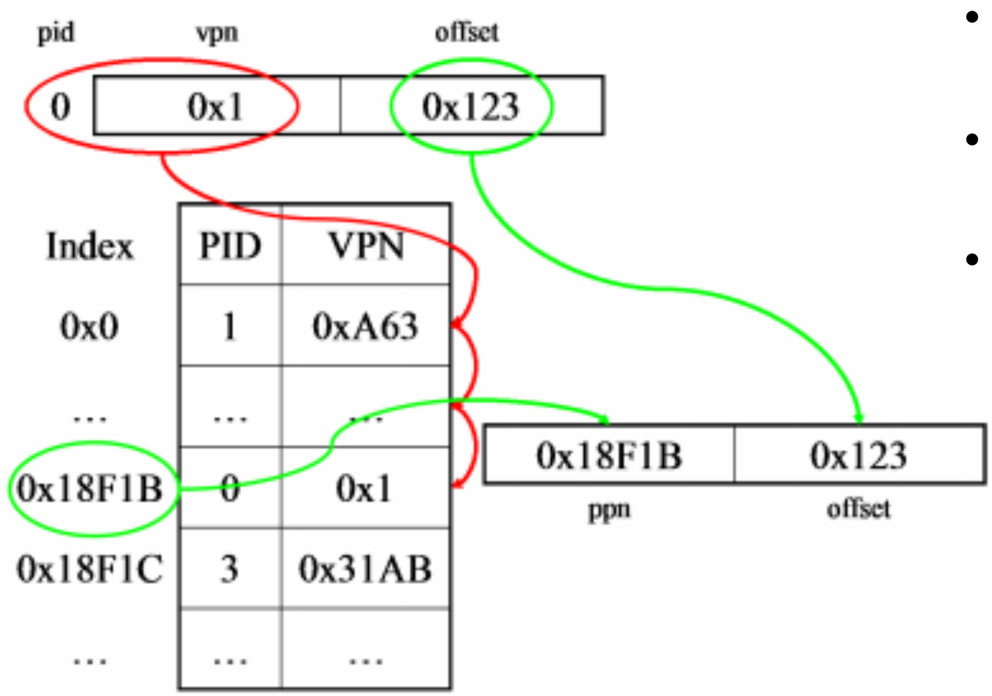
ARM A9 Page Table (1MB section)

L1+L2 Translation in A9



2KB pages

Linear Inverted Page Tables

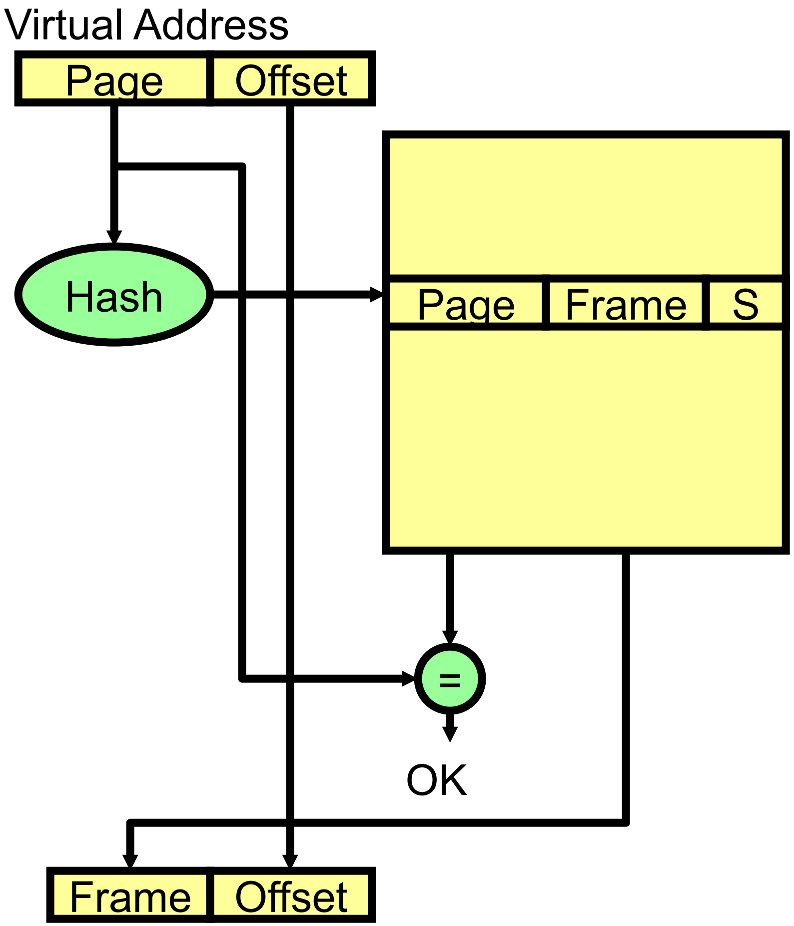


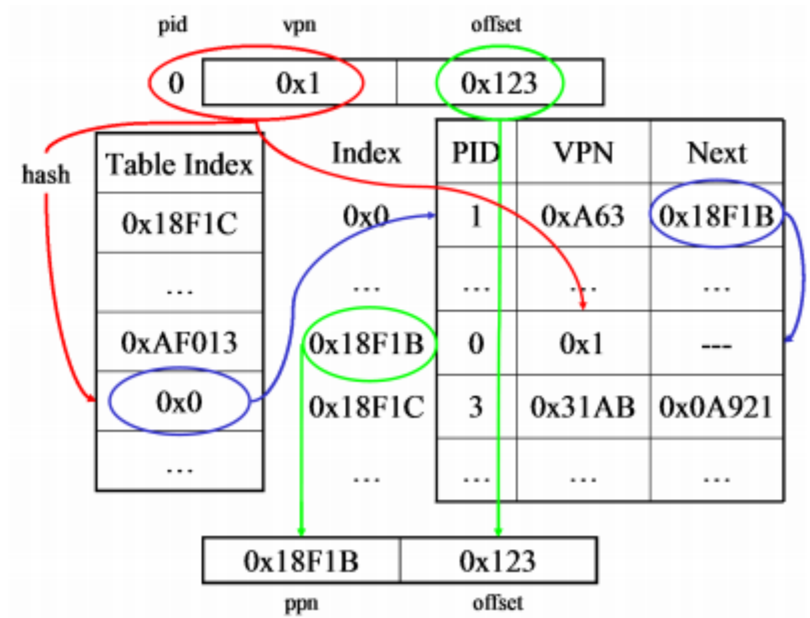
- Store only PTEs for pages *in* physical memory
- Miss in page table implies page is on disk
- Need KP entries for P page frames (usually K > 2)

Requires a large CAM

http://www.cs.berkeley.edu/~kamil/teaching/sp04/040104.pdf

Hashed Inverted Page Tables





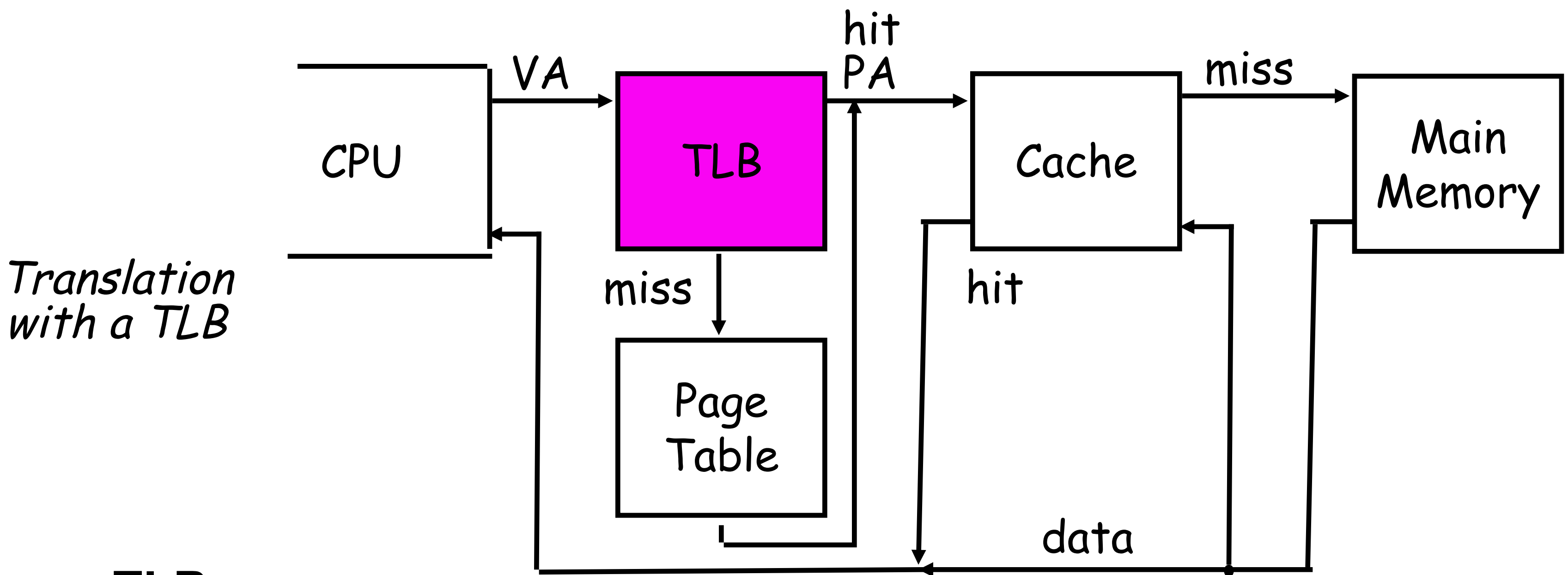
- **Chaining in order to solve collisions**
- **Chain is exhausted by hitting an invalid next pointer => page fault**

Virtual Address Translation - TLB

- What happens during a memory access?
  - map virtual address into physical address using page table
  - If the page is in memory: access physical memory
  - If the page is on disk: page fault
    - » Suspend program
    - » Get operating system to load the page from disk
- Page table is in memory - this slows down access!
- Translation lookaside buffer (TLB) special cache of translated addresses (speeds access back up)

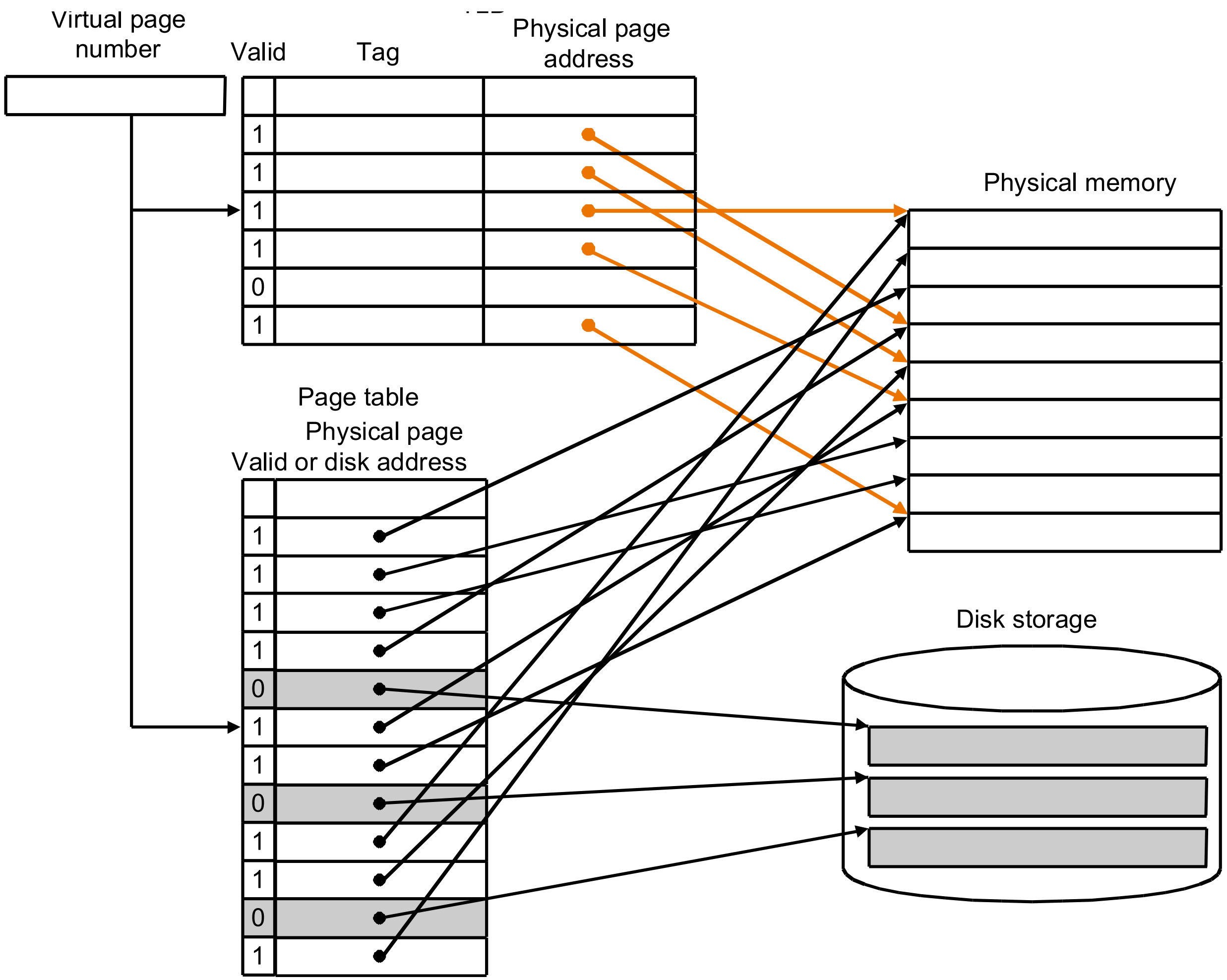
Translation Look-Aside Buffers

- **Translation Look-Aside Buffers (TLB)**
  - **Cache on translations**
  - **Fully Associative, Set Associative, or Direct Mapped**



- **TLBs are:**
  - **Small – typically not more than 128 – 256 entries**
  - **Fully Associative or 2-way set Associative**
    - **For example: A9 has 2 (instruction & data) 32-entry fully assoc. Micro TLBs and one 128-entry 2-way associative Main TLB**

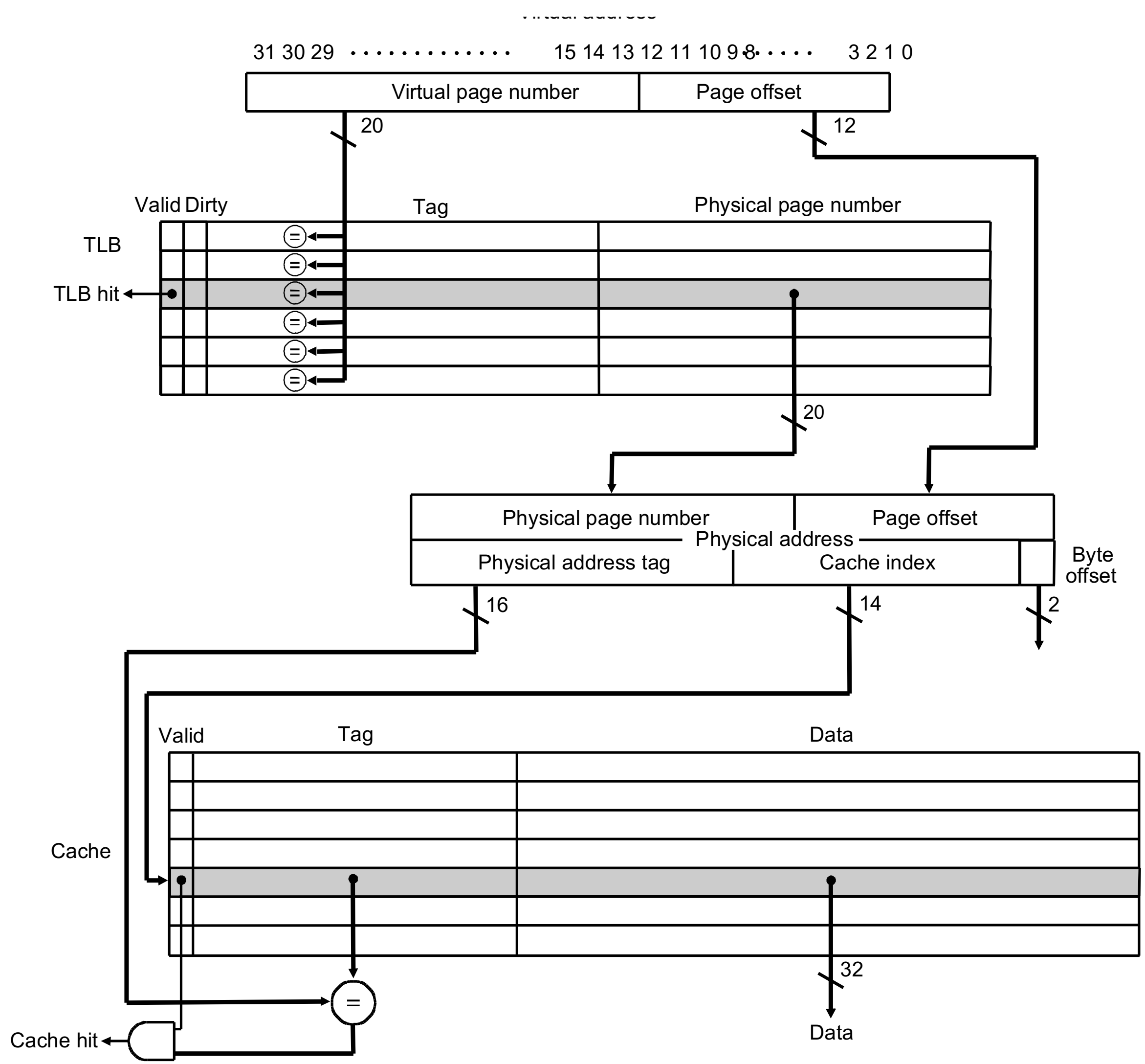
TLB Structure



What Actually Happens on a TLB Miss?

- Hardware-traversed page tables:
  - On TLB miss, hardware in MMU looks at current page table to fill TLB (may walk multiple levels)
    - » If PTE valid, hardware fills TLB and processor never knows
    - » If PTE marked as invalid, causes Page Fault, after which kernel decides what to do afterwards
- Software-traversed Page tables (like MIPS)
  - On TLB miss, processor receives TLB fault
  - Kernel traverses page table to find PTE
    - » If PTE valid, fills TLB and returns from fault
    - » If PTE marked as invalid, internally calls Page Fault handler
- Most chip sets provide hardware traversal
  - Modern operating systems tend to have more TLB faults since they use translation for many things
  - Examples:
    - » shared segments
    - » user-level portions of an operating system

TLB – Cache Interaction



TLB and Cache

- Is the cache indexed with virtual or physical address?
  - To index with a physical address, we will have to first look up the TLB, then the cache → longer access time
  - Multiple virtual addresses can map to the same physical address – can we ensure that these different virtual addresses will map to the same location in cache? Else, there will be two different copies of the same physical memory word

- Does the tag array store virtual or physical addresses?
  - Since multiple virtual addresses can map to the same physical address, a virtual tag comparison can flag a miss even if the correct physical memory word is present

C-36 in textbook

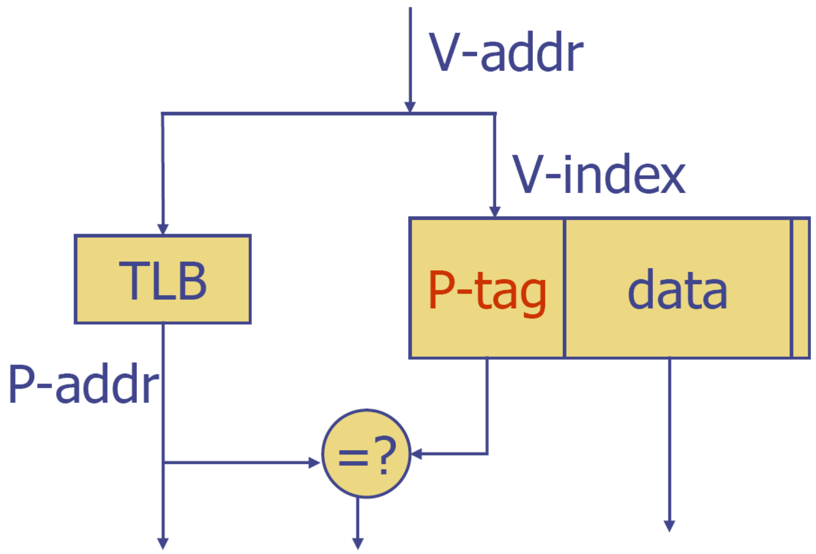
Virtual Indexed, Virtually Tagged Cache

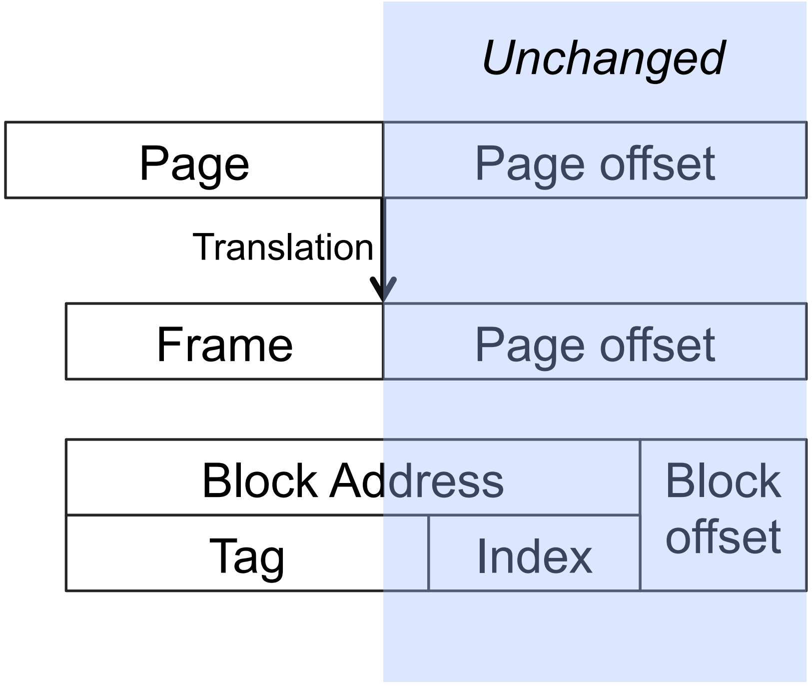
- **Protection bits** in cache
- **Cache flushing** on process switch or use **Process-identifier tag** (PID) (or Address Space Identifier=ASID)
- **Aliasing problem**: Two different virtual addresses sharing same physical
  – Page coloring: Forces aliases to share same cache block (i.e. alias addresses should have same cache index), thus aliases cannot co-exist in the cache

Better Alternative: Virtually Indexed, Physically Tagged Cache

What motivation?

- Fast cache hit by parallel TLB access
- No virtual cache shortcomings

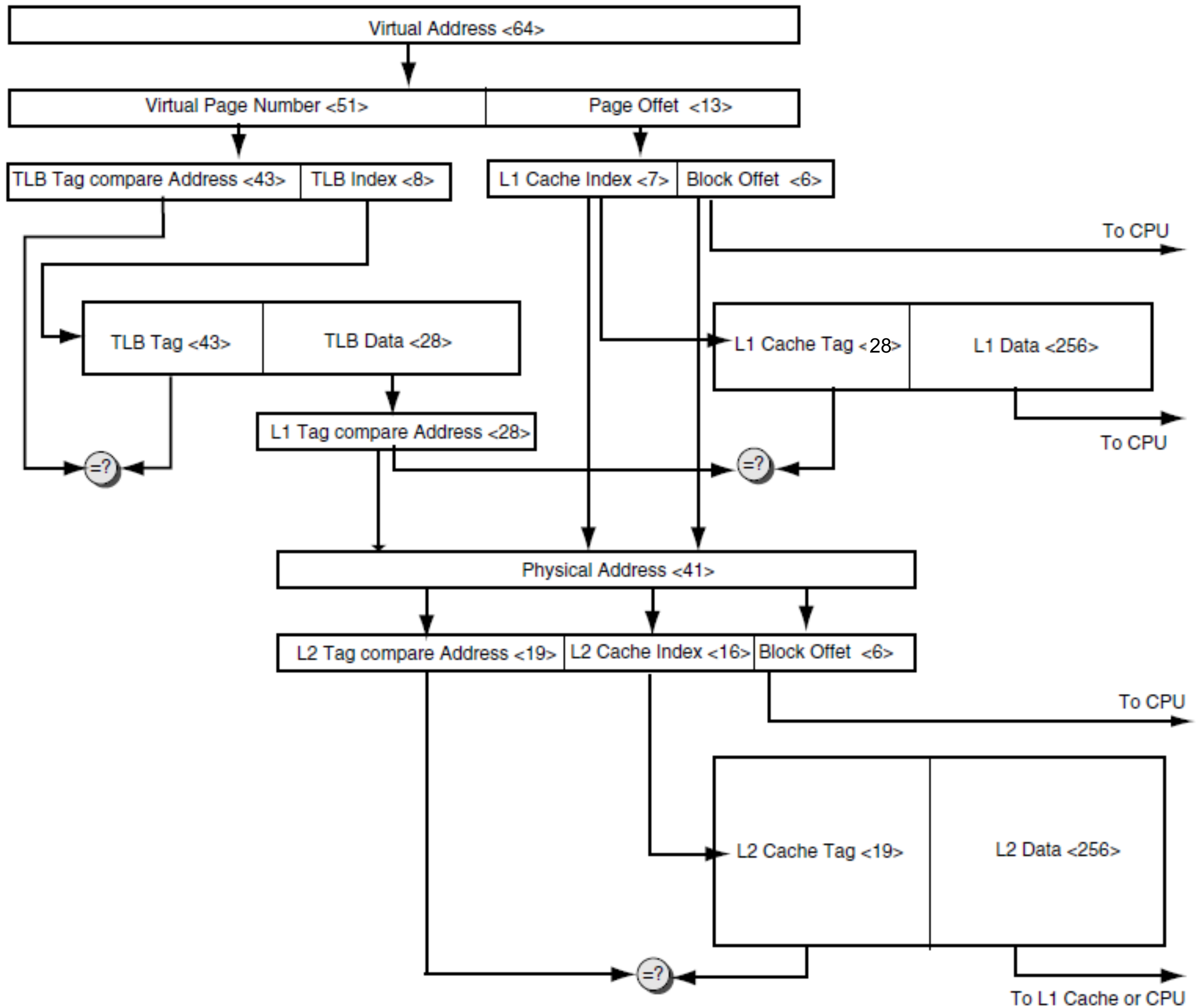




How could it be correct?

- Require #cache set * block size <= page size ⇒ physical index is from page offset
- Then virtual and physical indices are identical ⇒ works like a physically indexed cache!

Virtually Indexed, Physically Tagged Cache



Superpages

- If a program's working set size is 16 MB and page size is 8KB, there are 2K frequently accessed pages – a 128-entry TLB will not suffice
- By increasing page size to 128KB, TLB misses will be eliminated – disadvantage: memory wastage, increase in page fault penalty
- Can we change page size at run-time?
- Note that a single large page has to be contiguous and aligned in physical memory: 128KB (17bits) page includes 16 8KB(13 bits) pages

Superpages Implementation

- At run-time, build superpages if you find that contiguous virtual pages are being accessed at the same time
- For example, virtual pages 64-79 may be frequently accessed – coalesce these pages into a single superpage of size 128KB that has a single entry in the TLB
- The physical superpage has to be in contiguous physical memory – the 16 physical pages have to be moved so they are contiguous